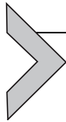

CHAPTER FIVE

Mineral Nutrition of Cocoa: A Review

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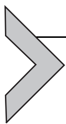
Abstract

Cocoa is an important global commodity. It is mostly grown on small farms by millions of cocoa farmers who depend on the crop for their livelihood. Although potential yields exceed 6000 kg/ha, average farm yields are often around 400 kg/ha. Among the production constraints met by farmers is nutrient limitation. In this review, we compile current knowledge on nutrient cycling in cocoa production systems, nutrient requirements of cocoa, and yield response to fertilizer application in relation to factors such as management, climatic, and soil conditions. Large amounts of nutrients are cycled within cocoa systems, mostly through 5–10 t/ha/yr litter fall. Still, harvesting and small nutrient losses such as leaching lead to nutrient exports causing gradual soil nutrient depletion. Exact nutrient requirements of cocoa are unknown. Leaf and soil test interpretation to identify additional nutrient needs remain ambiguous. Recommended nutrient application rates vary more than 10-fold. In several trials fertilizer application more than doubled cocoa productivity; in other cases response is minimal. Differences in response between regions, fields and even trees have yet to be explained. Interactions with agroecology and management (especially shade) are poorly understood. Without this fundamental knowledge, farm level recommendations have a weak scientific base. Different types of research are recommended to complement current knowledge. Existing data and trials can be exploited through additional analysis and more detailed measurements. Cocoa farms are highly diverse and on-farm trials offer opportunities for understanding variability in production and fertilizer response. Finally, multifactorial shade–fertilizer response trials will be essential to address some of the fundamental knowledge gaps.



1. INTRODUCTION

1.1 Cocoa Production

We all know cocoa as the key raw material for production of chocolate. Far less well known is the fact that cocoa grows in pods on a tree (*Theobroma cacao* L.) which originates from the tropical rainforests of the Americas. Cocoa was known in pre-Columbian times to the Mayas, who cultivated the tree in agroforestry systems (Almeida and Valle, 2007). Cocoa is grown almost exclusively within 10°N and 10°S of the equator. Here, the climate is warm

and humid and thus suitable for growing cocoa (Hartemink and Donald, 2005). At the beginning of the 19th century, almost all of the world's cocoa was produced in tropical Latin America and Trinidad (Cunningham and Arnold, 1962). Production has now shifted largely to Africa and Asia (ICCO, 2015). Global annual production of cocoa currently exceeds 4 million tons. About 72% of the world's cocoa is produced in Africa, with Côte d'Ivoire being the top producer at 43% of global production (ICCO, 2015). Cocoa is a major source of export earnings for many producing countries, especially in West Africa (ICCO, 2012). Most of this cocoa is processed and consumed in Western Europe and the United States, although grinding of cocoa in the country of origin is increasing (ICCO, 2012, 2015). Industry experts predict the demand for cocoa beans to increase to 5 million tons in 2020 (CacaoNet, 2012). This will result from increased demand for high-cocoa content chocolate in the mature markets as well as a rapidly increasing demand for cocoa-based products in emerging markets, such as the BRIC countries (Brazil, the Russian Federation, India, and China). Over recent years, concerns have been rising within the cocoa industry as the market seems to have entered a period of supply deficit (ICCO, 2012). Global demand for cocoa is expected to outstrip supply within the next decade (CacaoNet, 2012). Over the past 35 years, global production of cocoa has increased steadily. As can be seen from Fig. 1, this increase in productivity has been achieved largely through an increase in the area under production. Although there have been periods in which yields have increased significantly (e.g., in the 1980s), since the 1990s yields have stagnated and are even declining in many regions. Given that land availability constrains further expansion of the production area, there is an urgent need to increase cocoa yields (Gockowski and Sonwa, 2011).

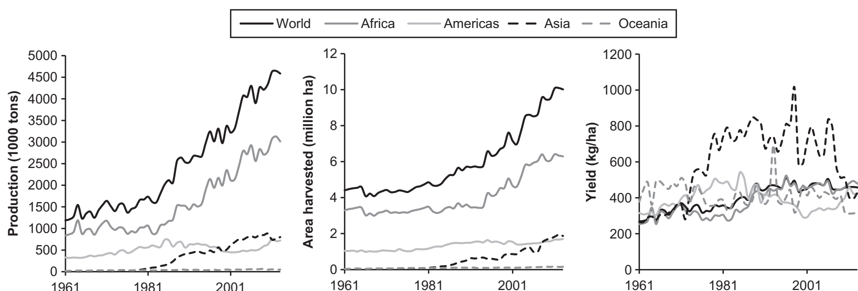


Fig. 1 Cocoa production, area harvested, and yields of different continents and the world. *Based on data from FAOSTAT (2016).*

Around 80–90% of global cocoa production occurs on smallholder farms, by about 5–6 million cocoa farmers worldwide (WCF, 2014). These farmers depend on cocoa for their livelihood. Current average yields in these farms are small. For instance, in Ghana yields are estimated at around 400 kg/ha (Aneani and Ofori-Frimpong, 2013) while potential yields under rainfed conditions are modeled at 5000 kg/ha (Zuidema et al., 2005). Cocoa trees have aged and are in need of replacement (CCC, 2014; Wessel and Quist-Wessel, 2015). Weather conditions show yearly fluctuations and often hamper yields, and predicted changes in climatic conditions in many regions are likely to decrease suitability for cocoa production (ICCO, 2012; Läderach et al., 2013). Soil nutrient levels have declined and can no longer support productive cocoa (Appiah et al., 2000). Pests and diseases reduce yields (CacaoNet, 2012). Farmers are reluctant to invest in inputs such as new planting material, fertilizers, and pesticides due to the low farm gate price of cocoa (ICCO, 2012), or do not have access to such inputs (Aneani and Ofori-Frimpong, 2013). The direct reasons of low yields are technical in nature. Underlying causes are often social or economic. Solving the problems requires the joint efforts of both the public and the private stakeholders involved in the cocoa sector. Indeed, as worries about supply deficits rose over the past years, there has been an increase in sector-wide approaches in sustainability, which are primarily focused on increasing productivity (Fountain and Hütz-Adams, 2015). In some programs, such as CocoaAction (WCF, 2015), globally important cocoa and chocolate companies work together in partnership with governments and cooperatives. Companies also have their own programs, commitments, and partnerships, such as Cocoa Promise (Cargill, 2016), Cocoa Plan (Nestlé, 2016), and Cocoa Life (Mondelez International, 2016). Part of the programs is designed to disseminate agronomic recommendations to improve the productivity of cocoa to farmers. However, the technical know-how on which these recommendations are based lacks a solid scientific basis. As Mars mentions on its website: "cocoa lags behind other crops in scientific research and understanding" (Mars, 2016).

Cocoa research began in the mid-1930s, when it was mainly focused on selection and breeding of cocoa varieties which are vigorous and disease resistant or tolerant (Lockwood, 1976). In West Africa, cocoa research intensified in the 1940s with an emphasis on the study and control of pests and diseases (Cunningham and Arnold, 1962). Research into cocoa requirements of shade and nutrients only started in the mid-1950s, when control of pests and diseases became effective (Cunningham and Arnold, 1962). In

1962, Cunningham and Arnold wrote "shade and fertilizer work on cacao is still at an early stage." Since that time, many cocoa-growing manuals and training programs have been used to disseminate agronomic recommendations to cocoa farmers. Apart from guidance on the establishment of cocoa, pruning, and pest and disease management, recommendations have been made regarding nutrient management. Yet we lack a solid scientific understanding on which to base such recommendations. In this review, the scientific research regarding the mineral nutrition of cocoa is synthesized. We bring together current knowledge on nutrient cycling in cocoa production systems, nutrient requirements of cocoa, and yield response to fertilizer application in relation to factors such as management, climatic, and soil conditions. Furthermore, we provide insight in the knowledge gaps and recommendations for further research on the potential of fertilizer for closing the yield gap under different production conditions. The review can assist in developing the research programs required to increase the sustainable productivity of cocoa. As such, we hope it will be an inspiration to the public and the private stakeholders involved in programs in the cocoa sector to intensify research efforts on the nutrient needs of cocoa.

1.2 The Cocoa Tree

Originally, cocoa was an understorey rainforest tree (Läderach et al., 2013). Most cocoa cultivation systems have been established as agroforestry systems in the shade of large forest trees, but more recently, monocrop plantations have been introduced and advocated (Boyer, 1973; Cunningham and Arnold, 1962; Gockowski and Sonwa, 2011). Under cultivation, cocoa is a rather small tree of about 3–10 m. Under natural heavily shaded conditions, it can be 20–25 m in height (Almeida and Valle, 2007; Toxopeus, 1985a). After 3–4 years of rapid growth, trees grow more steadily (Thong and Ng, 1978). Naturally, the tree grows orthotropically and forms a first plagiotropic "jorquette" at a height of 1–2 m. Here, five "fan branches" grow out sideways (Fig. 2A). Buds below the jorquette may grow out upward as orthotropic "chupons" and are capable of forming a new jorquette above the previous one. Thus, the height of the canopy is increased in a step-wise process (Toxopeus, 1985a). This is referred to as the Nozeran model of tree architecture (Tomlinson, 1987). Basal chupons may form at the base of the trunk and replace the main trunk if this is severely damaged (Toxopeus, 1985a). It is usually advised to remove all chupons to obtain single trunks and prevent formation of a canopy above the first.

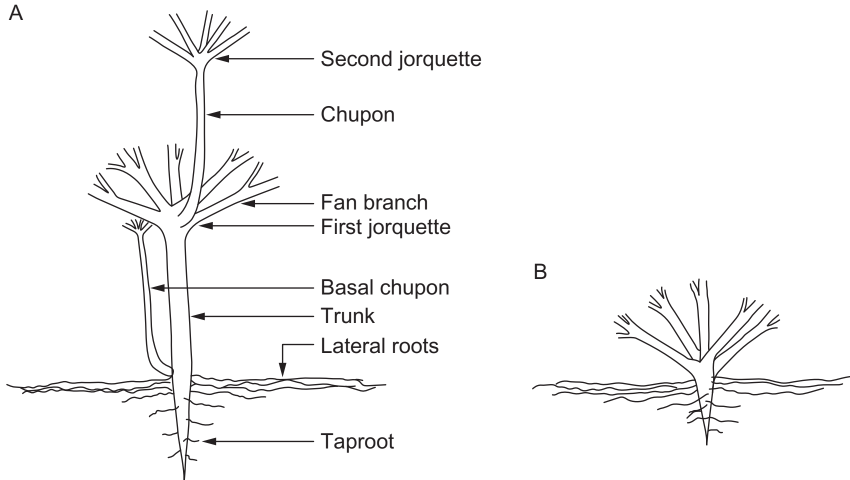


Fig. 2 Schematic representations of the cocoa tree, excluding further branching and leaves. A = Natural "Nozeran" cocoa tree architecture. B = Plagiotropic cocoa tree architecture.

A second jorquette should only be allowed to form when the first jorquette is too close to the ground. Further pruning may occur to remove unwanted and diseased shoots and reduce the density of the canopy (Wood and Lass, 1985). When cocoa is propagated using vegetative material, the most common practice is to root cuttings of plagiotropic shoots from the fan shoots (Miller and Guiltinan, 2003). This leads to a low, bushy growth pattern (Fig. 2B), while orthotropic chupon shoot cuttings will develop like a seedling.

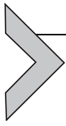
The root system consists of a large taproot of 0.8–1.5 m and a lateral root system in the topsoil (Fig. 2). The taproot may be deeper in deep soils and may not form in heavy clay soil. Most moisture and nutrients are taken up by the lateral roots (Gerritsma, 1995; Hartemink and Donald, 2005; Wood and Lass, 1985).

Leaf production occurs in flushes. Terminal branches produce 3–6 pairs of leaves after which the bud remains dormant for a period until a new flush occurs (Gerritsma, 1995; Toxopeus, 1985a). A flush usually coincides with leaf fall of older leaves. The nutrient demand of the new flush is partly met by translocation of nutrients and photoassimilates from the older leaves (Almeida and Valle, 2007; Toxopeus, 1985a). Flushing usually occurs in cycles of 4–10 weeks (Hutcheon, 1976). However, there is a lack of clarity on the factors which determine the length and intensity of the cycles. It has been proposed that the new flush is formed as soon as the carbohydrate supply is replenished after the previous flush, which could be related to the

effects of environmental conditions such as radiation, temperature, and soil moisture. The flush cycle, though influenced by environmental factors, is internally regulated, and also occurs under constant environmental conditions (Almeida and Valle, 2007; Asomaning et al., 1971). The cocoa leaves are normally completely renewed yearly (Hutcheon, 1976).

Cocoa is cauliflorous, that is, the flowers are formed on the trunk and branches (Toxopeus, 1985a). Although flowers are also formed on the secondary branches, most pods form on the trunk and main branches (Almeida and Valle, 2007; Groeneveld et al., 2010). Flowers are mostly pollinated by tiny midge species (Toxopeus, 1985a). Flowers which are not pollinated abscise 24–36 days after opening (reviewed in Asomaning et al., 1971). The percentage of flowers that set pods in cocoa is usually small at 0.5–5% (reviewed in Almeida and Valle, 2007). Groeneveld et al. (2010) conclude that pollination poses greater limitations on yields than limitation of the resources they studied. However, their study was limited in terms of the number of trees sampled, nutrient limitations may not have been an issue due to the fertile soils, and due to logistical constraints no whole tree pollination was executed, hence more research is needed to confirm their results. In case of Amelonado cocoa in Ghana the bulk of the pods are set in the flowering period during the main rainy season (around May–June, Fig. 4) (Gerritsma, 1995). The young pods are called "cherelles." During the first 50–100 days after fruit set, the growth of a cherelle can stop, and the cherelle then becomes yellow, shrivels, and blackens (Gerritsma, 1995; Valle et al., 1990). This process is known as cherelle wilt. Asomaning et al. (1971) found the incidence of cherelle wilt of Amazon cocoa in Ghana to be as high as 81%. It has been suggested that cherelle wilt is a mechanism to adjust fruit production to the bearing capacity of the tree (Asomaning et al., 1971; Valle et al., 1990). Competition for carbohydrates and nutrients, through their influence on hormones regulating cherelle wilt, has been suggested to induce cherelle wilt (Hutcheon, 1976; Valle et al., 1990). For nutrients, this is not always supported by data on cherelle wilt after fertilizer application (Asomaning et al., 1971). Wessel (1971) found increased wilting at the time of or immediately following leaf flushing, supporting the suggestion that competition is a cause of cherelle wilt. Cherelles may also wilt as a result of infestation with microorganisms (Asomaning et al., 1971). Pods which pass the wilting stage take about 5–6 months from flowering to develop (Gerritsma, 1995; Toxopeus, 1985a; Wessel, 1971). In West Africa, the main crop can be harvested following the minor rainy season (November–December), while the much

smaller mid-crop is harvested during the main rainy season (April–May, Fig. 4) (Ahenkorah et al., 1974; Asomaning et al., 1971; Wessel, 1971). During these harvesting seasons, harvesting in experimental settings is usually performed every 2 weeks (Ahenkorah et al., 1974, 1987; Groeneveld et al., 2010). In Ghana, 25% of the annual harvest occurs in the peak month November. In Malaysia, where there is no true dry season and production is more evenly spread throughout the year, harvest in the peak month is only 12% of the annual crop (Wood, 1985b).



2. COCOA PRODUCTIVITY

As for all crops, several factors together determine the actual yield of cocoa (Fig. 3). Potential yields are determined by location- and crop-specific characteristics under otherwise optimal conditions. These defining factors include local temperature, CO_2, sunlight radiation, and the crop physiology and phenology. However, the availability of water and nutrients may limit production and yields may be further reduced by weeds, pests, and diseases (van Ittersum and Rabbinge, 1997). Actual yields will be smaller than potential yields, giving rise to a yield gap (van Ittersum et al., 2013). This yield gap may be decreased by addressing the limiting and reducing factors with yield increasing and yield protecting measures. Variability in actual yields is caused by differences in defining, limiting, and reducing factors, and the management practices affecting them.

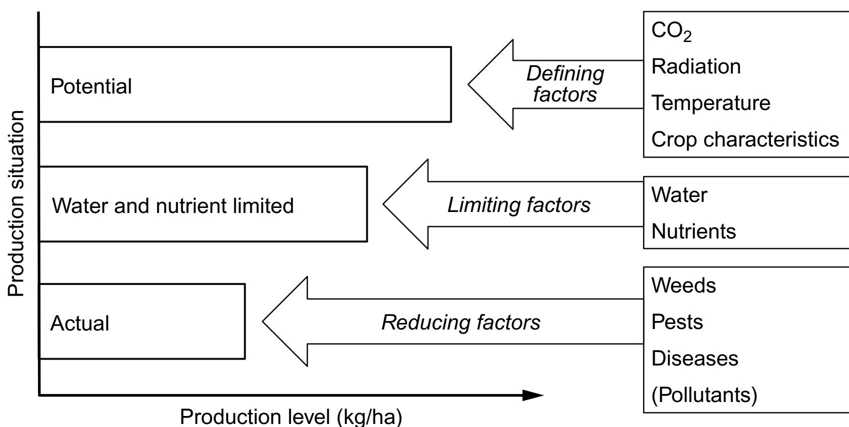


Fig. 3 Principles of production ecology (van Ittersum et al., 2013). Potential crop yields are determined by defining factors, but actual yields will be lower as a result of limiting and reducing factors.

Cocoa yields vary widely. For instance, within Ghana, Cunningham and Arnold (1962) report average yields in 53 plots that varied between 112 and 1345 kg/ha. Yields of around 3360 kg/ha have been achieved in on-station trials in Ghana, while the national on-farm average is around 400 kg/ha (Aneani and Ofori-Frimpong, 2013). Yields in research plots in Malaysia have exceeded 6300 kg/ha (Yapp and Hadley, 1991). Zuidema et al. (2005) developed a physiological growth and production model for cocoa. Through simulating annual yields over 10 years, they found water-limited yields in Ghana without nutrient limitations and without pests and diseases under 10% shade to be as large as 5000 kg/ha, and yields of 6100 kg/ha were achievable in Malaysia (Zuidema and Leffelaar, 2002). Seventy percent of the variation in simulated yields between regions was explained by differences in annual rainfall and radiation during the dry season (Zuidema et al., 2005). Actual yields are less than the simulated yields due to suboptimal management, nutrient limitations and pests and diseases. Variability in productivity can be large between years, but also among trees of the same population (Ahenkorah et al., 1987; Bartley, 1970; Lockwood, 1976). Part of the variability between trees may be explained by large but localized differences in soil fertility (Cunningham and Arnold, 1962; Wessel, 1971). Variability may be reduced by providing optimal growing conditions (Bartley, 1970). Indeed, Wessel (1971) found fertilizer application to increase yields mainly of poorly bearing trees, thus reducing yield variability among trees.

2.1 Crop Characteristics

Crop characteristics which define potential yields include physiological and phenological traits. The physical environment and management can influence these characteristics. However, the response of the crop and thus its potential yield under optimum conditions is genetically determined. Crop characteristics vary between varieties. Cocoa varieties are often classified into three groups: Criollo, Trinitario, and Forastero. The Criollo varieties have been praised for their fine flavor; however, they lack vigor, yield poorly, and are reported to be extremely susceptible to pests and diseases. Forastero varieties are much more vigorous and hardy than Criollos. Trinitario is generally assumed to have originated as a cross between Criollo and Forastero, and many of its features are intermediate between the two. Owing to their preferred crop characteristics leading to high productivity, Forastero varieties now account for about 80% of global production. These include both the Amazon and the Amelonado varieties, from which most hybrids also originate (Toxopeus, 1985a, reviewed in Almeida and Valle, 2007). Some

examples of important characteristics which differ between varieties are the canopy size and structure, harvest index, radiation tolerance, and leaf chlorophyll content (Hutcheon, 1976; Okali and Owusu, 1975; Yapp and Hadley, 1991). Furthermore, susceptibility to various pests and diseases differs among varieties (Adejumo, 2005; CacaoNet, 2012; Thresh and Owusu, 1986).

2.2 Climatic Conditions

2.2.1 Radiation

Radiation is one of the main factors which drives photosynthesis and thus yield (Fig. 3). This does not mean that more radiation will always lead to better growth and productivity. Full sunlight during the establishment of cocoa trees leads to an undesirable shape and slow growth (Almeida and Valle, 2007; Evans and Murray, 1953; Wessel, 1985). Therefore, cocoa is normally established under temporary shade for 2–3 years. After this time, optimum light intensity may increase as the cocoa canopy starts to provide self-shading, and overhead shade is often reduced (Evans and Murray, 1953). The effect of radiation on potential productivity, through its effect on photosynthesis, depends on light interception and photosynthetic efficiency of the tree. Light interception is determined by the amount of radiation reaching the cocoa tree and the arrangement, number, and size of the leaves in the canopy. Radiation affects cocoa leaf arrangement and physiology. Leaves under reduced radiation are usually thinner, but have a larger surface and hence leaf area index (LAI) is larger than in full sunlight (Almeida and Valle, 2007; Evans and Murray, 1953; Gerritsma, 1995) although Ahenkorah and Akrofi (1968) found that unshaded cocoa produced a greater number of leaves with a larger leaf area than shaded cocoa during the dry season. Thong and Ng (1978) report LAIs of mature cocoa trees up to 10, but LAIs around three or four seem more common (Corley, 1985; Yapp and Hadley, 1991). Under reduced radiation, cocoa leaves may have an increased chlorophyll content (Almeida and Valle, 2007; Evans and Murray, 1953; Okali and Owusu, 1975). However, some authors found that photosynthetic rate per unit of chlorophyll decreased in leaves of seedlings grown at high degrees of shade (Okali and Owusu, 1975). Cocoa leaves have a low maximum photosynthetic rate and reach light saturation at a low light intensity. Corley (1985) found maximum rates of CO_2 uptake of only 0.6–0.7 $g/m^2/h$, with 85% of the maximum rate being obtained under as little as 5% of full sunlight to be reported in the literature. This would mean that an increase in radiation on individual leaves above this level would hardly lead to increased photosynthesis. Cocoa leaves grown at low radiation

show higher photosynthetic rates under low light intensity than leaves grown at high radiation, but the latter have a higher light saturation point. Nevertheless, photosynthetic rate will be depressed at high exposure to radiation (Okali and Owusu, 1975). Through the various physiological adaptations to different degrees of radiation, productivity will not decrease linearly with reduced radiation. Still, many authors have reported higher yields when shade was removed upon maturity of the cocoa (e.g., Ahenkorah et al., 1974; Murray, 1955; Ofori-Frimpong et al., 2007). Cocoa trees flush more vigorously under high radiation (Asomaning et al., 1971; Gerritsma, 1995) and produce more flowers (Asomaning et al., 1971). According to Alvim (1966, in Asomaning et al., 1971), flowering is reduced by a period of low radiation. Cherelle wilt is reduced under full sun, which leads to a larger number of pods reaching maturity. This is possibly a result of increased carbohydrate availability under higher radiation and accompanying leaf growth, though the causes of cherelle wilt are debated (Asomaning et al., 1971). Despite the reputed increase of yield with increasing radiation, many authors stress that complete removal of shade trees decreases the economic life span of the tree while increasing nutrient requirements and risk of pests and diseases (e.g., Ahenkorah et al., 1987; Cunningham and Arnold, 1962; Zuidema et al., 2005). Unshaded leaves have a higher density of stomata, which may lead to excessive transpiration (Almeida and Valle, 2007; Evans and Murray, 1953). They age faster than shaded leaves (Gerritsma, 1995; Wessel, 1971). It is likely that these effects are not only related directly to increased radiation but are also due to other factors which are influenced by shade, such as temperature and transpiration. Most conclusions regarding the effects of radiation on productivity are based on shade tree studies. Unfortunately, the effect of shade trees on radiation is usually not quantified in a way that is comparable across studies (Wood, 1985a; Zuidema and Leffelaar, 2002).

2.2.2 Temperature and Rainfall

Temperature and rainfall have a large influence on attainable yields of cocoa (Fig. 3; Zuidema et al., 2005). Cocoa is grown in regions with temperatures varying between 18–21°C mean minimum and 30–32°C mean maximum (Wood, 1985a). According to Snoeck et al. (2010), the optimal mean monthly temperature for cocoa production in Ghana is around 26–27°C. Daymond and Hadley (2008) found that increasing mean growth temperature (tested within a range of 21–26°C) increased cherelle wilt, and decreased fruit maturation time. Higher temperatures may be suitable for

growing cocoa in regions where rainfall patterns are different. An increase in temperature will mostly affect cocoa through increases in evapotranspiration potential (ETP) and consequent decreases in water availability (reviewed in Läderach et al., 2013). The rainforest zone of Malaysia can be about 2°C hotter than that of West Africa. Still, it is very suitable for growing cocoa because rainfall is well distributed with no months in which rainfall is below 100 mm (Fig. 4, Läderach et al., 2013).

According to climatic models, temperatures are likely to increase by up to 2.0°C. This will lead to an increase in ETP which may not be compensated by changes in rainfall patterns, thus reducing the climatic suitability for cocoa in large parts of important cocoa-producing regions (Läderach et al., 2013). Wood (1985a) indicates that annual rainfall in most cocoa-growing countries is between 1250 and 2800 mm. Where rainfall is below 1250 mm, it is likely that evapotranspiration induces greater moisture losses than precipitation can compensate. Cocoa can only be grown here successfully if it can be irrigated (a practice hardly ever used in cocoa production, Carr and Lockwood, 2011) or if the groundwater table is high (Wood, 1985a). Annual rainfall above 2500 mm is likely to increase incidence of fungal diseases such as black pod, and vascular streak dieback (Wood, 1985a). High rainfall also leads to heavy leaching resulting in poorer soils, although in alluvial soils fertility may be replenished by flooding (Wessel, 1971; Wood, 1985a). Distribution of rainfall is more important than total annual rainfall (Wessel, 1971; Wood, 1985a; Zuidema et al., 2005). Soil moisture availability should not fall below adequacy for prolonged periods (Zuidema and Leffelaar, 2002). As discussed below, soil moisture availability depends on soil conditions as well as temperature and rainfall. Moreover, there is little quantitative information on crop water relations of cocoa (Carr and Lockwood, 2011). As such, it is difficult to establish generally applicable requirements for either of them.

2.3 Production Cycle

Annual productivity depends on the length of the growing and production season(s). The annual production cycle of cocoa follows a distinct seasonal pattern when there is climatic seasonality, particularly of rainfall. In West Africa, rainfall is not equally distributed throughout the year, and there are several months in which rainfall does not exceed 100 mm. In other production regions where this is not the case, cocoa growth and pod production are more continuous (Wood, 1985a,b). Therefore, in Fig. 4, climatic data

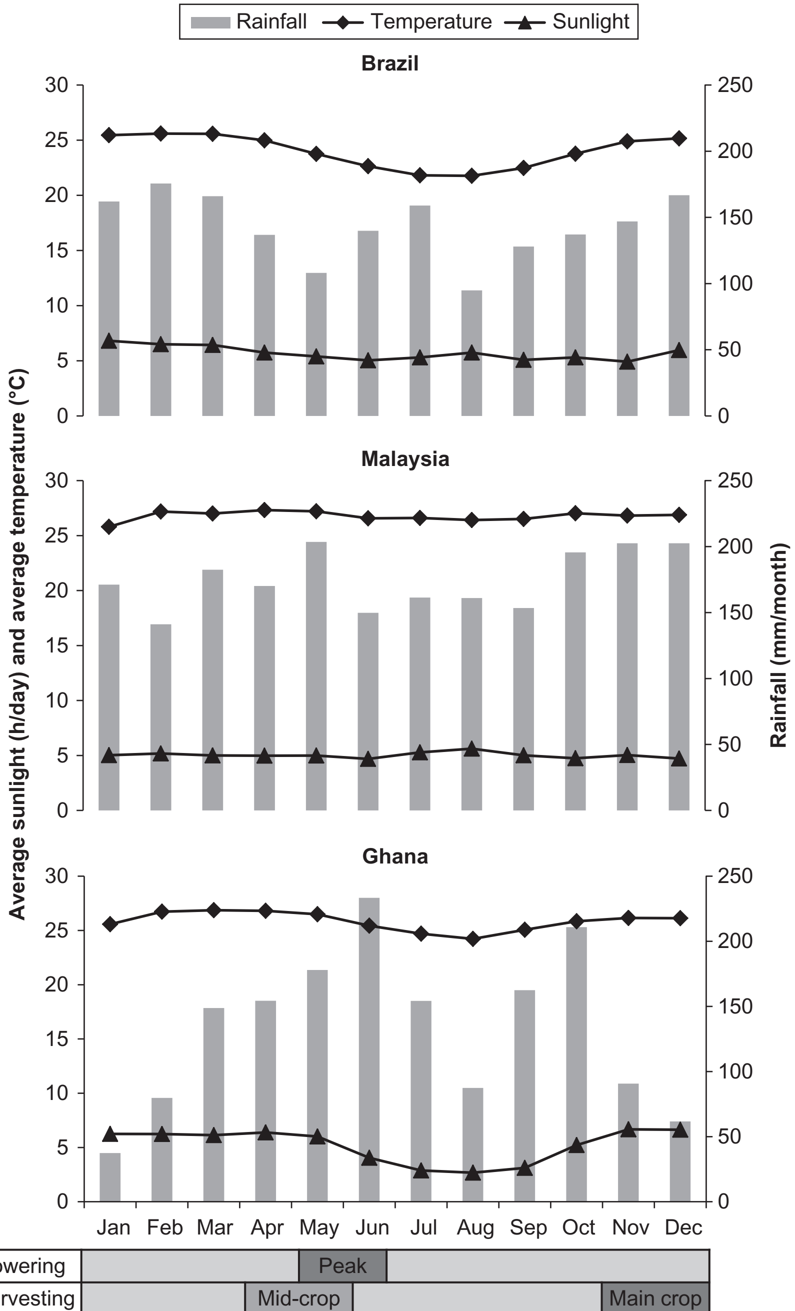


Fig. 4 Monthly data of sunlight, temperature, and rainfall of Brazil (Bahia), Malaysia (Sabah), and Ghana (Tafo) adapted from Wood (1985a) and annual cocoa cropping cycle of Ghana (for references, see text).

are presented for several regions, while only the annual cropping cycle of Ghana is shown. The annual cropping cycles in other regions follow a similar though less distinct pattern, with the main harvest 6 months after the start of the wet season (Wood, 1985b). Amelonado is thought to show more distinct seasonal variation than Amazon cocoa which reputedly produces pods throughout the year (Aneani and Ofori-Frimpong, 2013; Asomaning et al., 1971).

As cocoa is a perennial, the duration of its productive life should also be taken into consideration when assessing productivity. Trees come into bearing after 2–6 years depending on the variety and location (Wessel, 1971; Wood and Lass, 1985). Amelonado cocoa may continue to bear fruits for 40 years or more, while hybrid trees should be replaced every 15–20 years (Gockowski et al., 2013; Wessel, 1971). The start of the decline of production varies depending on factors such as variety, productivity of the tree, shading, pest and disease incidence, and soil nutrient status. For a graphical representation of the yield development during the life span of cocoa trees, see Fig. 5.

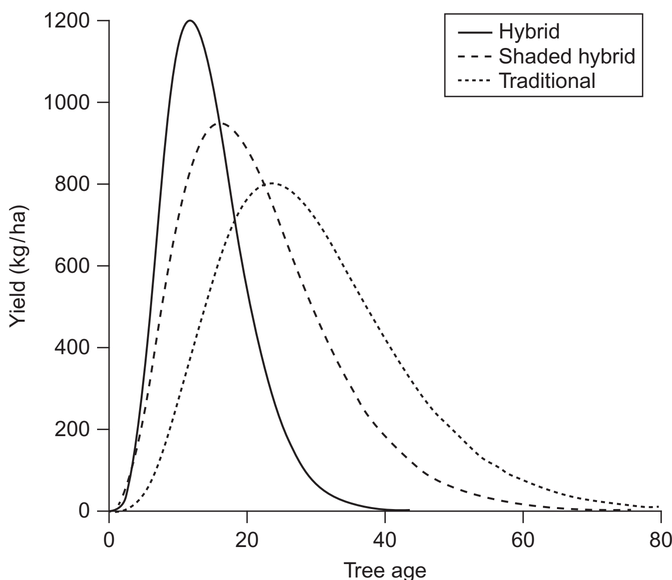


Fig. 5 Yield development in different cocoa systems plotted by the first author using equations of Obiri et al. (2007).

2.4 Soil Properties

2.4.1 Soil Nutrient Content

To achieve high productivity, cocoa requires a soil abundant in nutrients (Wessel, 1971). The importance of several other soil characteristics, such as pH and organic matter, is largely due to their influence on the availability of nutrients. Although nutrients have different functions in the development of the tree (e.g., canopy formation, flowering, pod production), all nutrient deficiencies will ultimately lead to decreased yields. This is the case in most cocoa production regions, for instance in West Africa (Appiah et al., 2000; Wessel and Quist-Wessel, 2015). Chlorophyll content of leaves, and hence rates of photosynthesis, increase when nutrients are in adequate supply (Okali and Owusu, 1975). It is hypothesized that pod production is fundamentally determined by the available nutrients in the tree at different stages from flower initiation to pod maturity (Hutcheon, 1976).

In Table 1, some chemical properties for soils under shaded, unfertilized cocoa systems from various studies are listed. It is clear that there is a wide diversity in soils on which cocoa is grown. This diversity is confirmed by the soil analysis from cocoa-growing regions across the world reviewed by Wood (1985a). From the values we can see that cocoa has often been grown on soils which can be considered as rather infertile. It is likely that low nutrient availability in many cocoa-growing regions is at least partially responsible for yield limitations. However, there is lack of consensus on nutrient requirements and how to establish which nutrients are limiting under different conditions, as discussed in this review.

2.4.2 pH

The pH of the soil affects uptake and availability of nutrients. The optimum range for growing cocoa is said to be pH 6.0–7.5 (Wood, 1985a). However, some cocoa soils are much more acid (Table 1). Although according to Shamshuddin et al. (2004), cocoa is very sensitive to acidity, Wood (1985a) argues that cocoa is tolerant to acid conditions as long as the soil provides adequate nutrients. A problem particularly associated with soil acidity is aluminum (Al) toxicity which is a major limiting factor in plant production on acid soils. Cocoa is an Al-sensitive crop (Delhaize and Ryan, 1995; Shamshuddin et al., 2004). What is known as the "soil acidity complex" is the combined impact of deficiencies of cations such as calcium and magnesium, of phosphorus due to fixation onto iron and Al sesquioxides and toxicity of Al. These combined effects can result in stunted growth of cocoa

Table 1 Chemical Soil Properties in Some Shaded Cocoa Production Systems Without Fertilizer Application

Soil Depth (cm)	pH	Organic C (g/kg)	% Total N	Available P (mg/kg)	Exchangeable Bases (cmol/kg)				Source	Country
					K	Ca	Mg	CEC		
0–15	5.9	19		12	0.4	5.3	2.0	9.5	Adejuwon and Ekanade (1987, in Hartemink and Donald 2005)	Nigeria
15–45	5.0	12		9	0.3	4.1	2.0	6.2	Idem	Idem
Not stated	5.9	18.5		12	0.4	8.3	2.8	12.5	Ekanade (1988, in Hartemink and Donald, 2005)	Idem
0–15	6.1	19	0.16	10	0.34	9.3	2.0		Wessel (1971)	Idem
0–15	5.7	13.5	0.16	1.20	0.19	8.0	1.8		Appiah et al. (2000)	Ghana
0–15	6.4	28	0.33	22.4	0.15				Ofori-Frimpong et al. (2007)	Idem
0–20	5.7	16	0.14	1.4	0.43	7.2		92	Dawoe et al. (2010)	Idem
0–5	6.7	23.3		0.7	0.34	13.3	2.2		Ahenkorah et al. (1974)	Idem
5–15	6.6	10.9		0.3	0.28	7.5	1.2		Idem	Idem
0–15	6.1	8.6	0.12	27.3	0.17	13.4	2.9		Ofori-Frimpong et al. (2002)	Idem
0–20			0.12	17	0.06	5.1	1.6		Boyer (1973)	Cameroon
20–40			0.07	18	0.05	2.8	1.4		Idem	Idem
0–20	6.7				0.8	11.3	2.2		Duguma et al. (2001)	Idem
0–20	7.4	15	0.62						Aranguren et al. (1982)	Venezuela
20–40	7.1	2.9	0.47						Idem	Idem
0–15	3.8		0.22	*583*[a]	0.57	2.4	0.95		Alpízar et al. (1986)	Costa Rica
15–30	3.9		0.19	*616*[a]	0.27	2.6	0.98		Idem	Idem
30–45	4.1		0.11	*559*[a]	0.17	3.3	1.0		Idem	Idem

[a]Values are given for total P instead of available P in the soil layer (in mg/kg).
Note that the age of the cocoa plantation is not taken into account although long-term cocoa cultivation without application of fertilizer will gradually deplete nutrient stocks.

seedlings (Shamshuddin et al., 2004). The amounts of lime required to increase the pH of tropical clay soils are prohibitive, and can result in additional problems such as inducing zinc deficiency. Low soil pH per se is not toxic for plant growth. Kamprath (1970) recommends the use of small(er) amounts of lime to correct the Al saturation of the cation exchange capacity to less than 15%. This is sufficient to overcome Al toxicity and provide calcium for crops. Chicken dung, green manure, and basalt applications increase soil pH and reduce Al toxicity, and have positive effects on cocoa seedling growth (Shamshuddin et al., 2004). Especially combinations of these with lime treatments are expected to give good results on soils with acid conditions (Shamshuddin et al., 2004). Generally, cocoa production will cause soil acidification, although this was not found by Ofori-Frimpong et al. (2007). Examples are decreases from pH 7.5 to 6.7 in the 0–5 cm layer and from 7.4 to 6.4 in the 5–15 cm layer (Ahenkorah et al., 1974) and from pH 6.7 to 6.2 (Ahenkorah et al., 1987) in 15 and 16 years of cocoa cultivation. Differences are even larger when comparing the pH of soils under cocoa cultivation with that of soils under forest. In Nigeria, pH under forest was found to be 6.8 while it was 5.5 after 10–15 years of cocoa cultivation (reviewed in Hartemink and Donald, 2005).

2.4.3 Soil Moisture

Besides nutrient availability, water availability in the soil also plays an important role in determining cocoa productivity. Cocoa is sensitive to both drought and waterlogging (Carr and Lockwood, 2011; Gattward et al., 2012). Even brief episodes of low water availability can lead to decreases in stomatal opening, photosynthesis, and transpiration of cocoa leaves and may reduce yields significantly (Gattward et al., 2012; Wessel, 1971). Waterlogging, which may occur during the wet season in some regions, leads to inadequate soil aeration (Evans and Murray, 1953). Waterlogging may prevent the initial growth and establishment of cocoa, and will reduce pod production in mature cocoa (Almeida and Valle, 2007). Both waterlogging and drought may lead to nitrogen deficiency symptoms in cocoa (Evans and Murray, 1953). The amount of water which can be stored in the soil depends on its structure, texture, and organic matter content. Whether the soil water holding capacity of a soil is suitable for cocoa production depends on climatic conditions. For instance, a poor water holding capacity can lead to temporary water deficits where there are dry periods (e.g., West Africa), and/or where radiation is high (e.g., Malaysia). This causes large decreases of photosynthesis and yield reductions. Poor water holding capacity is much

less of a problem when rainfall is well distributed and radiation is lower (e.g., Costa Rica) (Zuidema and Leffelaar, 2002). Soil conditions and (micro) climatic factors can to a large extent compensate for low rainfall (Wessel, 1971). Microclimatic conditions may be influenced by presence of shade trees, which generally buffer temperature, humidity, light, and wind and hence reduce evapotranspiration (Wessel, 1971). It is difficult to quantify yield limitations caused by water stress, as there is a paucity of reliable published data on yield responses to drought or irrigation (Carr and Lockwood, 2011).

2.4.4 Organic Matter

Large amounts of nutrients, and in particular N, are present in the soil in organic form. Organic matter improves the structure of the soil, facilitates aeration, and determines the capacity of the soil to hold water and exchange nutrients (Wood, 1985a). Thus, soil organic matter plays a crucial role in maintaining soil fertility (van Noordwijk et al., 1997). Most of the soil organic matter is found in the topsoil. Wessel (1971) found that under cocoa, the soil organic matter content is strongly positively correlated with total nitrogen, organic phosphorus, cation exchange capacity, and the sum of exchangeable bases (within certain pH limits). This does not hold true for all soils, as we can see in Table 1.

Cocoa is usually established on soils cleared from forest, which causes a disturbance of the organic matter equilibrium (Wessel, 1971). The soil organic matter initially declines rapidly as a result of erosion, decreased litter supply, and increased mineralization in the exposed soils. A new equilibrium is reached when a closed canopy is formed and can be maintained for a long period when yields are small and the canopy stays intact (Cunningham and Arnold, 1962; Wessel, 1971). Indeed, many authors have found losses of topsoil carbon (C) when comparing soils under mature cocoa plantings with forest soils. Ofori-Frimpong et al. (2007) found carbon to decrease from 4.0 to 1.7% in the 0–15 cm layer when comparing forest to unshaded cocoa in Ghana. In Nigeria, topsoil C has been found to be nearly 3% under forest while it was less than 2% under cocoa (reviewed in Hartemink and Donald, 2005). Tondoh et al. (2015) in Côte d'Ivoire found carbon content to be 2% under forest while it was only 1% under 5- and 10-year-old cocoa plantations. Under 20-year-old cocoa, however, carbon content was higher again at 1.5%. Carbon loss may continue after forest clearance in soils under cocoa. Ahenkorah et al. (1974) found significant reductions of C in the range of 40–60% (from 4% to 2% in the 0–5 cm layer and from 2% to 1% in the

5–10 cm layer) over 15 years of a cocoa trial in Ghana. They found losses of 55 t/ha of humus from the topsoil (0–15 cm) in this period. In another trial, Ahenkorah et al. (1987) found that about 44.5 t/ha of soil organic matter was lost in 16 years. Losses were larger when C concentrations in mature cocoa plots were compared with plots at planting after forest clearing (Ahenkorah et al., 1987). According to Wade et al. (2010), carbon losses under cocoa increase with increasing intensity of production and management. Ahenkorah et al. (1974) concluded that the rates of loss of soil C do not depend on shade. Yet their results show that without fertilizers, carbon losses were larger without shade. With fertilizer application, losses in the topsoil layer (0–5 cm) were larger under shade. Shade was not quantified. Ofori-Frimpong et al. (2007) found medium shade (15–18 forest shade trees/ha) to reduce C loss in the absence of fertilizer application. Beer et al. (1990) in Costa Rica found no significant changes in topsoil C in shaded cocoa systems in Costa Rica. Dawoe et al. (2010) found larger carbon concentrations under 30-year-old shaded cocoa systems than under 3-year-old shaded systems in Ghana. The latter suggests that carbon storage may even increase over time under shaded cocoa, but it is likely that carbon had first declined drastically following forest conversion as explained earlier.

Even when carbon is lost under cocoa cultivation, more carbon is stored in the soil under cocoa than in comparable soils under annual cropping (reviewed in Hartemink and Donald, 2005).

2.4.5 Soil Texture

The soil texture influences the soils' ability to store water and nutrients. Clayey soils generally contain more organic matter and nutrients than sandy soils (Feller and Beare, 1997). This increases the vigor of the trees (Wessel, 1971). Sandy soils are more susceptible to leaching (Aranguren et al., 1982). Clayey soils have a large moisture holding capacity, while sandy soils have good drainage. The water stored in clayey soils may not be easily available to the plants. The release of water to the plants is slower and more even than in sandy soils (Wessel, 1971; Wood, 1985a). Aeration in moist clay soils is poor (Wood, 1985a). Trees in a clayey soil with a good nutrient availability will have a better developed root system which makes them less susceptible to drought stress, on the other hand, the rooting depth may be deeper in sandy soils which also reduces drought stress (Wessel, 1971). Large quantities of gravel in the soil will reduce its water holding capacity (Wessel, 1971). A high moisture holding capacity will be especially important in regions with explicit dry seasons to provide trees with adequate moisture during

these months (Wessel, 1971). On the other hand, in acid clay soils in Peninsular Malaysia cocoa trees may die within a week due to waterlogging (Wood, 1985a). According to Zuidema et al. (2005), loamy soils will give best yields (compared with sandy and clayey soils) especially under suboptimal rainfall.

2.4.6 Soil Depth

Cocoa trees usually form a thick taproot up to a depth of 1.5 m or more and hence require deep soils (Wessel, 1971; Wood, 1985a). Even deeper soils are required when annual rainfall is low, especially when the water holding capacity is poor (i.e., on sandy soils, Wessel, 1971). Cocoa tends to root deeper in soils with a sandy topsoil than with a clayey topsoil, as sandy soils dry out to a greater depth during dry months. In absence of a dry season, roots are similar in sandy and in clayey soils (Wessel, 1971). When the development of the taproot is restricted, the tree lacks physical support and may fall over (Wood, 1985a).

2.5 Pests and Diseases

Even when defining and limiting conditions are optimal, factors remain which can severely reduce yields. In cocoa, pests and diseases are a major reason for poor yields on farm. Production losses are estimated between 20% and 40%, or even larger in the worst cases (Adejumo, 2005; CacaoNet, 2012; Duguma et al., 2001). The importance of cocoa pests and diseases differs per region. In West Africa, prominent pests and diseases are mirids, also called capsids (Adejumo, 2005; Ahenkorah et al., 1987; Wessel and Quist-Wessel, 2015), black pod disease caused by *Phytophthora palmivora* and *Phytophthora megakarya* (Adejumo, 2005; Wessel and Quist-Wessel, 2015), and cocoa swollen shoot virus (CSSV) spread by mealybugs (Adejumo, 2005; CacaoNet, 2012; Wessel and Quist-Wessel, 2015). In the Americas, witches broom disease and frosty pod rot, both caused by basidiomycetes, are important causes of production losses (CacaoNet, 2012). In the various Asian production countries, especially cocoa pod borer and vascular streak dieback (caused by a fungus) play a role (CacaoNet, 2012). Devastation of cocoa plantations and high costs of control have led to abandonment of cocoa production in several regions. This has been the case, for instance, for cocoa pod borer in Malaysia, frosty pod rot in Mesoamerica, Ecuador, and Venezuela, *P. megakarya* in Central and West Africa (CacaoNet, 2012), and CSSV in Nigeria (Adejumo, 2005).

2.6 Options to Ameliorate Defining, Limiting, and Reducing Factors

2.6.1 Breeding and Replanting

Through selecting and breeding of cocoa varieties, varieties with preferred crop characteristics have become available. Breeding efforts with cocoa started in the 20th century in Trinidad, where crossings between local selections and Amazon showed early high yields. In West Africa, crossings were made between Amazon and local Amelonado selections to obtain varieties with preferred features (Lockwood, 1976; Thresh and Owusu, 1986; Toxopeus, 1985b). Indeed, hybrids are now available which, compared to Amelonado, show superior vigor, early canopy closure, easier establishment, early and high yields, disease resistance, and greater tolerance to environmental stress (Asomaning et al., 1971; Lockwood, 1976; Thresh and Owusu, 1986). Many cocoa trees in cocoa production regions are in need of replanting (Wessel and Quist-Wessel, 2015). Cycles of 30–40 years are commonly practiced with traditional Amelonado varieties. According to Gockowski et al. (2013), hybrid tree stocks should be replaced every 15–20 years due to the physiological stresses of large yields. Lockwood (1976), on the other hand, did not find the early good yields of hybrids to be at the expense of yields in later years in a 20-year trial. Although Amazon hybrids were released to farmers in 1964 (Lockwood, 1976), and farmers are said to prefer hybrids over Amelonado, most farmers in West Africa still use unimproved Amelonado planting material (2001/2002 IITA STCP producer survey in Gockowski and Sonwa, 2011). Improved planting material is expensive and difficult to access. This is related to institutional problems, under investment in seed gardens, inappropriate breeding methodologies, and breeders' lack of interest in proliferating their best crosses (Aneani and Ofori-Frimpong, 2013).

It should be noted that differences in yields between varieties may only be visible when other conditions do not substantially limit and reduce yields (see Fig. 3) (Ofori-Frimpong et al., 2002). Hence, investments in planting new varieties may only pay off when nutrient requirements are met and pest and disease management is adequate.

2.6.2 Planting Density, Pruning, and Shading

A closed canopy is desired to maximize light interception, reduce weed growth, and provide self-shading. This could be achieved early through planting at a high density. However, after the canopy has closed a high planting density may increase intertree competition and reduce yields

(Corley, 1985; Yapp and Hadley, 1991). Planting density therefore is a compromise between reaching early closed canopies and yields and achieving larger yields at a later stage (Corley, 1985). Common planting densities in various cocoa production regions have varied from as sparse as 400 trees/ha to as dense as nearly 7000 trees/ha (Wood and Lass, 1985). Optimum spacing depends on shade conditions, climate, and the type and variety of planting material (Lockwood and Pang, 1996; Pang, 2006; Wood and Lass, 1985). Thinning cocoa which has been planted very densely has been shown to increase yields, even when this reduces total light interception (Yapp and Hadley, 1991). A better light distribution rather than a higher total light interception will lead to greater yields. This is related to the branching habit of the trees. The branching habit is in part depending on the variety but can be adjusted through pruning (Yapp and Hadley, 1991). Excess chupons and fan branches can be removed at an early stage to obtain a single trunk and an even distribution of 4–5 fan branches (Ahenkorah and Akrofi, 1968). Later, unwanted shoots and diseased branches can be removed to enhance light interception by leaves of the remaining branches (Aranguren et al., 1982). However, care must be taken not to remove too many branches, as this may reduce rather than stimulate reproductive growth. In many fruit trees pruning will stimulate reproductive growth if done correctly. This has not been described for cocoa. Hutcheon in 1976 mentioned that very little was known about the control of the balance between vegetative and reproductive growth. Little seems to have changed. Under normal conditions, abscission of leaves and branches follows senescence. Nutrients are withdrawn from leaves prior to senescence (Hutcheon, 1976). Upon pruning, these nutrients are removed from the tree. Additional assimilates and nutrients are needed for the replacement of branches and leaves. This is likely to depress pod production (Hutcheon, 1976). Upon pruning, leaf area is reduced and the tree reacts by emitting vigorous flushes to reestablish the canopy and increase leaf area (Jadin and Snoeck, 1985).

Especially when the cocoa canopy has not yet closed, additional overhead shade is required for adequate growth. Cocoa is normally established under temporary shade, which is gradually removed as the trees grow. After a few years, the canopy is formed and hence starts to provide self-shading. Trees established with little or no shade have an undesirable shape with short internodes, a low jorquette, and a dense crown (Wood, 1985a). Without shade, seedlings show slow growth, possibly as a result of reduced leaf expansion (Almeida and Valle, 2007). Wessel (1971) in Nigeria found that

establishment of cocoa in drought-susceptible soils was limited in presence of large forest trees due to competition for water. To reduce competition, either artificial shade or smaller shade tree species are recommended. Commonly used species to provide shade at cocoa establishment are cassava (*Manihot esculenta*) and banana (*Musa* spp.) (Ahenkorah and Akrofi, 1968; Evans and Murray, 1953; Wessel, 1971). Such shade crops have the benefit of providing economic yield to smallholders before the cocoa begins to bear fruit. The shade species may also reduce erosion, runoff, and leaching, which are more problematic on bare soils, and reduce weed growth, especially of the more aggressive weeds (Beer et al., 1998; Boyer, 1973; Cunningham and Arnold, 1962).

Once cocoa has formed a good canopy cover and a dense root network, some benefits of shade species become less prominent. The risk of soil degradation becomes negligible (Boyer, 1973; Hartemink and Donald, 2005; Santana and Cabala-Rosand, 1982). Through self-shading, individual leaves lower in the canopy are more protected against the harmful effects of full sunlight. These include higher temperatures, excessive transpiration, and moisture stress. However, other benefits remain. Besides reducing light intensity directly affecting the leaves higher in the canopy, shade trees also reduce air and soil temperatures, act as a wind break, and decrease fluctuations in atmospheric humidity and soil moisture (Beer et al., 1998; Cunningham and Arnold, 1962; Evans and Murray, 1953). Channels in the soil, left by dead roots, may improve aeration and drainage (Evans and Murray, 1953). Shade trees may also reduce soil degradation and increase nutrient availability through litter cycling and nitrogen fixation (Beer et al., 1998; Isaac et al., 2007; Ofori-Frimpong et al., 2007). Cocoa trees under shaded conditions seem to have a longer productive life and to be less susceptible to certain insect pests and weeds (Beer et al., 1998; Cunningham and Arnold, 1962; Wessel, 1971). Asomaning et al. (1971) suggested that pod set may be greater under light shade compared with no shade as a result of a more favorable microclimate for pollinators and higher pollen viability. Shade trees may offer further benefits by providing additional income through fruit and timber, and by increased biodiversity and carbon storage (Beer et al., 1998; Duguma et al., 2001; Gockowski and Sonwa, 2011). However, shade trees have also been shown to decrease yields and reduce the benefits of fertilizer application (Ahenkorah et al., 1974, 1987). This may be related not only to reduced light interception and hence reduced photosynthesis, but also to increased competition for water and nutrients (Evans and Murray, 1953; Wessel, 1971).

The effects of shade trees depend on the tree species (Isaac et al., 2007). Sometimes it is possible to choose the shade trees to be planted. Examples of factors to be taken into account are rooting depth and spread, canopy structure, possible additional income, seasonal dynamics in leaf shedding and amounts of litter fall, N_2 fixation, suitability of the tree to local agroecological conditions, and the quality of the litter.

For mature cocoa, the desirability of shade trees is heavily debated and depends on many complex and interacting factors. These factors include not only the many site- and species-specific agroecological factors which are emphasized in this review, but also the resources and objectives of the farmer (Beer, 1987; Duguma et al., 2001; Wessel and Quist-Wessel, 2015).

2.6.3 Reduction of Drought Stress

An obvious way to reduce drought stress is irrigation. However, only a very small proportion (c. 0.5%) of the area planted with cocoa is thought to be irrigated (Carr and Lockwood, 2011). Irrigation is regarded impossible due to economic and technical reasons, especially considering that most cocoa is produced by smallholder farmers with few resources (Carr and Lockwood, 2011; Wessel, 1971). In (seasonally) relatively dry regions, the use of drought tolerant varieties may be a better strategy to achieve good yields (Carr and Lockwood, 2011). Mulching, especially during establishment, may enhance water availability (Carr and Lockwood, 2011; Wessel, 1971). Shade trees buffer temperature, humidity, light, and wind and hence reduce evapotranspiration (Wessel, 1971).

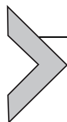
2.6.4 Pest and Disease Management

A variety of chemicals, cultural practices, and biological control methods can be used to control cocoa pests and diseases (Duguma et al., 2001). Certain varieties are more resistant or tolerant to diseases such as black pod (Adejumo, 2005), CSSV (Adejumo, 2005; Thresh and Owusu, 1986), frosty pod rot, and VSD (CacaoNet, 2012). Depending on regional differences in disease prevalence, these varieties can be recommended for replanting. Insect populations can be effectively controlled by various insecticides, and their use led to a dramatic increase in production in West Africa after 1960 (Wessel, 1971). Similarly, fungicides can reduce infection with diseases such as black pod (Adejumo, 2005). Although chemicals are usually quick and effective, they may be expensive and labor intensive for the small farmer and may pose a threat to human health and the environment if not used properly (Adejumo, 2005). Capsid populations thrive in full sunlight, and

capsid damage is reduced under shaded conditions (Ahenkorah et al., 1987). Black pod infestations, on the other hand, may increase under shade as its spread is favored by wet, humid conditions (Asomaning et al., 1971). A main source of inoculum is infected pods, so the most effective way to combat black pod disease (apart from chemical control) is to regularly inspect the cocoa trees and remove any infected pods (Adejumo, 2005). These pods should not be returned to the cocoa field, and neither should cocoa husks, as these may be a source of infection unless burnt or composted (Adejumo, 2005). In case of CSSV, the main control method besides the use of resistant and tolerant varieties is the eradication of diseased trees and the trees in their proximity (Thresh and Owusu, 1986). Insecticides may be used to increase the effectiveness of the eradication, as this will reduce the population of the vector (mealybugs) of the virus (Adejumo, 2005; Thresh and Owusu, 1986). As eradication is a drastic and costly control method which requires subsequent replanting, farmers are reluctant to apply this method and are likely to abandon their plantation upon heavy infection (Adejumo, 2005; Thresh and Owusu, 1986).

2.6.5 Reducing Nutrient Limitations

Last but not least, nutrient limitations can be reduced to increase yields. Obviously, fertilizing the cocoa is a way to reduce nutrient limitations through increasing soil nutrient availability. In order to recommend appropriate nutrient management, knowledge is required of the present availability of nutrients in the soil, the ability of the plant to take up these nutrients, and the nutrient requirements to attain the targeted yield. These in turn depend on soil characteristics, climatic conditions, management practices (including shade management), and crop characteristics. In the remainder of this review, relevant knowledge on the mineral nutrition of cocoa is synthesized in order to understand how the nutrient status of the trees can be enhanced to improve yields sustainably.



3. NUTRIENT CYCLING IN COCOA

To understand the nutrient requirements of cocoa, it is important to consider nutrient cycling. There is great variability among different cocoa production systems with regards to nutrient cycling and the nutrient balance (Tables 3–5; Fontes et al., 2014; Hartemink and Donald, 2005). This variation may be caused by climatic and soil conditions, characteristics such as age, cultivar/species, and planting density of cocoa and, if applicable, shade

trees. However, part of it may also be caused by differences in research approach and methods employed (Hartemink and Donald, 2005).

3.1 Nutrient Inputs and Outputs

The main sources of nutrient input in cocoa production systems are (in)organic fertilizers, rainfall deposition, and nitrogen fixation (Table 2). Fertilizer use will be discussed later. Nutrients in rainfall differ per region, depending for instance on nearby industrialization (Prospero et al., 1996). Dinitrogen (N_2) fixation by leguminous trees, if included in the cocoa system, may provide a major source of N (Hartemink and Donald, 2005; Kähkölä et al., 2012; Santana and Cabala-Rosand, 1982) though some consider the input to be of limited importance (Beer et al., 1998). The N contribution of the trees will depend on factors including shade tree density, fertilization, pruning management, and choice of species/clones (Beer et al., 1998). See also Section 4.3.2.

The main source of nutrient export is offtake through harvesting (Table 2). In the table, this is given as kilograms of nutrients per 1000 kg of dry beans. Of course, annual harvest may exceed or may be less than 1000 kg/ha, causing a different nutrient removal. It is clear that nutrient removal per hectare will be much less in countries like Ghana, where average annual yields amount to only about 400 kg/ha (Aneani and Ofori-Frimpong, 2013).

Most of the variability of nutrient content of the harvest between studies can be attributed to differences in the nutrient content of the husks rather than that of the beans. Variability is especially large in the case of potassium (K). Husks demonstrate a much larger variation as a result of environmental conditions than do beans (Fontes et al., 2014; Hartemink and Donald, 2005). Regardless of variability between studies, nutrient content of husks is large. According to Boyer (1973), the husks contain 44% of the nitrogen (N), 29% of the phosphorus (P), 86% of the K, 90% of the calcium (Ca), and 54% of the magnesium (Mg) exported by harvest. Hartemink and Donald (2005) and Thong and Ng (1978) come to similar conclusions. Returning of husks to the soil thus decreases the rates of nutrient export in cocoa systems (Boyer, 1973; Fontes et al., 2014; Thong and Ng, 1978). This is common practice in many Latin American cocoa plantations (Santana and Cabala-Rosand, 1982). However, husk return is risky due to sanitary reasons, especially when there is a risk of infection with black pod disease, which is a major problem in West Africa (Adejumo, 2005; Ahenkorah and Akrofi, 1968; Boyer,

Table 2 Nutrient Inputs Into and Removal From Cocoa Systems

		N	P	K	Ca	Mg	Source	Country
Inputs	Rainfall deposition	5.0–12	0.2–3.0	2.5–12[a]			Reviewed in Hartemink and Donald (2005)	Range of various studies around the world
	N_2 fixation by leguminous shade trees	35–60					Reviewed in Beer et al. (1998)	Venezuela and Costa Rica
Removal	Harvest: removal of beans and husks (kg/1000 kg dry beans)	31.0	4.9	53.8	4.9	5.2	Thong and Ng (1978)[b]	Malaysia
	Idem	30–40	5.7–7.0	58–71	8.6	4.8	Reviewed in Wessel (1971)	Ghana and Trinidad
	Idem	35	6	60			Reviewed in Hartemink and Donald (2005)	Approximation of various studies around the world
	Idem	24.1	6.1	20.0			Urquhart (1955, in Appiah et al. (2000)	Unknown
	Idem	34	6	73	8	7	Boyer (1973)	Cameroon
	Idem	45	5.7	54	7.2	7.8	Jadin and Snoeck (1985)	Used as reference for Côte d'Ivoire
	Harvest: removal of beans without husks (kg/1000 kg dry beans)	20	4	10			Reviewed in Hartemink and Donald (2005)	Approximation of various studies around the world
	Leaching	5.5	0.5	1.5			Reviewed in Hartemink and Donald (2005)	Venezuela and Costa Rica
	Capture in cocoa trees by cocoa growth	3–4	0.1	4–5	4.5–6	1–1.5	Boyer (1973)	Cameroon

[a]The highest value of 12 kg/ha/yr was recorded by Boyer (1973) in Cameroon, who says himself that this value may be an anomaly. The next highest value was 8.0 kg/ha/yr.
[b]Thong and Ng (1978) found export of Mn to be 0.11 and Zn to be 0.09 kg/1000 kg dry beans.
All units are in kg/ha/yr unless otherwise indicated.

1973). To prevent sanitary problems, cocoa husks can be burned or composted prior to application although this is not common practice. Because N is lost during burning, composting is preferable.

Except on steep slopes and bare soils, runoff and erosion are considered negligible in mature cocoa plantations (Boyer, 1973; Hartemink and Donald, 2005). Plantation soils may be vulnerable during the establishment phase of the trees when, in the absence of shade trees, there is no fully developed canopy (Hartemink and Donald, 2005). Losses due to leaching may occur during intense rainfall (Boyer, 1973; Santana and Cabala-Rosand, 1982; Snoeck et al., 2010). Well-established cocoa plantations have a dense root network which prevents leaching (Boyer, 1973). Although some authors have found the losses due to leaching to be negligible (Hartemink and Donald, 2005; Santana and Cabala-Rosand, 1982), others suggest they are considerable, although much less than under annual crops (Hartemink and Donald, 2005). Deep rooting shade trees may recycle N from deeper soil layers than cocoa and hence reduce leaching (Aranguren et al., 1982; Hartemink and Donald, 2005). However, according to Beer et al. (1998), the majority of the roots of shade trees in the humid tropics is found near the soil surface and will hence induce competition with the cocoa trees rather than preventing leaching. Nutrient leaching of N may be decreased through fertilization with P and K. These nutrients increase root development and thus the nutrient uptake capacity of the cocoa (Hartemink and Donald, 2005; Santana and Cabala-Rosand, 1982). However, leaching may be intense when inorganic fertilizers are applied on light-textured soils (Aranguren et al., 1982).

The nutrients captured in the woody parts of trees during growth are often considered as a removal from the nutrient cycle as they are no longer available to the plants. Although Thong and Ng (1978) calculate annual nutrient requirements to sustain growth, it seems that their figures are actually the amounts of nutrients locked up in the cocoa tree after a certain number of years, rather than annual requirements. Therefore we do not include these figures here. According to Boyer (1973), 30-year-old cocoa trees require about 10% of the amount of nutrients accumulated in their trunks and large branches each year for growth (Table 2).

Without added fertilizer, the nutrient balance in cocoa systems is negative for all nutrients considered when assuming a yield of 1000 kg/ha/yr. Cocoa established from virgin forest on fertile soils may not require fertilizers for many years (Charter, 1953 in Appiah et al., 2000). Still, eventually, cocoa production will deplete the soil of nutrients especially when no fertilizers are

applied (Gockowski et al., 2013). Gradually, the so-called forest rent (the benefit of planting on virgin forest rather than replanting) is lost as soil fertility declines (Ruf and Schroth, 2004). This has been confirmed both directly in long-term cocoa trials (e.g., Ahenkorah et al., 1974) and indirectly in comparative research of forests and cocoa production systems in various stages following forest conversion (e.g., examples in Hartemink and Donald, 2005; Ofori-Frimpong et al., 2007). For instance, Ahenkorah et al. (1974) in Ghana found significant reductions of soil N content after 15 years of cocoa production, regardless of fertilizer application or shading. Nutrient reserves will be more rapidly depleted with increased production, for instance when agronomic practices are improved and/or shading is reduced (Appiah et al., 2000; Cunningham and Arnold, 1962). Even the most fertile forest soils will not be able to support vigorously growing cocoa for more than a few years unless fertilizer is used, especially in absence of leguminous shade trees.

3.2 Nutrient Stocks

Considerable amounts of nutrients are present in the soils and biomass of cocoa systems, especially when compared with the removal of nitrogen from the system (Tables 2 and 3). Availability of the nutrients present in the soil and fertilizer use efficiency depend on the quantity/intensity relationships of each nutrient. The studies reviewed here do not take these relationships into account, which makes it difficult to draw conclusions regarding nutrient availability. Nutrients stored in the vegetation will return to the soil through litter fall and pruning of both the cocoa and the shade trees, where they can become available for uptake after decomposition. Other nutrients remain locked in the wood. It is unclear to what extent the vegetative nutrient

Table 3 Nutrient Stocks in Shaded Cocoa Systems in kg/ha

	N	P	K
Vegetation (cocoa trees)	103–438	10–57	52–633
Vegetation (shade trees)	245–263	20–32	140–258
Topsoils 0–30 cm	4782–6699	30–79	103–557
Total	5171–7367	39–136	417–1304

All values are summaries of data in Hartemink and Donald (2005), who review a range of several studies around the world. Not all values were measured in each study, so the number of studies on which the ranges are based differs per value range ($n=3$–6). Values for soil refer to total N, available P, and exchangeable K.

reserves of the cocoa tree can be partitioned to reproductive growth (Hutcheon, 1976).

Hartemink and Donald (2005) in their literature review found total N content in the upper 30 cm of the soil to vary from about 4800 to 6700 kg/ha. Some 91–94% of the N in cocoa systems is found in the topsoil. N content of soils with leguminous shade trees can be larger than with non-leguminous shade trees, and a difference of 1000 kg N/ha was found between the two systems in Costa Rica. Nitrogen accumulation in the above- and below-ground biomass of cocoa ranged from about 100 to over 400 kg/ha. The large variation is explained by the age of the trees, differences among cultivars, and environmental conditions (Hartemink and Donald, 2005). Aranguren et al. (1982) found branches, stems, and roots to contribute 30%, 20%, and 29%, respectively, of a total N store of 302 kg/ha in cocoa plants in Venezuela. Shade trees may also contain considerable amounts of N up to around 250 kg N/ha. The accumulation of P in cocoa ecosystems is small. The P stored in the soil amounted to 30–79 kg/ha in the studies reviewed by Hartemink and Donald (2005). Variability of accumulated K in cocoa systems is extremely large. Stocks of exchangeable K in the topsoils of mature cocoa varied from about 100 to 560 kg/ha, which was between 27% and 61% of total exchangeable K accumulated in the cocoa systems (Hartemink and Donald, 2005).

3.3 Nutrient Transfer

Large amounts of nutrients are cycled within cocoa plantations. They are taken up from the soil by both shade trees and cocoa trees and are returned to the soil through litter fall, pruning, root turnover, and rainwash. These transfers do not add to the total amounts of nutrients present in the system. However, their magnitude and speed play a major role in controlling the availability of the nutrients in the soil. The transferred nutrients are recycled between the plants and the soil except in the case of nitrogen in litter and roots from leguminous shade trees, and nutrients added in fertilizers.

Considerable amounts of carbon and nutrients are returned to the soil through litter production of both cocoa and shade trees (if present) (Dawoe et al., 2010; Fontes et al., 2014; Hartemink and Donald, 2005). These amounts depend on the amount of litter fall and the nutrient concentrations in the litter (Table 4). The amount of litter fall in a shaded cocoa system usually lies between 5 and 10 t/ha/yr of dry matter (Dawoe et al., 2010; Fontes et al., 2014; Hartemink and Donald, 2005). Most of this litter

Table 4 Concentrations and Amounts of Nutrients in the Litter Fall and Standing Litter of Cocoa and Shade Trees Combined, Nutrient Transfer Through Fine Root Turnover of Shade Trees in Cocoa Systems, and Nutrient Transfer Through Rainwash in Shaded and Unshaded Systems

	N	P	K	Ca	Mg	Source	Country
Nutrient concentrations in litter (g/kg)	11.1–19.6	0.8–2.0	2.1–15.3			Hartemink and Donald (2005)	Range of several studies around the world
Nutrients returned to the soil through litter (kg/ha/yr)	84–175	5.8–17	16–124			Fontes et al. (2014) and Hartemink and Donald (2005)	Range of several studies around the world
Nutrient transfer from fine root turnover of shade trees[a] (kg/ha/yr)	23–24	2	14–16			Muñoz and Beer (2001)	Costa Rica
Nutrients in rainwash without shade (kg/ha)	6.3	1.3	101	34.6	32	Boyer (1973)	Cameroon
Nutrients in rainwash with shade (kg/ha)	5	1.8	74.5	38.1	32.4	Idem	Idem
Idem	8.0	<1.0–8.0	38.0–47.0			Hartemink and Donald (2005)	Malaysia and Costa Rica

[a] *Erythrina poeppigiana* and *Cordia alliodora*.

consists of leaves (Boyer, 1973; Dawoe et al., 2010; Fontes et al., 2014). Shade trees may contribute around 2–3 t litter/ha/yr or more (Aranguren et al., 1982; Boyer, 1973; Fontes et al., 2014). Different factors influence the amount of litter fall. Climate plays a major role. For instance, trees drop more leaves during drought (Boyer, 1973; Dawoe et al., 2010; Hartemink and Donald, 2005). On the other hand, biomass production is greater with more rainfall, which will also influence the amount of litter produced. The density of both shade and cocoa trees and the type of shade trees are important factors to consider. More trees will produce more litter and different tree species produce different amounts of litter (Fontes et al., 2014; Hartemink and Donald, 2005). The amount of litter produced depends on the age of the plantation as there is more litter fall in older systems (Dawoe et al., 2010; Hartemink and Donald, 2005). Soil conditions play a role. For instance, litter production was greater on Latosols than on Cambisols in Bahia, Brazil, although it is unclear why (Fontes et al., 2014). Amounts of litter may be increased by returning prunings to the soil under cocoa, but it is unclear what the effects of pruning are on the natural litter fall of the trees (Alpízar et al., 1986). Fallen cocoa leaves have smaller nutrient concentrations than pruned leaves as nutrients are withdrawn prior to senescence (Fontes et al., 2014; Hutcheon, 1976). It is not clear whether all the concentrations and amounts given in Table 4 take this into account. The variability in nutrient concentrations and nutrients returned among the different studies reviewed is large, especially for K.

According to Hartemink and Donald (2005), nutrients in the annual litter fall represent 20–45% of the total N in the vegetation and 2–3% of the total N in the soil; 10–30% of the total P in the vegetation and 10–40% of the available P in the soil; and 15% of total K in the vegetation and 10–20% of exchangeable K in the soil.

The speed at which the nutrients returned to the soil through litter fall become available for plant uptake depends on decomposition rates. Calculated decomposition rate coefficients (k-values) in cocoa litter vary. Dawoe et al. (2010) found k-values of 0.221–0.224 per year in Ghana, while Fontes et al. (2014) found rates of 0.51–1.11 per year in Brazil. This is perhaps related to more pronounced annual dry spells in Ghana. The pattern of decomposition largely follows the rainfall pattern with slower decomposition rates during dry periods (Boyer, 1973; Dawoe et al., 2010). However, the main determinant for annual decomposition rates is litter quality (Cadisch and Giller, 1997; Fontes et al., 2014). Litter quality may vary strongly among the systems (Fontes et al., 2014). This could explain, at least

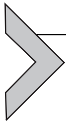
in part, the large differences between *k*-values calculated in different regions. There are strong positive correlations between decomposition rate and N concentration and strong negative correlations with lignin and lignin: N ratio. Negative correlations were also found with polyphenols and cellulose, while positive correlations were found with P (Dawoe et al., 2010; Fontes et al., 2014). According to Hartemink and Donald (2005), decomposition is most rapid if the N:P ratio is around 10. Tondoh et al. (2015) found wide C:N ratios of over 30 in the litter of cocoa plantations. Dawoe et al. (2010) reported larger concentrations of polyphenols and lignin and lower N:polyphenol ratios in litter in cocoa systems compared with forests, most likely caused by the large amount of cocoa leaves in the litter fall. Aranguren et al. (1982) found a smaller N concentration in fallen cocoa leaves than in shade tree leaves, and Osman et al. (2004) found large concentrations of polyphenols in cocoa leaves. This poor leaf quality of cocoa is the most likely cause of the smaller decomposition coefficients of cocoa compared with forests (Dawoe et al., 2010). Inclusion of shade trees from which fallen leaves have a favorable leaf quality could therefore increase decomposition and hence nutrient availability. According to Fontes et al. (2014), shade tree leaves (of *Cabruca* and *Erythrina*) function predominantly as a source of nutrients, while cocoa tree leaves function as a sink except for Mg. Ofori-Frimpong et al. (2007) found decomposition rates and nutrient release to be faster in shaded than in unshaded farms. This may also be related to increased humidity under shade trees (Beer et al., 1998). However, 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. Quantity and quality of the shade tree litter will depend on the tree species (Aranguren et al., 1982). Cocoa drops less leaves under shade trees (Boyer, 1973; Evans and Murray, 1953; Ofori-Frimpong et al., 2007). It is unclear whether shading has a net positive or negative effect on nutrient cycling.

The rate of release differs among nutrients. Boyer (1973) found K (which is mainly present in the cell cytoplasm as a free ion) to be released the fastest, with 75% of K being released within 3 months, while a total leaf dry weight loss of 75% was reached after 1 year. Ca and Mg (which are mainly present in cell walls and chlorophyll, respectively) showed a more gradual release, following leaf decomposition rates. N and P were released more slowly as they are mostly present in organic form.

Fine root turnover can contribute substantially to return of nutrients to the soil (Table 4, Hartemink and Donald, 2005). Although it has generally

been assumed that the transfer of N fixed or extracted from the soil by leguminous shade trees occurs largely through above-ground pruning residues and litter fall, several studies suggest that a significant proportion of N is transferred below ground through fine root and nodule senescence and decomposition (Beer et al., 1998; Santana and Cabala-Rosand, 1982). Still, above-ground litter is generally a stronger source of N return than below ground (Ledgard and Giller, 1995).

Rainwash transfers nutrients which are leached from the leaves back to the soil (Table 4, Hartemink and Donald, 2005). Although the transfer of N and P is limited, transfer of soluble bases, and especially K, is highly important (Boyer, 1973; Hartemink and Donald, 2005). Nutrient rainwash from cocoa without shade is higher than under shade, probably as a result of leaf damage associated with the high temperatures caused by direct sunlight (Boyer, 1973).



4. COCOA AND NUTRIENT APPLICATION

As indicated in the previous section, cocoa production will gradually deplete the soil of nutrients. Even if soils are initially high in nutrients, in the long-term additional nutrients are needed to sustain cocoa productivity. Nutrients can be added most readily as mineral fertilizer. Cocoa fertilizer trials have been conducted both on research stations and in farmers' fields. Beside fertilizer applications, treatments have often included different degrees of shading, as the effects of light and nutrition are interrelated (Wessel, 1985). Perhaps the most cited shade–fertilizer trials are the long-term trials K1 and K2-01 conducted at the Cocoa Research Institute in Ghana (CRIG). Nutrient applications in these and several other trials are compiled in Table 5.

N was normally applied as urea, except in 1956 in the trial described by Ahenkorah et al. (1974), when it was applied as ammonium phosphate. P was applied as triple superphosphate, except in 1956 in the trial described by Ahenkorah et al. (1974), when it was applied as ammonium phosphate and single superphosphate, and in the trial described by Appiah et al. (2000) when it was sometimes applied as single superphosphate. K was applied as sulfate of potash in the trials described by Ahenkorah et al. (1974) and Wessel (1971), and as muriate of potash in the trials described by Ahenkorah et al. (1987) and Appiah et al. (2000). Ca was applied as calcium sulfate and Mg was applied as magnesium sulfate.

Table 5 Nutrient Application in Several Trials

Source	Experimental Year/Series	Rate	N	P	K	Ca	Mg
Ahenkorah et al. (1974)[a]	1956		15	45	84		30
	1957		112	15			
	1958		112	49	69		34
	1959–61		112	49	93		34
	1962–64		112	49	140		34
	1965–71			49	140		
Ahenkorah et al. (1987)[b]	1963–71	1	84	15	70		
		2	140	29	140		
	1972 onwards	1	84	29	93		
		2	140	59	186		
Wessel (1971)	Series I	1	45	15	47	40	34
		2	90	29			
		3	135	44			
	Series II	1	90	15	47		34
		2	179	29	93		68
	Series III	1	135	15	47		
Appiah et al. (2000)				56	63		

[a]Experiment K1, first described by Cunningham and Lamb (1959).
[b]Experiment K2-01. Ahenkorah and Akrofi (1968) in their description of the same experiment give different values, all of which are a factor 1.25 less. Asomaning et al. (1971) give different values still (same N as Ahenkorah and Akrofi (1968)), but P about twice as large and K also larger). Here we present the values as given in Ahenkorah et al. (1987), as this was published later than the other two studies.
All values in kg/ha/yr, on an elemental basis (own calculations based on values in sources). For general yield results of trials K1 and K2-01, please refer to Figs. 6 and 8.

4.1 Fertilizer Response Trials

Below, some general effects of fertilizer application, sometimes in combination with shade effects, on cocoa yields in several trials are given. Fig. 6 shows the results of trial K1. This trial consisted of 3 ha of Amelonado cocoa and was terminated in 1971. There were four treatments: no shade with fertilizer (NSF), no shade no fertilizer (NSNF), shade with fertilizer (SF), and shade without fertilizer (SNF). See Table 5 for fertilizer application rates.

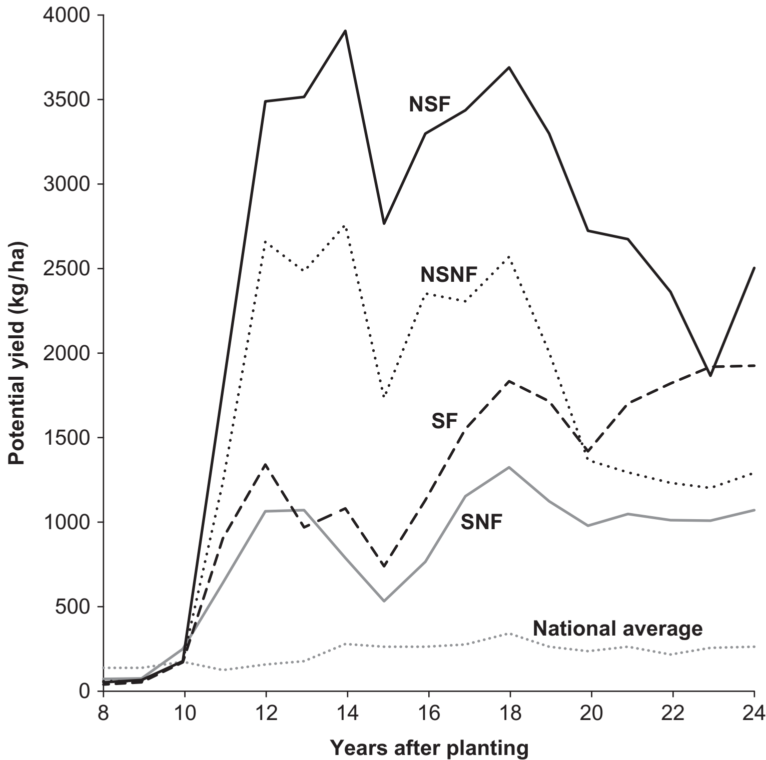


Fig. 6 Results of application of fertilizers with and without shade in trial K1, data from Ahenkorah et al. (1974). Treatments (fertilizer application and removal of shade) started when the trees had reached the age of 10. Treatments are NSF: no shade with fertilizer, NSNF: no shade no fertilizer, SF: shade and fertilizer, SNF: shade, no fertilizer. The national average yields of Ghana for each corresponding year are also presented.

It is easy to see that the treatments including fertilizer application give greater yields than those without, and those treatments excluding shade give yields greater than those with shade. The positive impact of fertilizer application is stronger in absence of shade throughout the trial. The positive impact of shade removal decreased over time. That is, in the last 6 years of the trial, the yields in the treatments without shade showed a much more severe decline than those with shade. Deterioration in the absence of shade may be caused by the greater stress that is caused by the larger yields in the earlier years. This stress also increases the trees' susceptibility to insect pests and diseases (Ahenkorah et al., 1974). Ahenkorah et al. (1974) argue that the economic life of unshaded Amelonado cocoa may not last for more than 10 years of intensive cropping. Yields in the treatments with shade declined

much less. During the last 5 years, SF out-yielded the NSNF and showed a moderate upward trend in yield. Within the last years of production, the yields of NSF and SF in some years show some aberrant fluctuations. Fluctuations in the earlier years were large, but followed a similar pattern in all treatments. These later fluctuations were found only in single treatments. As no differences in the conditions of the treatments in these years have been noted in the reviewed paper, these aberrations may be artifacts. Unfortunately, the trials were ended before trends in yields in these later years could be established with certainty.

Shade, no fertilizer (SNF), which is the usual Ghanaian practice, gave the smallest yields, though far exceeding the estimated national average (Ahenkorah et al., 1974). Soils at the research station were known to be fertile at the start of the trial, so nutrient availability may not have limited yields as much as on many of the smallholder farms in Ghana. Management practices such as pruning, pest and disease management, and timely harvesting on the research station were likely better than on the average smallholder farm. It is known that fertilizer application will be most successful when other management practices are performed well (Appiah et al., 2000; Cunningham and Arnold, 1962). As this may not be the case in actual field situations, results of trials under research conditions may lead to overestimation of the likely impact of fertilizer application for farmers. As only presence and absence of both shade and fertilizers have been considered, no conclusions can be drawn about optimal degrees of shade and composition and amounts of fertilizer application.

The K2-01 trial was planted with Amazon hybrid cocoa in 1959. It included three degrees of shade (no shade, and two densities of the shade tree *Terminalia ivorensis*) and three rates of N, P, and K (a zero treatment and the rates given in Table 5) in all combinations, leading to 81 treatments. This trial was terminated in 1982. In the graph on which Fig. 8 is based, yield data were averaged. Data for individual treatments were not provided, although some yields in the paper were given per nutrient and/or shade level as for example in the graph depicted in Fig. 7. However, it is not clear what is presented in this graph. The original caption reads "Cumulative mean effect of shade and fertilizer on Amazon cocoa yield over the 20 year period," but according to the axis label the yield is expressed per year. The text states "The dominant influence of overhead shade and the effect of the various fertilizer treatments under different shade regimes are shown (...)." If yields are indeed per year, it is likely that they are expressed in hectograms instead of tons per hectare, although in that case the numbers still do not correspond

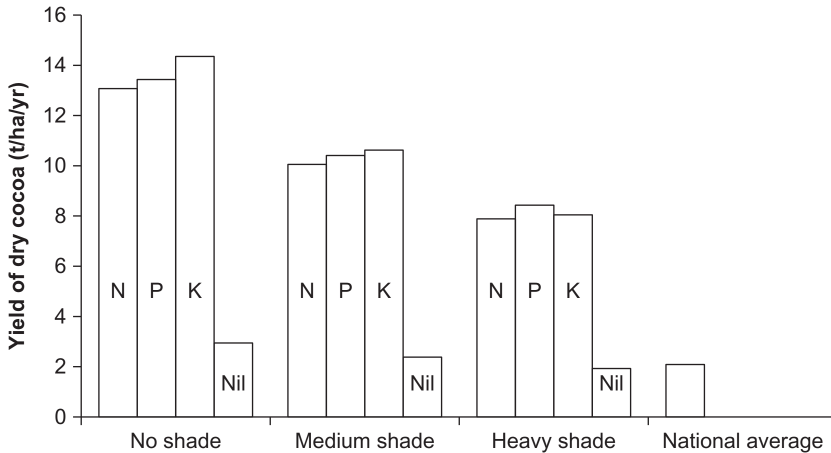


Fig. 7 Results of application of fertilizers per nutrient under different degrees of shade in trial K2-01, data from Ahenkorah et al. (1987). For interpretation, see text.

to data given elsewhere in the paper. It is not clear on which treatments these results have been based (which rates of the specified nutrient, which rates of the other two nutrients). Several tables in the paper also give yields for specific nutrient rates and/or shading degrees, but unspecified treatment characteristics always remain (e.g., rates of P and K are given, but no information on N and shade are provided). Although some conclusions about effects per treatment level and interactions are drawn by the authors, these are not always supported by the data provided. For instance, although in one table it is shown that the largest yields were obtained in the absence of nitrogen application, this is not supported by the data presented in Fig. 7.

Generally speaking, in the K2-01 trial (Fig. 8), similar to the K1 trial, the largest yields but also the greatest yield fluctuations were found in the first 7–8 years of treatment. Again, application of fertilizer led to higher yields, and these effects were larger with less shade. After one very poor production year (1971/72), in which especially the fertilized plots showed a large yield dip, yields in none of the treatments fully recovered. Still, reasonably high production was achieved until some 5–6 years later a rapid decline in yields brought all yields below 400 kg/ha in 1981, when the trial was terminated. The decline was more intense with less shade, although the largest yields were still achieved in absence of shade. Ahenkorah et al. (1987) claim that the decline rate was larger on unfertilized than on fertilized plots, yet this does not appear to be supported by their data. Interestingly, the difference between the treatments without fertilizer and the national average in this

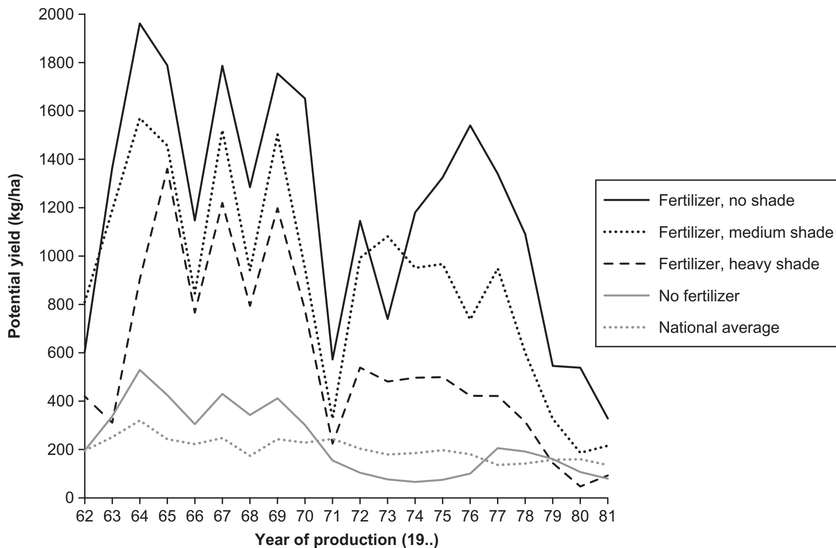


Fig. 8 Results of application of fertilizers under different degrees of shade in trial K2-01, data from Ahenkorah et al. (1987). Of the unfertilized plots, average yields for all three shade treatments are given. Of the fertilized plots, average yields of both fertilizer rates are given for each degree of shade. The national average yields of Ghana for each year are represented as well.

trial was much smaller than in the K1 trial, which raises questions about the management practices applied in these treatments. Some fertilizer effects were only significant in the minor season and not in the main season, which also influenced the significance of the effects on total annual production (Ahenkorah and Akrofi, 1968; Ahenkorah et al., 1987). This may be the case in more regions with distinct seasonal production patterns.

Wessel (1971) describes several fertilizer trials conducted in Nigeria. Sites with 25–35-year-old cocoa were selected on farms in various parts of the Nigerian cocoa belt. The cocoa had been randomly planted under irregularly spaced shade trees. Yield recording began at least 2 years prior to the introduction of fertilizer treatments to obtain pretreatment data to be used to correct the treatment yields for existing yield differences, considerably reducing variability. Fertilizer application rates of the nutrients are stated in Table 5, and also included a zero application for each nutrient. Nutrients were applied in all combinations of rates, except for Series II in which K and Mg were applied together. From the results of the trials, it can be concluded that yields of Amelonado cocoa in Nigeria responded mostly to application of N, P, or a combination of both N and P (Wessel, 1971). However, yield

responses and optimum rates and combinations varied strongly between locations, with no response at some sites. All reported yields (which did not include the yields of controls without any fertilizer application) were between about 600 and 1900 kg/ha. Largest yields differences were found among sites and not between treatments in one site.

Jadin and Snoeck (1985) applied fertilizers to smallholder farmers' fields in Côte d'Ivoire. The amounts of nutrients added differed among the fields and were calculated using the Soil Diagnostic Method (see Section 7.3). Unfortunately, neither the soil values on which the calculations were based, nor the calculations themselves or the subsequent application rates, are provided in the literature consulted. It is clear that the application of fertilizers increased the yields in these fields (Fig. 9), but conditions under which these results have been achieved are unclear and it is not known which nutrients were applied and in which amounts.

Others have also found large yield increases due to fertilizer application. Appiah et al. (2000) found yields in fertilized farmer plots to be 97%, 296%, 243%, and 169%[a] larger in years 1, 2, 3, and 4 of treatments, respectively,

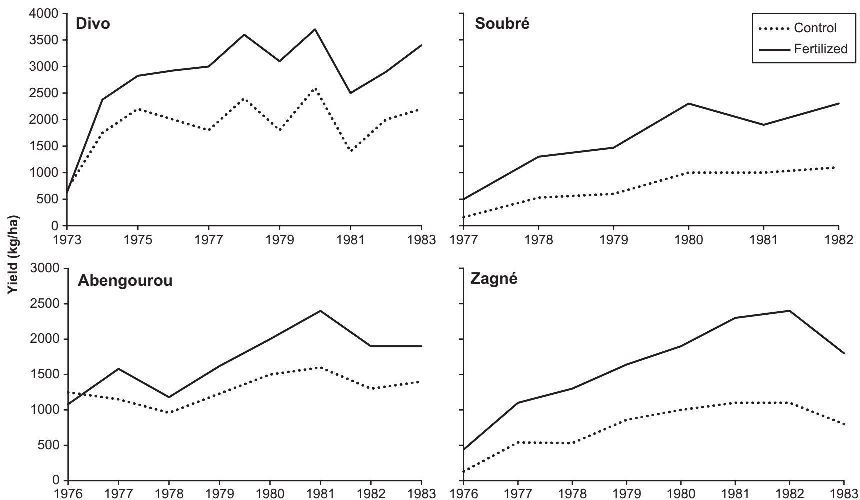


Fig. 9 Results of application of fertilizers in several regions in Côte d'Ivoire. *Based on data from Jadin and Snoeck (1985).*

[a] In the paper, different percentages increase are given (61.7%, 99.8%, 116%, and 106%), but these are the increases when comparing the yield averages of the different plots with and without fertilizers instead of averaging the relative yield increases per site.

compared with unfertilized plots. Plots were selected based on good farm maintenance (weeding, chupon and mistletoe removal, pest and disease control) and farmer attitude, and most farmers in this trial followed CRIG recommendations of pest and disease control and shade reduction. For application rates, see Table 5. Gockowski and Sonwa (2011) in their survey found average cocoa yields in Ghana to be more than double those of Ivoirian farmers which they attributed largely to more fertilizer use in Ghana. Many more examples exist which show that fertilizer application has a large potential to increase yields. However, in most cases it cannot be established which nutrients, in which amounts and in which combinations are most effective in increasing cocoa yields, let alone for which soil, climatic, and management conditions this would hold. Also, most trials are relatively short term when considering that the life span of the cocoa tree may be 40 years or more.

Several authors have found that yield increases due to fertilizers resulted from increases in the number of pods rather than in the number and weight of beans (Asomaning et al., 1971; Wessel, 1971). This justifies the decision made in many cocoa trials to calculate yields from pod counts using a set estimate of weight of dry beans per pod rather than actually measuring dry bean weights. However, pods which are damaged by insects or diseases, or otherwise not suitable for commercial use, are sometimes still part of the commercial yield (e.g., Ahenkorah et al., 1987; Asomaning et al., 1971; Groeneveld et al., 2010), even though the beans of these pods are worthless. It is sometimes argued that there is an increase in pest and disease incidence in fertilized plots as a consequence of larger yields and vegetative production in these plots (Ahenkorah et al., 1987). This could provide better shelter and food for insect pests and accelerate disease spread. On the other hand, adequate nutrition may strengthen the cocoa trees, hence making them less susceptible to pests and diseases (Ofori-Frimpong et al., 2007). So far, the effect of fertilizer application on incidence of various pests and diseases remains unclear (compare for instance Ahenkorah et al., 1987; Appiah et al., 2000; Asomaning et al., 1971).

4.2 Nutrient Functions and Effects

4.2.1 Nitrogen

As with most crops, nitrogen (N) is the nutrient required in the largest quantities by cocoa. N stimulates leaf flushing, resulting in increases in leaf area and canopy formation. Wessel (1971) found that N additions stimulated growth of young seedlings and jorquette formation in interaction with K and Mg application. This stimulates early closure of the cocoa canopy.

Evans and Murray (1953) found positive effects of N application to young cocoa plants, but only in the absence of shade. Positive responses of young seedlings to N application have been found in some experiments in Ghana (Appiah et al., 2000). Negative effects on cocoa seedling growth after N applications, sometimes in combination with other nutrients, have also been found. Applying the nutrients in bands around the plants instead of in the planting holes may solve this problem (Wessel, 1971). Wessel (1971) reviewed a few trials in Ghana in which the negative effect of N was related to a reduction of P uptake. However, high rates of N and P also depressed early growth of cocoa seedlings if K and Mg were not applied (Wessel, 1971).

Wessel (1971) in several experiments with mature Amelonado in Nigeria found that yields increased steadily with increasing rates of N application. However, the largest rate of N (Experiments Series I) gave a response only when additional P was applied (Wessel, 1971). Interactions between N and P application have been observed frequently (e.g., Ahenkorah and Akrofi, 1968; Ahenkorah et al., 1987; Wessel, 1971). Lack of response to N may be explained by P limitation, and vice versa—N may be deficient especially when P is readily available leading to greater N fertilizer demand (Wessel, 1971). Ahenkorah and Akrofi (1968) in Ghana found no response to either sole N or P application after 2 years of treatment, although the combined effect of N and P was significant. According to Wessel (1971), effects of annual N and P applications on mature cocoa usually start to appear only after 2–3 years. First the general nutritional status and vegetative growth of the trees has to be improved before more pods can be produced. Jadin and Snoeck (1985) argued that mature trees may only respond to N when they are pruned and thinned, because new leaves have to be formed after pruning. A negative yield response of mature cocoa to N has sometimes been observed, especially in shaded and/or closely spaced plots (Ahenkorah et al., 1987; Wessel, 1971). Wessel (1971) found dense shade to reduce yield response to N, and visual symptoms of N deficiency were more commonly found in unshaded than in shaded cocoa. This was also observed in Trinidad by Evans and Murray (1953) who attributed these symptoms to inadequate soil aeration during the wet season. According to Wessel (1971), the cocoa in Nigeria, which was grown under little or no shade, required additional N for large yields, while in Ghana, where cocoa was heavily shaded, cocoa failed to respond to N. In trial K2-01 negative effects of N application were found in absence of shade, although it is unclear how this was related to the application of other nutrients (Ahenkorah et al., 1987). In shaded farmers'

fields, negative responses to N were found more often, but responses were positive when combined with P and/or K application (Ahenkorah et al., 1981). Santana and Cabala-Rosand (1982) in Brazil found soil N contents to be greater under shade trees than without shade, which would explain a lack of response to N application under shade. It has been argued that when adequate N is already present, additional fertilizer N could create unfavorable conditions for efficient N utilization by the cocoa tree (Ahenkorah et al., 1981). In some experiments in Ghana mature cocoa showed no response regardless of shading (Appiah et al., 2000). The Cocoa Research Institute of Ghana (CRIG) and the Center National de Recherche Agronomique (CNRA) of Côte d'Ivoire do not currently include N in their national fertilizer recommendations. At the time the recommendations were established, cocoa was grown under shade on relatively fertile soils that had not been under cultivation for a long time. This may explain a lack of response to N application on-farm fields at that time. However, lack of response to N would not be expected in unshaded research conditions, and especially the reported negative responses remain unexplained. Perhaps the negative response to application of N is only found in absence of other nutrients. This is not always clear from the papers consulted. N application may then stimulate leaf production, diverting other nutrients to the leaves instead of to pod production. Both CRIG and CNRA are currently involved in research to reassess the relevance of N application. Another point of interest in this matter is whether there is a difference in response between nitrogen applied in the form of urea or as calcium nitrate. It has been suggested that application of urea increases incidence of black pod disease, although no literature supporting this statement could be found. The proposed reduction of black pods when calcium nitrate is applied may also be caused by the added calcium rather than the form of N.

4.2.2 Phosphorus

Phosphorus (P) is only exported through harvest in small amounts. Overall, the amount of P in the above-ground vegetation in cocoa plantations is similar to the amount of available P in the topsoil (Table 3) (Hartemink and Donald, 2005). P stimulates flowering in cocoa (Asomaning et al., 1971; Jadin and Snoeck, 1985). Strong yield responses to P application were found in Ghana. Responses to P were greater than those to N or K (Ahenkorah et al., 1987). Wessel (1971) also found positive responses to P in Nigeria, often in interaction with N. The yield increase was mostly due to increased yields of the poorly bearing trees within the plantation. Wessel (1971)

suggested P response to be hampered by excessive competition for P with shade trees. By contrast, Ahenkorah et al. (1987) observed a large P response under heavy shade. While Ahenkorah et al. (1987) concluded that the requirement of Amazon cocoa for P and K tends to increase with age, especially when shade density is reduced, Wessel (1971) argued that annual P application can be reduced once a reserve of available P has been built up in the soil. Jadin and Snoeck (1985) hold a similar view. This is supported by the fact that generally, only 10–20% of P applied as fertilizer is taken up by crops in the first year following application. The remainder is held in the soil and becomes gradually available in subsequent years thus building up a stock of available P over time (Sattari et al., 2012; Wolf et al., 1987). Perhaps soil P reserves had not yet been adequately replenished in the research by Ahenkorah et al. (1987), or strong P sorption capacity of the soil could have rendered the added P unavailable for plant growth. Soil available P of unfertilized and of unshaded plots decreased throughout the experiment. However, when P was applied on shaded plots, the soil available P continued to increase, while yield responses to P fertilization continued to be observed (Ahenkorah et al., 1987). Based on their findings, Ahenkorah et al. (1987) recommend large rates of P application especially under shaded conditions.

4.2.3 Potassium

A large part of the potassium (K) in cocoa ecosystems can be found in the biomass of cocoa and shade trees rather than in the soil (Hartemink and Donald, 2005). Large amounts of K are exported in the harvest, especially when the husks are not returned to the field (see Section 3.1). K is important for translocation of carbohydrates (Boyer, 1973) and is thought to increase tolerance to water stress (reviewed in Almeida and Valle, 2007). K comprises some 70% of the minerals in the xylem sap of cocoa (reviewed in Almeida and Valle, 2007). Wessel (1971) in Nigeria found that K application did not raise K leaf concentration on soils with an adequate K status. However, Hartemink and Donald (2005) in their review concluded that large concentrations of K in the soil lead to luxury uptake of K, suggesting a wide variability in K uptake depending on the availability in the soil. Variability in uptake can explain the wide variation of K content in the cocoa husks and litter fall. Boyer (1973) emphasized that the K in leaves is highly soluble, as it is largely present in the cytoplasm of cells. This further explains the large concentrations of K transferred to the soil by rain wash and the rapid release

of K from litter as concluded by Hartemink and Donald (2005). The K cycle in cocoa systems is very fast (Boyer, 1973). Large amounts of K present in the system are mobilized and returned to the soil through litter and rainwash (Tables 3 and 4). In a study in Cameroon this amounted to half of the exchangeable soil K reserve (Hartemink and Donald, 2005).

Although no K deficiency symptoms were detected in the K2-01 experiment after 7 years of cropping, exchangeable K concentrations in the soil were small after this time (Ahenkorah and Akrofi, 1968). Exchangeable K continued to decline regardless of K applications (Ahenkorah et al., 1987). Wessel (1971) did not find Amelonado cocoa to exhaust exchangeable K in Nigeria and concluded that the soils had large K reserves. However, he found Amazon cocoa to be more K demanding than Amelonado cocoa and mentions that K availability may be too poor for production of Amazon cocoa. This would be the case especially in absence of shade, on sandy soils and soils developed on sedimentary deposits. The relation between absence of shade and increased response to K application was also found in experiment K2-01. K fertilizers increased yields especially in absence of shade, where the largest yields in the experiment were reported (Ahenkorah and Akrofi, 1968; Ahenkorah et al., 1987). By contrast, under heavy shade, P fertilized plots yielded more than K fertilized plots (Ahenkorah et al., 1987). Ahenkorah et al. (1987) found that the good yields associated with K application did not last beyond the juvenile phase under medium shade. Large K application was therefore especially recommended in absence of shade.

4.2.4 Other Nutrients

Some fertilizer trials examined response to application of calcium (Ca) and magnesium (Mg) (see e.g., Table 5). The fertilizer formula most used and recommended for cocoa in Ghana, Asaase Wura, and cocoa fertilizer blends on the market in Côte d'Ivoire, such as SuperCao, also contain these elements. However, little data regarding the response to these elements have been published. Ca is said to be especially important for establishment of cocoa, while Mg is favorable to the retention of leaves and delays leaf senescence (Jadin and Snoeck, 1985; Thong and Ng, 1978). This is presumably due to its role in chlorophyll. Wessel (1971) did not detect Ca and Mg deficiencies in leaves. Soil analyses and fertilizer trials suggested that Mg may become a limiting factor in some sites in Nigeria, especially when N and P supply is increased. Ahenkorah et al. (1987) found no appreciable changes

in exchangeable Ca and Mg over the last 15 years of trial K2-01. Ahenkorah et al. (1974) report that exchangeable Ca, Mg, and K decreased by 10%, 22%, and 23% in absence of shade and fertilizers in the last 15 years of trial K1. From the data presented it seems that these percentages are incorrectly calculated as the sums of the percentage changes in nutrient content of the two soil layers 0–5 and 5–15 cm. It is difficult to draw conclusions regarding the changes in soil content of Ca, Mg, and K from the data presented. In some cases, content increased in one layer while it decreased in the other. Increases in nutrient content also occurred in absence of fertilizers, which seems unlikely. Cocoa soils only contained about one-third to one half of the concentrations of Ca, Mg, and K in bush soils (Ahenkorah et al., 1974). The results suggest that the highest depletion of these bases occurs in the first years of cocoa cultivation, as is the case for carbon stocks after deforestation (see Section 2.4.4). Part of the depletion could be due to erosion.

The Ghanaian fertilizer Asaase Wura and the Ivorian fertilizer SuperCao also contain sulfur (S), but even less information is available on the requirements and application of this element. S deficiencies have been reported across Africa, more commonly on sandy soils (e.g., Grant and Rowell, 1976). Cocoa fertilizer formulas may also contain micronutrients such as boron and zinc. In their review, Cunningham and Arnold (1962) found no evidence for increases in yield from application of the micronutrients Mn, Fe, Cu, Zn, B, and Mo. They highlighted, however, that small responses could not be detected because of the large variability in yields before the treatments were applied, despite pre-treatment data collection. Deficiencies of micronutrients are widespread in Africa (Le Mare, 1984 and supported by the references following). They occur not only because of their scarcity in the soil but also because of factors such as pH which affect their availability. Baligar et al. (2006) in their review suggest that Zn deficiency is more likely to occur on soils with a higher pH, and high amounts of clay and P. Zn deficiencies are also observed in other crops on African sandy soils (e.g., Zingore et al., 2008).

Some nutrients are toxic when available in large concentrations. This tends to occur especially at low pH (e.g., aluminum (Al) and manganese (Mn)) or under reducing (waterlogging) conditions (e.g., Mn). Although copper (Cu) and zinc (Zn) are toxic when bioavailable in large quantities such conditions rarely occur in cocoa plantations.

4.3 Increasing Soil Fertility Through Alternative Fertilizers and Nitrogen Fixation

The use of organic fertilizers and the inclusion of N_2 fixing trees can greatly contribute to nutrient availability in cocoa production. This may be important especially for farmers to whom it is difficult to access inorganic fertilizers due to problems with supply and/or cost (Agbeniyi et al., 2011; Smaling et al., 1992). The use of alternative soil amendments must be feasible and profitable. Waste materials produced close to the cocoa production site may offer opportunities (Wichmann, 1992).

4.3.1 Alternative Fertilizers

Organic residues have the advantage over standard NPK fertilizers of adding other nutrients such as Ca, Mg, and micronutrients. They also assist in maintaining soil organic matter. A large soil organic matter content is favorable for cocoa production. A number of organic fertilizers are used in cocoa. Commonly mentioned is the scattering of pod husks and residues in the fields (Boyer, 1973; Fontes et al., 2014; Thong and Ng, 1978). Especially in areas prone to black pod disease, husks should be burned or composted prior to field application. Adejobi et al. (2014) obtained good responses in leaf nutrient content and growth measurements of cocoa seedlings after applying cocoa husk ash. Leaf content of P and K increased the most, probably due to the high content of these nutrients in the ash. However, N is lost by volatilization during burning (Adejobi et al., 2014). Agbeniyi et al. (2011) found cocoa pod husk to increase yields and profitability of cocoa production in Nigeria.

Other organic fertilizers studied by Adejobi et al. (2014) which enhanced cocoa seedling growth are kola pod husk and cowpea pod husks but these are unlikely to be available in any significant quantity. Similarly, waste products from oil palm and rubber plantations can enhance yields and reduce expenditure on chemical fertilizers (Sharifuddin and Zaharah, 1991). These products are not likely to be available for cocoa production as they can be applied in the same oil palm and rubber plantations that they originate from.

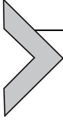
Shamshuddin et al. (2011) used peat, chicken dung, and basalt mainly to reduce Al toxicity, and these sources also contain additional nutrients. For instance, basalt contains large amounts of Ca, Mg, and K and also some P and S. Basalt can be seen as a slow-release fertilizer as it may take more than 9 months for basalt to react effectively in soils. After 27 months, still not all basalt had dissolved in the field (Shamshuddin et al., 2011).

Little research seems to have been done regarding the potential effect on cocoa yields of animal manures. The use of chicken manure by cocoa farmers in Côte d'Ivoire has increased over the last decade. Farmers report significant increases in yield as a result (Ruf et al., 2015). Composition of manure may vary widely depending on the diet, health, and type of animal. The nutrients transferred to the soil further depend strongly on the handling, storage, and application of the manure (Ahn, 1993; Rufino et al., 2007).

4.3.2 Nitrogen Fixation

Some of the trees commonly used for shade in cocoa plantations are N_2 fixing legumes that contribute N to the plantation (Giller, 2001). Estimates of N input through leguminous trees vary considerably. N input depends on the tree species, shade tree density, fertilization, and pruning management (e.g., Beer et al., 1998; Hartemink and Donald, 2005; Santana and Cabala-Rosand, 1982). Giller (2001) stresses that it is very difficult to measure N input from leguminous trees in the field. Beer et al. (1998) from various sources found that N_2 fixation in unfertilized coffee and cocoa plantations ranged between 35 and 60 kg/ha/yr for *Inga jinicuil*, *Gliricidia sepium*, and *Erythrina poeppigiana*. These seem to be reasonable estimates for average conditions although much larger estimates have been recorded. Beer et al. (1998) consider this to be a relatively small contribution. Others maintain that leguminous trees may provide a considerable source of N and hence reduce the need for nitrogen fertilizers. This seems likely when comparing N input through N_2 fixation with N exports (Table 2) (Hartemink and Donald, 2005; Kähkölä et al., 2012; Santana and Cabala-Rosand, 1982). The N_2 fixed by the trees is for a large part transferred to the soil by aboveground litter fall, which may be enhanced by pruning (Beer et al., 1998). Another part of the fixed N is released below ground through nodule senescence and decomposition (Beer et al., 1998). N transfer of N_2 fixing shade tree species may be seasonal if litter fall is seasonal as is the case with, for instance, *Erythrina* (Santana and Cabala-Rosand, 1982). *G. sepium* (syn. *Gliricidia maculata*) on the other hand is an evergreen tree (Ahenkorah and Akrofi, 1968). Decomposition characteristics of the litter also play a role in the availability of the fixed N. Leaves of *Gliricidia* are rich in N, contain little lignin or polyphenols, and decompose and release N rapidly (Handayanto et al., 1995). By contrast, leaf litter of *Inga edulis* decays more slowly and provides a good surface mulch rather than increasing N availability (reviewed in Kähkölä et al., 2012) (see also Section 3.3). These and other attributes should be taken into account when choosing among

different leguminous shade species. While leguminous trees may provide substantial input of N, deficiencies of other nutrients such as P can reduce the amount of N fixed (Giller, 2001, p. 260). Shade trees may also compete with cocoa for nutrients and water.



5. INTERACTION OF SHADE WITH FERTILIZER RESPONSE

As seen in Figs. 6–8, shading has an influence on the response of cocoa to fertilizer. Many authors have described this interaction. Generally speaking, fertilizers result in stronger positive impacts on cocoa growth and yield in absence of shade.

5.1 Optimal Degree of Shade

How shading affects fertilizer response depends on the degree of shade. The degree of shade is usually not quantified in a way that is comparable across studies. In Fig. 10, a graph based on data from Murray (1975) is depicted. This graph is frequently used to illustrate the interaction between the degree of shade and fertilizer response.

From Fig. 10, we can conclude that NPK fertilizer application increased cocoa yields. However, under heavy shade, yields remained small irrespective of fertilizer application. With fertilizer application, yields increased with increasing light intensity. Above 50% of full daylight, this increase levels off and yields may even decrease slightly with light intensity above 75% of full daylight. In the absence of fertilizer application, though, there was an optimum at 50% of full daylight, below and above which yields decreased considerably.

This figure is helpful to understand the interaction between fertilizer application and light intensity in a qualitative way. However, the results show no differentiation for different application rates or soils. The optimal shading densities may shift with different rates of fertilizer and soil fertility. The shading density is expressed as percent of full daylight transmitted. As radiation intensity at "full daylight" will vary between regions, so will the optimal percentages of daylight for cocoa production. Different variables such as soil moisture or management are not taken into account which may also cause differences in optimal degrees of shade. Also, the interaction between light intensity and fertilizer application may change during the lifetime of the cocoa trees.

The qualitative conclusions that can be drawn from the figure have also been found by other authors. Beer et al. (1998) found reports of a positive

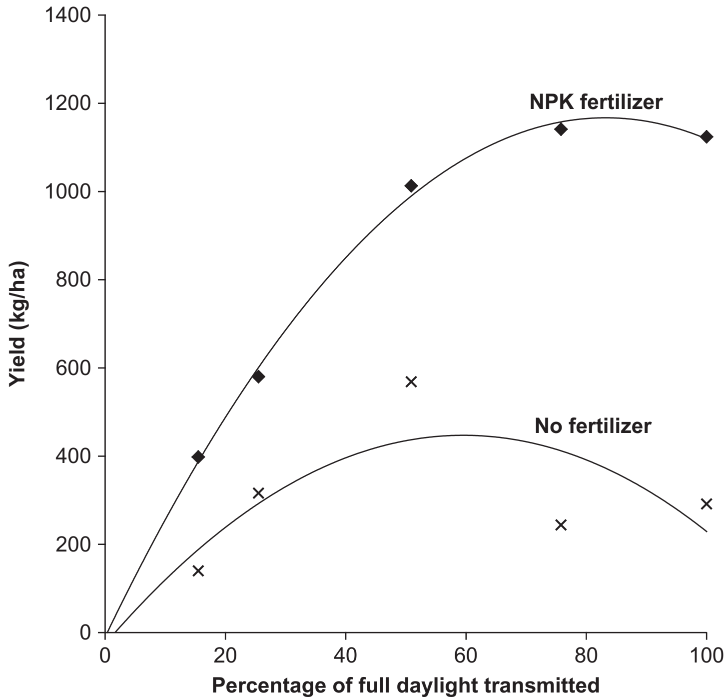


Fig. 10 The interacting effect on cocoa yields of shade and fertilizer, data from Murray (1975). Trendline drawn using Excel second-order polynomial trend line. These results are from the continuation of the experiment of Evans and Murray (1953), when trees came into bearing in their third year. Nutrient application rates unknown.

correlation between cocoa yields and light availability when nutrient availability is not limiting growth. Asomaning et al. (1971) have found the strongest effects of fertilizers on lightly shaded plots. Wessel (1985) found that when soils are chemically poor and not fertilized, cocoa gives the highest yield under shade. On fertile soils or with adequate fertilizer, well-established cocoa yields most with little or no shade. In Ghana, shade reduction in combination with fertilizer application has been recommended following the shade–fertilizer trials at CRIG. Unfortunately, fertilizers saw little adoption while the low-shade recommendation was widely followed. It is argued that cocoa production cannot be sustained in such a system (Gockowski et al., 2013).

5.2 Long-Term Effects

In experiment K1 (Fig. 6), yields increased spectacularly in the nonshaded treatments over the first 8 years of treatment. However, after this period

these treatments also exhibited the most spectacular decline in yields. When the trial was terminated, yields of the shaded fertilized plots (SF) had exceeded those of the unshaded unfertilized plots (NSNF) for several years. SF yields had even exceeded those of the unshaded fertilized plots (NSF) in the one but final year. Yield differences between the shaded and unshaded plots without fertilizer (SNF and NSNF) were small. Ahenkorah et al. (1974) state that the fertilizer effect without shade tends to last longer than with shade. However, it can clearly be seen that the yield increase due to fertilizer declined over time in absence of shade while it increased under shade (compare NSF with SF). From these results, it can be concluded that the beneficial effect of no shade on fertilizer response decreases and perhaps even disappears after some years of heavy production. In general, the beneficial effect of no shade on cocoa yields is limited to about 10–15 years (e.g., Ahenkorah et al., 1974, 1987). After this time, lack of shade seems to lead to early degeneration, especially when nutrient availability is limited and a high standard of maintenance and crop protection cannot be maintained (Wessel and Quist-Wessel, 2015).

5.3 Dependence of the Effects on Other Conditions

Yields in the K1 experiment were much larger than the national average, even in the SNF treatment which is suggested to resemble farmers practice. This is likely to be related to better management practices such as pest and disease control, better initial fertility of the soil, and younger average age of the trees. It is often argued that removal of shade is only beneficial if other factors are favorable (Beer et al., 1998; Cunningham and Arnold, 1962; Mossu, 1995). These factors include not only soil fertility, which can be improved through fertilizer applications, but also climatic factors and pest and disease management. For instance, lack of shade creates favorable conditions for mirids, which increases the need for chemical control of this insect pest (Wessel and Quist-Wessel, 2015). It is likely that the large yields achieved without shade in the K1 experiment, both with and without fertilizer application, are not easily achieved without the management practices allowed under experimental conditions. The yields of the unfertilized plots in the K2-01 experiment were similar to the national average and even fell below it in some years. This suggests that management of the plots in this experiment may have been representative of general management of cocoa in Ghana. From the results of experiment K2-01, it could be concluded that the overall impact of fertilizer on cocoa yield is much larger than the overall effect of shade, although increased shading

reduced the response to fertilizer. The effects of different degrees of shade with and without fertilizer application may also depend on the cocoa variety (Okali and Owusu, 1975).

5.4 Physiological Processes Underlying the Effects

It is not completely understood what physiological processes in cocoa cause the differences in fertilizer response under shade.

High radiation has negative effects on individual leaves. Leaves grown in full sun contain less chlorophyll and leaf expansion is reduced compared to leaves grown in the shade (see Section 2.2.1). Fertilizer application may offset these negative effects in several ways. Leaf production is enhanced in response to nutrient application (Okali and Owusu, 1975). This increases mutual shading, so that relatively less leaves will suffer from the negative effects of growing under high radiation. Furthermore, nutrient application at least partially prevents the reduction of chlorophyll content in sun leaves (Okali and Owusu, 1975). The resulting photosynthetic rate could offset the effects of reduced leaf area. The research of Okali and Owusu (1975) was performed on cocoa seedlings. Therefore, extrapolations of these results to explain yield effects of shade and fertilizers on mature cocoa can only be made with caution.

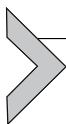
The amount of photosynthetically active radiation (PAR) received by the cocoa trees is greater with less shade. This will potentially lead to higher photosynthesis, even if the relation is not linear. However, as long as nutrients are limiting, this cannot lead to higher productivity. This could explain why fertilizer application will have the most effect if shading is removed. In absence of shade, not only yields increase. Leaf flushing is also more vigorous (Asomaning et al., 1971). Cocoa drops more leaves in full sun (Boyer, 1973; Evans and Murray, 1953; Ofori-Frimpong et al., 2007). This increases the demand for a continuous supply of nutrients.

Competition between the shade and cocoa trees for the applied nutrients is likely to reduce the benefits of the fertilizer (Wessel, 1971). Fertilizer application will stimulate the growth of the shade trees. The resulting increase in the degree of shade may further depress the yield response of the cocoa (Cunningham et al., 1961). Competition for other nutrients than those applied with the fertilizers and for water may also play a role in depressing the yield response (Wessel, 1971). Differences in fertilizer response between shaded and unshaded cocoa may be further influenced by the effect of shade trees on nutrient cycling. Shade trees take up nutrients from the soil,

but may extract them from deeper soil layers than the cocoa trees. Presence of shade trees may lead to increased nutrient mineralization through favorably influencing the microclimate and litter quality (see Section 3.3). This could contribute to differences in fertilizer response.

Some authors suggest that increased production in the absence of shade in combination with fertilizer application increases physiological stress. This would contribute to the more early and rapid deterioration of the unshaded, fertilized cocoa trees (Beer et al., 1998; Gockowski et al., 2013). Direct sunlight and consequent high leaf temperatures, lack of wind protection, increased pest and disease incidence, and increased soil moisture evaporation in absence of shade trees may also cause physiological stress to the trees, contributing to accelerated tree deterioration in absence of shade (Beer et al., 1998; Cunningham and Arnold, 1962; Wessel, 1971).

Shading also alters the relative requirements of the cocoa tree for different nutrients. For instance, Ahenkorah et al. (1987) recommend large rates of P addition especially for shaded systems, and large rates of K especially for unshaded cocoa. N fertilizer is recommended for unshaded systems but not for shaded systems (Ahenkorah et al., 1987; Wessel, 1971). See also the different paragraphs on specific nutrients in Sections 4.2.1–4.2.3. Little explanation is given by these authors for the differences in fertilization requirements for shaded and unshaded cocoa with N, P, and K. The difference in recommendations for N fertilizer is readily understood. Increased N stimulates leaf production, which is required for the increased leaf flushing in absence of shade. Higher N concentration of leaves also result in larger concentration of chlorophyll and Rubisco in the leaves. This leads to greater photosynthetic efficiency, so that better use can be made of the increased radiation in absence of shade.



6. COCOA FERTILIZER RECOMMENDATIONS

6.1 Various Past and Present Cocoa Fertilizer Recommendations

Based on his research in Nigeria, Wessel (1971) set preliminary fertilizer recommendations for newly established cocoa (Table 6). For his recommendations based on soil and leaf nutrient content in mature cocoa, see Table 15. In the first 3 years, the fertilizers are applied on the soil surface in circular bands starting at 15 cm from the stem. In the year of planting, one half is applied in July and one half in September. In the first to third year after planting, one

Table 6 Preliminary Fertilizer Recommendations for Cocoa Established According to Modern Planting and Maintenance Methods on Soils Derived From Metamorphic Igneous Rock According to Wessel (1971)

	Soils Cleared From Forest: Only N		Soils Cleared From Cocoa and Arable Crops: N as Soils Cleared From Forest, With Additional P		
Year	**g N/tree**	**kg N/ha**	**g P_2O_5/ tree**	**kg P_2O_5/ha**	**kg P/ha**
Year of planting	10	13[a]	10	13[a]	6
First to third year after planting	20–30	27–40[a]	20–30	27–40[a]	12–17
Fourth and fifth year after planting		50–67		34	15
Sixth and following years[b]		67–101		50	22

[a]Assuming a tree density of 1333 trees/ha.
[b]These rates have to be adjusted according to the criteria given for mature cocoa (Table 15) and N fertilizers should be omitted in heavily shaded cocoa.

half is applied in April and one half in August. From the fourth year onwards, the fertilizers are broadcast every year with one half being applied in April and one half in August.

For Côte d'Ivoire (Table 7), several fertilizer treatments were recommended in three different regions during the 1956 campaign to promote the general application of fertilizers to cocoa (Loué, 1961).

According to De Geus (1973), based on various publications from Ghana in the early 1960s, under shade in Ghana the soil may provide enough N for the crop's needs, but requires 45–90 kg P_2O_5 (or 20–39 kg P) per hectare. However, good-yielding cocoa under reduced shade may require additional N. Moreover, where yields are greatly increased by reducing or removing shade and by N and P dressings, the soil's K reserves may also have to be supplemented to maintain these yields. In that case it is possible that the need for Mg should be taken into consideration.

Cocoa in Grenada (Cruickshank, 1970 in De Geus, 1973) during the establishment phase received applications increasing from 110 g NPK 12-8-24 or NPK 11-11-33 to 450 g per plant per year. From the sixth year onward, application was 900 g NPK 12-8-12 per plant per year. Plants were also usually mulched at the rate of 10–12.5 t/ha/yr.

In Mexico, Maliphant and Walmsley (1961 in De Geus, 1973) recommended applications of 60 g N, 120 g P, 90 g K, and 500 g Ca per tree.

Table 7 Fertilizer Recommendations in Côte d'Ivoire Based on Loué (1961)

	g/tree			kg/ha[a]				
	N	P_2O_5	K_2O	N	P_2O_5	K_2O	P	K
Potassium deficient region	60	50	100	80	67	133	29	111
	60	60	100	80	80	133	35	111
	60	60	120	80	80	160	35	133
Granito gneissic region	60	80	60	80	107	80	47	66
	60	80	80	80	107	107	47	89
Schistic region	60	50	60	80	67	80	29	66
	60	60	80	80	80	107	35	89

[a]Assuming a planting density of 1333 trees/ha.
NB: It is unclear why there are several recommendations per region, and on what the decision between them should be based.

Recommendations for cocoa in Bahia, Brazil (Cabala-Rosand, 1966a,b, 1967; all in De Geus, 1973) are 65–100 g of a mixture of 50% ammonium sulfate, 30% triple superphosphate, and 20% KMg sulfate per planting hole, 130–200 g/tree/yr after the first year and 200–300 g/tree/yr after the second year. Adult trees should receive 325–500 g/tree/yr.

Recommendations of Hardy (1962, in De Geus, 1973) were calculated based on twice the amounts of nutrients removed by the crop to make up for fixation and leaching losses, and assuming that the pod husks are returned to the field. For shaded cocoa, they are 12 g/tree of ammonium sulfate (21% N), 4 g/tree of triple superphosphate (47% P_2O_5), 6 g/tree of K_2SO_4 (48% K_2O), and 2 g/tree of $MgSO_4$ (c. 33% MgO). For unshaded cocoa, they are 24, 6, 10, and 3 g/tree, respectively, of the same compounds.

The above recommendations were recalculated and summarized for comparison in Table 8. Based on their knowledge at that time, von Uexküll and Cohen (1980) estimate the recommendations for young, mature, and unshaded cocoa as shown in Table 9. Wyrley-Birch (1972, in von Uexküll and Cohen, 1980) presents fertilizer recommendations of different authors from various cocoa-producing countries (Table 10).

In Côte d'Ivoire, the current official recommendations are two times 150 g (in the East) or 200 g (in the West) of 0-23-19 NPK/tree/yr. In Ghana, an annual application of three bags per acre, or 300–400 g/tree,

Table 8 Various Fertilizer Recommendations Described in De Geus (1973)

Country	Recommendation	N (kg/ha)	P_2O_5 (kg/ha)	K_2O (kg/ha)	P (kg/ha)	K (kg/ha)	Source
Ghana			45–90		20–39		De Geus (1973)
Grenada	Establishment phase (increasing over time): NPK 12-8-24	18–72	12–48	35–144	5–21	29–119	Cruickshank (1970, in De Geus, 1973)
	Idem, but for NPK 11-11-33	16–66	16–66	48–198	7–29	40–164	
	Year 6 and onwards	144	96	288	42	239	
Mexico		80	366	144	160	120	Maliphant and Walmsley (1961, in De Geus, 1973)
Brazil[a]	Upon planting	9–14	12–18	4–6	5–8	3–5	Cabala-Rosand (1966a,b, 1967; all in De Geus, 1973)
	After first year	18–28	23–36	8–12	10–16	6–10	
	After second year	28–42	36–54	12–18	16–24	10–15	
	Adult	45–70	58–90	19–29	26–39	16–24	
Unknown	Shaded, applications per 100 kg crop	3.4	2.5	3.8	1.1	3.2	Hardy (1962, in De Geus, 1973)
	Unshaded, applications per 100 kg crop	6.7	3.8	6.4	1.6	5.3	

[a]Rates were calculated assuming ammonium sulfate contains 21% N, triple superphosphate contains 45% P_2O_5, and KMg sulfate contains 22% K_2O. When rates were given in g/tree, rates in kg/ha were calculated assuming a planting density of 1333 trees/ha.

Table 9 Recommended Fertilizer Rates for Young, Mature, Unshaded Cocoa as Described in von Uexküll and Cohen (1980)

Targeted Yield (Dry Beans[a]/ha)	N (kg/ha)	P_2O_5 (kg/ha)	K_2O (kg/ha)	MgO (kg/ha)	P (kg/ha)	K (kg/ha)	Mg (kg/ha)
1	40	40	40	10	17	33	6
2	80	60	120	30	26	100	18
3	130	80	250	60	35	208	36
4	190	110	385	100	48	320	60

[a]Although this is not indicated in the original text, it is assumed here that dry beans is given in tons.

of the Asaase Wura blend (0–22–18 NPK, with additional Ca, S, and Mg) is recommended. More recently, Nitrabor (a calcium nitrate) has been introduced for cocoa in Ghana, though uptake has been slow (YARA, 2012). It is recommended to be applied at one bag per acre, or 100–150 g/tree. As can be seen in Table 11, fertilizer recommendations in Indonesia are higher, especially for N and K.

More fertilizer recommendations from different authors of different regions exist, but from the above it can already be concluded that the amounts of fertilizer recommended vary enormously. The underlying reasons for these differences are unclear as authors rarely state how the recommendations were derived. Recommendations are applied to cocoa of different age, shading density, region of production, climatic and soil conditions, etc. Some authors recommend different amounts of fertilizers depending on such factors, but this is not always the case. Below, some of the methods used to establish fertilizer recommendations are discussed.

6.2 Recommendations on Method and Timing of Fertilizer Application

Cocoa seedlings are usually fertilized upon planting in experiments. Fertilizer is (recommended to be) applied in the planting hole (e.g., Ahenkorah and Akrofi, 1968; Evans and Murray, 1953; Jadin and Snoeck, 1985). However, Wessel (1971) found negative effects of applying NPK in the planting hole and advised fertilizers at planting should be applied on the soil surface in a circle around the stem.

Once the cocoa has matured, fertilizers are either broadcast or applied in a circle around the stem. Mature cocoa forms a dense layer of lateral roots in the topsoil. Therefore, broadcasting seems appropriate and is much less time

Table 10 Rates of Application of Nutrients to Cocoa According to Various Authors in Wyrley-Birch (1972, as Presented in von Uexküll and Cohen, 1980)

N (kg/ha/yr)	P (kg/ha/yr)	K (kg/ha/yr)	Remarks
37	41	100	Light shade, yields 450 kg. East Malaysia
105	30	167	Unshaded cocoa
–	50	–	Shaded Upper Amazon
58	33	–	Smallholder cocoa in Ghana
115	26	198	Unshaded cocoa, yield 2.5 t/ha
–	37	133	P applied as rock phosphate
132	13	–	Smallholder cocoa in Nigeria
22–34	18–22	28–37	Cocoa up to 3 years old
34–68	13–26	56–84	Mature cocoa over 3 years old
100–156 or 150–233	44–68	83–129	Planting density 1100 trees/ha
97	25	61	Trinidad, young trees
195	50	123	Trinidad, old trees
16	68	69	Bahia Brazil, shaded
23	6	19	Jamaica, shaded, first and second years
47	12	37	Jamaica, shaded, third year
31	12	75	Jamaica, shaded, fourth year
16–37	5–11	11–28	Côte d'Ivoire, 2–6-year-old trees, P as rock phosphate

Table 11 Current Fertilizer Recommendations in Ghana, Côte d'Ivoire, and Indonesia

	N (g/tree)	P_2O_5 (g/tree)	K_2O (g/tree)	N (kg/ha)	P_2O_5 (kg/ha)	K_2O (kg/ha)	P (kg/ha)	K (kg/ha)
Ghana[a]	15–23[b]	66–88	54–72	17–26[b]	73–97	59–79	32–42	49–66
Côte d'Ivoire[c]	0	69–92	57–76	0	92–123	76–101	40–54	63–84
Indonesia				130	120	190	52	158

[a]Asaase Wura (0-22-18) at 300–400 g/tree, 1100 trees/ha.
[b]If Nitrabor is included at 100–150 g/tree.
[c]0-23-19 at 2 × 150–200 g/tree, 1333 trees/ha.
For Ghana and Côte d'Ivoire, recommendations are given per tree and are recalculated to kg/ha based on recommended tree densities. Recommendations for Indonesia are given in kg/ha and are based on FAO (2005).

consuming than application per tree. However, as long as the cocoa is young and the roots may not have extended between the trees, application in a circle around the stem may give better recovery. Forking the fertilizers into the topsoil is not advised because in mature trees the roots come to the surface under the litter (Jadin and Snoeck, 1985). After application of ammonium or urea forms of N, covering by litter is recommended to prevent volatilization of ammonia (Jadin and Snoeck, 1985).

In most trials, P is applied as either single or triple superphosphate. Wessel (1971) indicates that P responses were observed only with superphosphate in Ghana and not with rock phosphate. However, the source of rock phosphate is not specified. The availability of P from rock phosphate is highly variable depending on the solubility of the phosphate rock (Wolf et al., 1987). Under more acid conditions, the rock phosphate will dissolve more easily and the P will be available sooner. Some acidic tropical soils (notably Nitisols) can fix P strongly into unavailable forms. Even in soils without such a strong sorption capacity, only a small portion of applied P will become available in the first year. The remainder will only gradually become available over the subsequent years. Application of P close to the roots of the cocoa tree can increase uptake in the first year after application (Wolf et al., 1987).

K is usually applied as either sulfate of potash or muriate of potash. Ca is usually applied as calcium sulfate. Jadin and Snoeck (1985) recommend either lime (form not specified) or dolomitic lime (calcium magnesium carbonate) to be used depending on the need for magnesium. Similarly, they advise Mg to be applied either as dolomite (if calcium is also required) or kieserite (magnesium sulfate, as also used in several trials) (Jadin and Snoeck, 1985).

For many crops, foliar application is considered an efficient way to apply minor elements which are needed in small quantities and which may become unavailable if applied to the soil (Ahn, 1993; De Geus, 1973; Wichmann, 1992). In general, macronutrients are not suitable for foliar application as the quantities to be applied are too high (Ahn, 1993; De Geus, 1973; Wichmann, 1992).

Many authors have suggested that rates of fertilizer application should increase over time as the cocoa tree grows (Thong and Ng, 1978; Wessel, 1971). According to Wessel (1971), rates could remain equal once the trees are about 6 years old. Ahenkorah et al. (1987) suggested that requirements of mature Amazon cocoa for P and K increased with age especially under reduced shade. It is unclear whether this was related to specific soil characteristics influencing the availability of these nutrients. If soils are already depleted upon planting, larger initial fertilizer rates may be required. The rates may be reduced once a nutrient reserve has been built up (Jadin and Snoeck, 1985; Wessel, 1971), which will be especially the case for phosphorus. Appiah et al. (2000) found no significant relationships between the age of cocoa trees and fertilizer response on farms in Ghana. Farm ages ranged from 9 to 27 years.

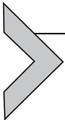
In mature plantations in West Africa, N is normally applied in split doses: once at the start of the main rains in April/May and once around September. Other fertilizers are usually applied at once in April/May (Ahenkorah et al., 1987; Appiah et al., 2000; Wessel, 1971). Nutrient demands of the cocoa trees will fluctuate throughout the year. For instance, according to Santana and Cabala-Rosand (1982), N demand is greater during leaf fall and shoot production. In April/May, young fruits are setting, while in September, the developing pods have their greatest demand for nutrients (Wessel, 1971). Jadin and Snoeck (1985) suggest that further splits would lead to better uptake. For instance, Mg is best applied in November, at the end of the second rainy season in West Africa. However, they acknowledge that many different times of fertilizer application are not economically feasible. They advise three application times during the year. According to them, P should be applied before flowering, half of K and all Ca and Mg during flowering, and the other half of K 2–3 months later (Jadin and Snoeck, 1985).

Little is known about the differences in fertilizer requirements among cocoa varieties. Wessel (1971) found Amazon to be more K demanding than Amelonado. Other differences in fertilizer demand most likely arise from the fact that Amazon hybrids under good circumstances give greater yields,

which increases nutrient demand. Furthermore, Amazon hybrids show less seasonality in the annual production cycle, reducing fluctuations in nutrient demand throughout the year. However, fertilizer application is largely determined by seasonality of climate, especially of rainfall patterns. If this is the case in a region, the recommended timing to add fertilizer will be the same for all varieties.

6.3 Applicability of Recommendations

Of numerous fertilizer regimes recommended by various authors, countries, and organizations, it is unclear what scientific research has been conducted to arrive at them. In some cases, there is differentiation among regions or soils. Most often, recommendations are generalized for a whole country, despite the diversity of conditions under which cocoa is produced. In Table 12, some of this diversity is exemplified with information on cocoa production systems in West Africa. It is clear from this review that the response of cocoa to nutrient application will vary with conditions such as initial soil fertility, climate, and management. The ideal fertilizer recommendation should take all these conditions into account per cocoa field. This degree of specificity is practically infeasible, but recommendations per country are clearly too broad.



7. METHODS USED TO ESTABLISH FERTILIZER RECOMMENDATIONS FOR COCOA

Various methods are used to establish fertilizer recommendations in agricultural production. In general, these can be divided into five different groups:

1. Visual deficiency symptoms
2. Nutrient balance
3. Soil chemical analysis
4. Plant (leaf) chemical analysis
5. Fertilizer response trials

Below, these methods and their application to establish fertilizer recommendations in cocoa are discussed.

7.1 Visual Deficiency Symptoms

The majority of nutrient deficiencies is characterized by changes in the appearance of the plant. Most common is discoloration of the leaves. Other deficiency symptoms can include malformation of the leaves and growth

Table 12 Type of Cocoa Production, Land Use Prior to Establishment, Type of Establishment, Quality of Planting Material and Planting Technique in the Cocoa Sectors of Côte d'Ivoire, Ghana, Nigeria, and Cameroon in 2001

	Proportion of Farms			
	Cameroon	**Côte d'Ivoire**	**Ghana**	**Nigeria**
Type of production system				
Full sun	8%	28%	28%	3%
Shaded	92%	72%	72%	97%
Land cover/use prior to cocoa establishment				
Forest	78%	72%	30%	56%
Fallow	21%	27%	68%	44%
Savannah	1%	1%	3%	0%
Cocoa establishment field type				
Understory planting into thinned forest	59%	21%	20%	65%
Slash and burn field establishment	41%	79%	81%	35%
Cocoa planting material				
Improved	18%	14%	42%	9%
Unimproved from own tree stock	88%	91%	73%	93%
Planting technique				
Seeded directly into field	50%	58%	91%	46%
Transplant polybag seedling	55%	59%	14%	12%
Transplant bareroot seedling	39%	16%	9%	73%

Note: There are some contradictions with findings of other authors. These are possibly caused by different cut-off values of the dummy variables (e.g., shaded is anything above 13 shade trees/ha), or changes in the production systems over time.
Based on data from the 2001/2002 IITA STCP producer survey in Gockowski and Sonwa (2011).

retardation. For many crops, including cocoa (Loué, 1961), color pictures are available to illustrate the deficiency symptoms of different nutrients. These pictures are usually based on controlled nutrient studies in which all but one nutrient are in adequate supply. The pictures can be used to recognize the deficiencies in the field. However, symptoms only occur when the nutrient deficiency is acute. In the field, multiple deficiencies are often present, which means the plant shows multiple symptoms which are difficult

to attribute to specific nutrient deficiencies. Moreover, most deficiency symptoms are easily confused with symptoms of extreme temperatures, diseases, spray damage, etc. (Wichmann, 1992).

7.2 Nutrient Balance

The use of nutrient balance analysis in establishing fertilizer recommendations is based on the principle of replacement: the nutrients added in fertilizers should replace the nutrients leaving the system. Nutrient balances may take into account all nutrient flows into and out of the system. Usually only the nutrients removed in the harvested crop are taken into account. In the case of perennials, sometimes nutrients immobilized in the tree for growth are also considered as offtake (see e.g., Goh, 2005). To calculate fertilizer requirements using this method, only information about yields is required. Due to its simplicity, this is an attractive approach. Fertilizer recommendations for cocoa of some authors are largely based on the nutrient balance method, as their recommendations depend solely on the harvest obtained (e.g., Hardy in De Geus, 1973; von Uexküll and Cohen, 1980). Yet the method has several shortcomings:

1. The nutrient composition of the harvested crop varies depending on climate, soil, management conditions, and variety. Thus the nutrient composition must be established at least for each major production situation. This could explain part of the variation in the estimates of annual nutrient offtake as seen in Table 2.
2. Nutrient losses such as leaching, as well as nutrient inputs through nitrogen fixation or atmospheric deposition, may be considerable. Partial balances based only on fertilizer inputs and crop removal may be misleading.
3. The main concern is that the nutrient removal has little relation with the crops' nutritional requirements to obtain satisfactory yields (De Geus, 1973). Current nutrient availability is not taken into account. A negative nutrient balance implies that soil stocks of a certain element are decreasing, which is unsustainable in the long run. However, if soil reserves are large, this does not necessarily constitute a constraint for production (Vanlauwe and Giller, 2006). Applying fertilizers will not influence yields. On the other hand, if soil reserves are small and the soil has a high fixing capacity for the nutrient, and/or the nutrient is limited in mobility, the amounts of fertilizer applied based on this method will be too small (De Geus, 1973).

7.3 Soil Chemical Analysis

The assumption underlying the use of soil chemical analysis to establish fertilizer recommendations is that a crop needs a certain amount of available nutrients in the soil for it to produce an optimal yield. In case the soil does not contain enough nutrients, fertilizers are applied. Sampling, analysis, and interpretation of soil tests require expert knowledge. Substantial research is required to select appropriate extractants for varying conditions, to correlate nutrient levels according to the extractant to crop response, and to calibrate how much fertilizer is required to obtain satisfactory yields given a certain soil test result. Sometimes greenhouse studies can be useful in identifying which secondary and micronutrients are lacking in a given soil (e.g., using the double pot method, Janssen, 1974). However, results from greenhouse trials cannot be extrapolated to estimate rates of nutrients required in the field due to the restricted volume of soil explored by plant roots in pots. Thus dose–response experiments in the field on different soil types over multiple years are required to establish critical concentrations for different soil tests. This research is demanding in time and space. Without it, it is impossible to use soil analyses to establish fertilizer recommendations. For more details about the research required, see for instance Van der Paauw (1956), Smilde (1985), and Bruulsema (2004). No record has been found indicating that such extensive experiments have been carried out for cocoa. Still, several authors refer to critical soil nutrient concentrations for cocoa production. These critical soil nutrient concentrations are based on a limited number of old publications. Numerous authors refer to the limits of adequacy as presented by Wessel (1971) who in turn refers to publications from 1939 to 1966 (Table 13). Only one publication was found in which soil nutrient criteria from another source are mentioned (Aikpokpodion, 2010, Table 13). It is unclear what research has been conducted to establish these critical soil nutrient concentrations, and under what conditions. Even if research at that time was extensive, these critical soil nutrient concentrations need to be reexamined. Soil testing methods, cocoa varieties used, cocoa production management, and soil and climatic conditions all may have changed. Criteria of suitability may be applicable in one country but not in another (Wood, 1985a). Different chemical soil characteristics interact with each other. They also interact with other soil characteristics and with factors such as shade management and climatic factors. This makes it difficult to set general standards. Ling (1990) mentions that there is a lack of data from fertilizer trials, and that there is a "need to carry out more

Table 13 Lower Limits of Adequacy of Soil Characteristics

			Available P (mg/kg)		Exchangeable Bases (cmol/kg)				
pH	**C (g/kg)**	**% Total N**	**Sandy Soil**	**Clayey Soil**	**K**	**Ca**	**Mg**	**Soil Depth**	**Source**
5.5	17.5	0.150	12[a]	24[a]	0.20	8.0	2.0	0–15 cm	Several references cited by Wessel (1971)
		0.09	10[b]		0.03		0.8	0–30 cm	Egbe et al. (1989, unpublished but cited by Aikpokpodion, 2010)

[a]Truog.
[b]Bray and Kurtz. No distinction between sandy and clayey soils.

complete long-term fertilizer experiments to define more precisely the nutritional needs of older cocoa under various environmental conditions." Little has changed since.

N is taken up by plants largely in mineral form, which is only a fraction of the total N content of the soil. Both mineral N and total N content in the soil at any point in time may have little relation with subsequent N availability to the plant. Indices of mineralization have been sought, but finding a useful measure of N availability using soil analysis remains problematic (Geypens and Vandendriessche, 1996; Smethurst, 2000). For lack of a better method, total N is nevertheless used by many authors to estimate additional N requirements. Much of the total P present in the soil is unavailable for plant growth, particularly in strongly acid or strongly alkaline soils, so available P is a more useful indicator of P deficiency. The availability of phosphorus is determined using a range of extractants. In soil analysis, potassium is determined as exchangeable K, commonly using ammonium acetate or ammonium chloride as extractants.

Often, soil test results are interpreted independently for each nutrient. However, nutrients have interactive effects on crop growth (Anderson and Nelson, 1975; Fitts and Nelson, 1956) and the expected response to a specific nutrient will only occur if there is no limitation of other nutrients (Janssen, 1998; Johnston, 2005). Janssen et al. (1990) developed the Quantitative Evaluation of the Fertility of Tropical Soils (QUEFTS) system. In

QUEFTS, the availabilities of N, P, and K are taken into account simultaneously. The potential supply of the soil of each nutrient N, P, and K to the crop is calculated based on the results of soil analysis. Actual uptake of each nutrient is calculated taking into account the supply of each of the other nutrients. From the actual uptake of nutrients, achievable yield is estimated. The calculations give an indication of which nutrients are currently deficient in the soil, relative to the other nutrients. QUEFTS has to be calibrated to a particular crop using soil analysis and yield response of fertilizer trials. The system has been calibrated to different crops and climates (Sattari et al., 2014), including plantation crops such as banana (Nyombi et al., 2010) and coffee (Maro et al., 2014). It has yet to be calibrated for cocoa.

Once nutrient limitations have been established based on the results of soil analysis, there are different philosophies on how to translate this into a fertilizer recommendation. A main difference is whether fertilizers should only be added when the current nutrient availability is insufficient to meet crop requirements, or whether additional fertilizer should be added to replace nutrients projected to be removed by the crop. According to some, the additional fertilizer added in the latter approach will lead to excessive nutrient build-up, is economically unfavorable as the additional nutrients do not increase yields, and lead to environmental risks (Hochmuth et al., 2014; Olson et al., 1982). Others, however, maintain that it is beneficial to invest in nutrient stocks, especially of P, due to residual effects in subsequent years (Godden and Helyar, 1980; Janssen, 1998; Smilde, 1985). Which approach is most sensible no doubt depends on which nutrient is considered. While is would be foolish to apply more N than the crop needs due to the likelihood this will be lost (Giller et al., 2002), building up soil reserves of P may be sensible on some soils that are not strongly P fixing (Janssen et al., 1987; Wolf et al., 1987).

Jadin (Jadin, 1972, 1975; Jadin and Snoeck, 1985) developed a Soil Diagnostic Method for calculating cocoa fertilizer requirements based on soil testing. According to this method, first, fertilizers should be applied until optimum nutrient ratios for cocoa production are reached. Then, these ratios should be maintained by replacing the nutrients taken off through harvesting cocoa. It is assumed that optimal soil TEB is $8.9 \times N - 6.15$. TEB refers to total exchangeable bases, which is the total of the cations Ca, Mg, and K in exchangeable form, expressed in cmol/kg. N is expressed in ‰ total N. Jadin and Snoeck (1985) indicate that total N concentrations are "low" when they are 1.0–2.0‰. Still, they only recommend N application when TEB exceeds $8.9 \times N - 6.15$. P is applied if the N/P

ratio is above 2, with N expressed in ‰ total N and P expressed in ‰ total P_2O_5. If available P is below 130 mg/kg (according to the Olsen–Dabin analysis), P is also recommended to be applied. Note that in the N/P ratio, P is expressed as "‰ total P_2O_5," while the absolute value is expressed as mg/kg available P. 130 mg/kg available P is a very large concentration, as critical values of Olsen P are normally given as 15 mg/kg. The optimal ratio between K–Ca–Mg is considered to be 8%, 68%, and 24%. It is calculated what fertilizers should be applied so that the soil will approach this balance. If after this correction, the base saturation (% exchangeable bases of total exchange capacity) is still below 60%, more fertilizer should be added, but the optimum ratio should be maintained. Although part of the calculations is implemented in Excel, using this program requires substantial agronomic knowledge. For instance, fertilizer utilization coefficients need to be estimated and the calculated fertilizer doses may have to be split into applications in multiple years. The optimal ratios were established using pot experiments and field trials. Based on publications found about this method, it seems that the number of trials used to establish the method is limited. It is not clear how the figures presented in the papers support the proposed optimum ratios. The full datasets from the trials are not available in any of the publications cited. Trials have been carried out to verify the suitability of the Soil Diagnostic Method. In these trials, yields of plots in which fertilizers were applied according to the Soil Diagnostic Method were compared to yields of plots without fertilizer application. Although these fertilizer regimes led to significant yield increases, they were not compared with other fertilizer regimes in the same locations. Hence, it cannot be established whether the fertilizer regimes used were indeed optimal. The research on which the method is based was conducted in Côte d'Ivoire. The method has been applied without amendment in Ghana (Snoeck et al., 2010) and Togo (Jadin and Vaast, 1990). Moreover, there is little theoretical support for the supposed optimal ratios. Soil total P and soil total N are poor predictors of the amounts of P and N available to the plant. Too large a quantity of either of the cations K, Ca, and Mg can suppress uptake of another cation. However, there is little reason to assume that there should be such a strict optimal ratio among them.

7.4 Plant (Leaf) Chemical Analysis

Plant chemical analysis may be another helpful tool in establishing fertilizer requirements. Usually leaves are used in the analysis, although other tissues

may also be used (e.g., the rachis in oil palm, Foster and Prabowo, 2002). Plant analysis gives a direct indication of the nutritional status of the plant and may show a strong correlation with yields (Ahn, 1993; Foster and Prabowo, 2002). The plant's nutritional status is the net effect of variables related to soil, plant, climate, and management (Ahn, 1993). It may have a cause which remains undetected with soil analysis. In perennials, nutrient deficiencies can be detected through plant analysis and corrected before they have an effect on production (Ahn, 1993; Smilde, 1985). As with soil testing, extensive research is needed to go from the results of leaf analysis to fertilizer recommendations. "All fertilizer recommendations must eventually be correlated with yield data from fertilizer trials which are adequately replicated in time and space" (De Geus, 1973) and have to be specific to the conditions under which the crop is grown. Critical values for leaf nutrient analysis are referred to for cocoa (Table 14). These values are nearly always based on the research of Loué and Murray (publications 1961–66). Loué (1961) reports values based on a combination of pot experiments and field leaf sampling. He stresses the difficulties of applying the results of pot experiments to field conditions, the variation in leaf nutrient concentrations depending on age, position, and light conditions of the leaves, and the requirement for more research to derive critical nutrient ranges in relation to yields under field conditions. It is not clear what research Murray (1966, in De Geus, 1973) based his critical values on, nor what sampling procedure was used. Yet these values are frequently referred to without reservation.

Variations in cocoa leaf nutrient content do not necessarily indicate variations in the nutritional status of the cocoa tree. A main problem with using cocoa leaf analysis is that cocoa leaf nutrient content depends on many factors. These include leaf age, the development of new leaves, fruit bearing, light intensity, and seasonal effects. Wessel (1971) has investigated the effects of several of these factors extensively. He found that the leaf N percentage based on dry weight decreased during the first few weeks after which it gradually increases to reach a peak after 8 or 9 weeks, to then decline again. Percentage P decreases while percentage Ca increases with increasing leaf age. Mg percentage first decreases and later increases. The absolute content of N, P, and K increases in the first weeks of leaf growth after which there is a progressive decrease. When expressed as a percentage of fresh weight, N and Ca increase with age while P and K are more or less constant. The changes may be influenced by the development of new leaves and fruit bearing. The decrease in nutrients after the first 9–10 weeks may be caused by the transfer to the leaves of new flushes which start to develop around that

Table 14 Normal, Low, and Deficient Concentrations (% dm) of Nutrients in Cocoa Leaves According to Different Authors

Source	N			P			K			Remarks
	Normal	Low	Deficient	Normal	Low	Deficient	Normal	Low	Deficient	
Loué (1961, 1962, in De Geus, 1973)	2.35–2.50	1.80–2.00	<1.80	>0.18	0.10–0.13	0.08–0.10	>1.2	1.00–1.20	<1.00	
Murray (1966, in De Geus, 1973)	>2.00	1.80–2.00	<1.80	>0.20	0.13–0.20	<0.13	>2.00	1.20–2.00	<1.20	
Wessel (1971)			<1.8	>0.20	0.16–0.20	<0.16				Young leaves[a] sampled in April/May
Idem			<1.6	>0.13	0.11–0.13	<0.11				Old leaves[b] sampled in April/May
Egbe et al. (1989, unpublished but cited by Aikpokpodion, 2010)			<0.9			<0.2			<2.0	

[a]Second and third fully green leaves of the last flush below the apex of fan branches.
[b]Leaves directly adjacent to the young leaves.
NB: Wessel (1971) notes that N:P ratios can also indicate N and/or P deficiencies. An N:P ratio below 9 indicates severe N deficiency, N:P ratio from 9 to 10 indicates moderate N deficiency, and an N:P ratio of 10–11 indicates no N deficiency. On non-N-deficient soils, an N:P ratio above 11 indicates P deficiency in young leaves. In older leaves, the N:P ratio should be above 14.

time. Nutrient uptake of the leaves may also be reduced at this time. Many young pods wilt at the time of or immediately following leaf flushing. Leaf nutrient content decreases during the cropping season reaching a minimum during the peak of crop production. Both suggest competition for nutrients between young fruits and leaves. Light intensity also influences the nutrient content of leaves. Light intensity is determined by radiation of the sun but also by the presence of shade trees, the tree density, and the position of the leaf in the canopy. Leaf N and K have been found to decrease with increasing light intensity (as also found by Murray, 1975), while leaf P and Mg were little affected, and leaf Ca was raised. Dry matter content also increases with increasing light intensity. It seems that unshaded leaves are physiologically older than shaded leaves of the same age. In Ghana and Nigeria, leaf N, P, and K concentrations were largest from November/December to May/June, and least from July to October. Ca concentrations varied inversely. Mg either varied little (found in Ghana) or followed the Ca trend (found in Nigeria). The trends may be related to flushing and pod production dynamics, in interaction with various climatic factors. According to Wessel (1971), the best times of sampling in Nigeria are from mid-April to mid-May. Slightly less appropriate is sampling from mid-December to mid-January.

To derive leaf nutrient norms and apply them, leaf nutrient content has to be related to cocoa production rather than to the various factors mentioned earlier. Therefore, uniform sampling of leaves is crucial both for derivation and application of norms. Yet, in the case of cocoa leaves, this is very difficult. For instance, according to Wessel (1971), the age of cocoa leaves cannot be determined from its position on the twigs or branches. Although the percentage of dry matter is highly related to leaf age, it is also influenced by shading and hence cannot be used easily to determine age of leaves. Leaf color is also unsuitable. The petiole color may be the most useful for age determination. Another complication is that the availability and uptake of one nutrient may affect the uptake of other nutrients. For instance, Wessel (1971) found that increases in soil N depress leaf K concentration, increases in soil P and K depress leaf N concentration (but only at high light intensities) and increases in soil N and K depress leaf P. Wessel (1971) concludes that leaf analysis is mainly useful for detecting and identifying pronounced nutrient deficiencies. It will be difficult to use leaf analysis to establish a quantitative fertilizer recommendation, especially in small farms where trees are highly variable. Based on his research in Nigeria, he does give an indication of the nutrient values at which nutrient deficiencies

can be expected at certain leaf ages and time of sampling (Table 14). A range of optimum concentrations has to be established for different leaf ages and shade intensities. Acquaye (1964) acknowledges that the variability in nutrient concentrations of leaves arises from many other factors besides the availability of nutrients in the soil (similar to those pointed out by Wessel, 1971). However, he concludes that this "does not in any way invalidate the usefulness of foliar analysis in cocoa nutrition studies. It rather points to the factors which should be taken into consideration in taking samples for analysis and in interpreting results." Unfortunately, his experiment did not include soil and yield analyses. No critical concentrations were derived or applied. Hence, the results cannot be used to detect nutrient deficiencies. Although it is mentioned that "attempts will be made later to relate foliar analyses to cocoa yields in a survey which is being carried out," we could not find a publication showing results of any such survey. De Geus (1973) also acknowledges and accepts the various limitations of techniques for leaf analysis and the interpretation of its results as put forward by Wessel (1971). He too remarks that only if a marked deficiency exists, the small concentration in the leaf will override problems of sampling. In that case, leaf analysis can be used to indicate the type of fertilizer required to correct the deficiency. Apart from the limits of adequacy found by Wessel (1971), De Geus (1973) in his book presents critical levels established by Murray (1966) and Loué (1961) (Table 14). Wessel (1985) refers to the same values. Both De Geus (1973) and Wessel (1985) note that the concentrations set by Loué are probably for somewhat older leaves than those of Murray. von Uexküll and Cohen (1980) also refer to the difficulty of obtaining representative and reproducible leaf samples. Moreover, they mention the problems with varying "critical" values depending on nutrient capacity/intensity factors, soil moisture, evapotranspiration, the amount of climatic and artificial shade, etc. They argue that when conditions in the rhizosphere are favorable, cocoa will tolerate lower leaf nutrient content. The general guidelines for leaf nutrient content they propose are the same as those of Murray (1966) (Table 14). Verlière (1981) conducted extensive research on different soils in Côte d'Ivoire and determined the relation between the results of leaf nutrient concentrations and yields. The nutrient content and ratios which correlated with large cocoa yields varied between soils. Even for the same soil, the ranges corresponding to good yields were wide while the difference between the ranges corresponding with large yields and those corresponding with small yields were sometimes marginal. Therefore, we present no quantification of his findings here. However, for different soils, the comparison of

the results of leaf nutrient analysis between the good yielding and the poorly yielding plots gave an indication of the most important nutritional limitations.

Nelson et al. (2011) base their conclusions regarding the nutritional status of cocoa in Papua New Guinea on comparison of leaf nutrient content of their samples with critical values, in combination with similar comparisons for soil samples. They refer to Wessel (1985) as their source of critical nutrient values. Those for leaves are most likely the values of Table 14. It is not clear which critical values are used for soil nutrients. Aikpokpodion (2010) also uses both soil and leaf samples to analyze nutrient dynamics in cocoa soils for his study in Nigeria. Critical values are based on Egbe et al. (1989, unpublished but cited by Aikpokpodion, 2010) (Tables 13 and 14). The critical values used for soil nutrients, especially of the bases, seem extremely low. Nelson et al. (2011) found a reasonable relationship between soil and leaf nutrient concentrations for P and K. For other nutrients, no relationship was found between soil and leaf nutrient concentrations. The K concentrations in leaves were often not below the critical concentrations while those of the soils for the same site were. A possible explanation for the discrepancy between foliar and soil K given by the authors is that widespread N deficiency may have been more limiting. As a result, the expression of K deficiency in the leaves may have been masked. However, Pushparajah (1994) argues the opposite: that uptake of K in crops can be reduced by lack of N. Aikpokpodion (2010) has found K concentrations in leaves nearly always being below the critical value, while soil K concentrations were well above the critical concentration. Since the critical concentration for soil K is set very low while that of leaf K is rather high, this is not surprising (Table 14). Aikpokpodion (2010) did not find any N deficiencies in either leaf or soil. For all nutrients under study besides K, the results when comparing both leaf and soil concentrations with critical values were comparable.

Few authors have used the combination of results of soil and leaf analysis to establish fertilizer recommendations. Wessel (1971) set preliminary fertilizer recommendations based on his research in Nigeria as presented in Table 15. Pushparajah (1994) refers to Ling (1989) for ranges of N, P, and K in cocoa leaves and soil and guides to fertilizer rates (Table 16).

To summarize, the usefulness of leaf analysis in the establishment of cocoa fertilizer recommendations remains debated. Some authors use the method, sometimes in combination with soil analysis. However, the critical nutrient ranges referred to do not seem to be based on the extensive research

Table 15 Preliminary Fertilizer Recommendations for Mature Amelonado Cocoa on Soils Derived From Metamorphic Igneous Rock as Described in Wessel (1971)

Nutritional Status	Nutrient Content		Fertilizer Rate	
	Soil	Leaf[a]		
Severely N deficient	–	%N < 1.80 or 1.80 < %N < 2.00 and N/P < 9	135 kg N/ha	
Moderately N deficient	–	1.80 < %N < 2.00 and N/P > 9	67–101 kg N/ha	
Not N deficient	–	%N > 2.00	No N fertilizer	
P deficient	Available P < 10 mg/kg	%P (dm) < 20	50–67 kg P_2O_5/ha	=22–29 kg P/ha
Not P deficient	Available P > 12 mg/kg	%P (dm) > 20	No P fertilizer	

[a]5–10-Weeks old leaves sampled in April/May. Percentages based on dry matter.

Table 16 Range of Values of N, P, and K in Cocoa Leaves and Soil, and Guide to Nutrient Application Rates as Described by Ling (1989) in Pushparajah (1994)

Nutrient	Nutrient Content		Nutrient Application Rate (kg/ha)
	Soil[a]	Leaf (% dm)	
N	–	<2.0	100–150
	–	2.0–2.6	60–80
	–	>2.6	0
P	<15 mg/kg	<0.2	40–70
	<15 mg/kg	>0.2	15–30
	>15 mg/kg		0
K	<0.3 cmol/kg	<2.0	100–150
	<0.3 cmol/kg	>2.0	70–80
	>0.3 cmol/kg		0

[a]P = Bray 2 extr. P; K = exch. K.

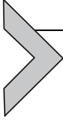
required to establish such ranges. Many authors conclude that factors such as leaf age and light override the nutritional effects on leaf composition except when deficiencies are severe. As long as there is no agreement on a standard sampling procedure, results across studies cannot be compared.

Nutrient interactions play a role in the difficulties encountered in interpreting the results of cocoa leaf analysis. Instead of applying critical ranges per nutrient, it is possible to derive norms based on ratios between nutrients. The norms are based on the leaf nutrient ratios of a high-yielding subgroup of a large population. Comparison of the found nutrient ratios to the norms indicates the deficiency of each nutrient relative to the other nutrients. In the Diagnosis and Recommendation Integrated System (DRIS) method, first developed by Beaufils, dual ratios are used (Walworth and Sumner, 1987). The Compositional Nutrient Diagnosis (CND) method developed by Parent and Dafir uses multielemental ratios (Parent and Dafir, 1992). Application of both DRIS and of CND in cocoa production are currently being researched (personal communication Didier Snoeck, February 2015; and Laurence Jassogne, March 2015), but their relevance has yet to be confirmed.

7.5 Fertilizer Response Trials

The most direct way to establish fertilizer recommendations is to test different rates and compositions of fertilizer on the crop and determine the optimum fertilizer application (which is expected to result in the highest yield or the largest economic benefit). In order to determine the optimum fertilizer rates, response curves are fitted. The choice of model (e.g., quadratic, square root, linear plateau) will affect the resulting optimum, and the choice will depend on the type of response to application of the nutrient and the objectives and resources of the research (Anderson and Nelson, 1975; Neeteson and Wadman, 1987). This approach is required to arrive at reliable fertilizer recommendations. Results of fertilizer trials and subsequent fertilizer recommendations are only valid for the conditions under which the trial has been executed. Trials need to be executed over multiple years to account for residual effects and soil fertility changes and conducting the trials requires heavy investments. Therefore, the number of sites where trials are executed will usually be limited compared with the need to serve different agroecologies (Ahn, 1993). But when combined with soil or plant testing the results of the trials can be extrapolated more widely, for instance using QUEFTS (see Section 7.3). Fertilizer trials are required in any case to

calibrate the soil and leaf testing methods. To the best of our knowledge, there are few fertilizer response trials with cocoa, and soil and leaf testing methods have not been calibrated to the extent that results can be widely extrapolated.



8. KNOWLEDGE GAPS AND RECOMMENDED RESEARCH

8.1 Current Understanding and Knowledge Gaps

As we have learned from the detailed review of the literature presented above, cocoa currently yields much less than its potential in almost all regions. Poor mineral nutrition is a key limiting factor as can be seen from the large responses to fertilizer seen in many trials. However, there are large differences in yields and fertilizer response among different trials, regions, plots, and even individual trees. The effects of the application of fertilizer on yield depends on the cocoa tree requirements and current nutrient availability from the soil, but also on other soil characteristics, climatic conditions, presence of pests and diseases, and, of great importance in cocoa production systems, the management of shade trees, and the pruning of the cocoa canopy. Most cocoa researchers agree that the largest cocoa yields can be obtained in systems with little shade and high rates of fertilizers under good management (e.g., phytosanitary spraying), but evidence suggests that these yields show a sharp decline after about 10 years of full production. Under shade, fertilizer response is less, but the yield decline is also less severe. However, the causal relations between the factors mentioned earlier and yields and fertilizer response, and the fertilizer response to different nutrient applications are poorly understood.

Various lines of research related to cocoa nutrition have contributed to current understanding, including the establishment of nutrient balances in different cocoa production systems, pot experiments, and short- and long-term fertilizer field trials on experimental plots or existing farms. Much of the primary research related to nutrition in cocoa production was conducted over 40 years ago. In many trials, only the yields of cocoa under different fertilizer and/or shade regimes were compared and the number of treatments was limited. Few experimental reports provide full details of how the trees were managed, or measurements of variables such as the amount of radiation reaching the cocoa trees, cocoa canopy cover, LAI, and plant nutrient concentrations—variables which could be used to explain variability in yield responses. Further, interactions among the various essential nutrients are often overlooked. Weather information (daily mean, minimum and

maximum temperatures, and rainfall), soil description, and chemical and physical analysis are lacking from many experimental reports. Moreover, the long-term effects of fertilizer application, shading, and other management practices are largely unknown. Even the long-term experiments reviewed in this report were not continued sufficiently long to evaluate cumulative yield differences of treatments over the total life span of cocoa. The conclusions drawn from many of the old, primary studies may only be valid under the circumstances under which the research has been conducted. Nevertheless, these conclusions continue to be reused and extrapolated to the present day, for instance for the establishment of fertilizer recommendations.

Current fertilizer recommendations may also be based on research which has been reported only in annual reports without detailed analysis and review. The quality of such research cannot be evaluated, nor is it possible to evaluate under what conditions these recommendations may be valid.

Currently, the knowledge of the mineral nutrition of cocoa is insufficient to understand the variability in yield response to fertilizer application. It is unknown under which conditions particular nutrients should be applied and at which rates. Some factors are known to influence the yield response, including shading, soil conditions, and climatic factors. However, these influences have not been quantified. Especially, their interactions with nutrition and with each other remain a black box. Some examples of questions which need to be addressed are:

- What are the interactions in nutrient uptake and requirements (micro- and macronutrients) throughout the cocoa life cycle?
- How do (micro)climatic conditions such as humidity, soil moisture, and temperature affect nutrient availability and uptake and cocoa productivity over time, and how does shade affect these conditions?
- How does shade management (including pruning) affect effective radiation interception through effects on leaf physiology and arrangement of leaves in the canopy?
- Is there an interaction between cocoa nutrition and prevalence of different pests and diseases?
- What determines the partitioning of carbohydrates and nutrients within the cocoa tree, and how could pruning and other management practices affect this partitioning?
- How do the results of soil analysis relate to fertilizer response?
- How does leaf nutrient content relate to fertilizer response?

In order to truly understand the nutritional requirements of cocoa, answers need to be found to these questions. Nutrient management recommendations to farmers need to be tailored to the conditions under which they work. As long as fundamental knowledge is lacking, current farm level recommendations have a very weak scientific basis.

8.2 Research Requirements

Different types of research are recommended to complement the knowledge currently available.

8.2.1 Further Analysis of Existing (Data From) Trials

In this review, the results of research on nutrition in cocoa production as they have been published in scientific literature have been compiled. Many more trials have been performed on both experimental research stations and in farmer fields. Results of these trials have never been published except in annual reports of companies and research institutes. Of most trials, little data are shared. Sharing of results and data of trials would allow researchers to analyze existing data rather than having to set up their own resource consuming trials. The information that can be obtained from analysis of combined datasets could be a great step forward to disentangle the complex questions involved in understanding nutritional aspects of cocoa production. Similarly, more use can be made of trials which are currently in place through more detailed measurements.

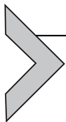
8.2.2 On-Farm Trials

There is a huge diversity among cocoa production systems, with varying management practices, climatic conditions, and soils and diverse resource status of cocoa producers. This diversity explains the wide variation in cocoa yields and fertilizer response. Variables such as amount of radiation reaching the cocoa trees, cocoa canopy cover, LAI, plant nutrient concentrations, temperatures, rainfall and soil description, and chemical and physical analyses can be used as explanatory factors in analysis of yields and fertilizer response. A greater intensity of data collection of more variables throughout trials is required to enhance the interpretation of trial results and increase our understanding of the response of cocoa to changes in management. Using existing farms to take these measurements will capture the wide diversity which exists and allows for simple trials to assess the impact of different management practices and fertilizer applications under different conditions. This will be of great use in tailoring recommendations to site-specific conditions.

When conducting on-farm trials to examine fertilizer response, basic sanitation and pruning measures must first be addressed to minimize pest and disease problems and ensure that the crop response to fertilizer will be optimal. On-farm research will also allow for a better understanding of the variety of socioeconomic conditions under which farmers operate. Final recommendations will have to be based not only on biophysical conditions, but also on socioeconomic conditions to increase adoption.

8.2.3 Multifactorial Shade–Fertilizer Response Trials

In the longer term, multifactorial experiments are essential to address some of the fundamental knowledge gaps. Factors to take into consideration include at least different rates of the major nutrients N, P, and K, and ideally also different shade levels. Trials should be conducted on the most important soil types for cocoa production for at least 5 years of production. The role of secondary nutrients (S, Ca, and Mg) and micronutrients (notably B and Zn) must also be considered. Such trials would enable the collection of robust data on cocoa yield response to fertilizers in relation to soil type, climatic conditions, degree of shading, etc. They would also allow norms for critical soil and leaf concentrations of different nutrients to be established and calibrated with cocoa yield responses. This knowledge would allow robust fertilizer recommendations to be developed and tailored to different soil conditions and production targets. As this type of trial requires commitment of land over a number of years it would be difficult to conduct on smallholder farms.



9. CONCLUSIONS

Despite the importance of cocoa as a global commodity and as a major source of income to support the livelihoods of millions of smallholder farmers, our current knowledge of the mineral nutritional needs of the cocoa crop is sadly lacking. A major investment has been made on unraveling the cocoa genome (CGD, 2016), in breeding new cocoa varieties and in new high-intensity production systems. Yet there has been a dearth of investment in research on the mineral nutrition of cocoa and on the needs for additional nutrients across the different agroecologies where cocoa is grown. Unless the current knowledge gaps are addressed, the potential genetic gains of new cocoa varieties cannot be realized. We hope that this review will assist in drawing attention to these knowledge gaps and help to mobilize the funding and science needed to meet the future global demand for cocoa.

ACKNOWLEDGMENTS

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