Mineral Nutrition of Cocoa

A Review

Jiska A. van Vliet, Maja Slingerland and Ken E. Giller
Plant Production Systems Group, Wageningen University

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Authors of this report and contact details

Name: Jiska A. van Vliet
E-mail: jiska.vanvliet@wur.nl

Name: Maja Slingerland
E-mail: maja.slingerland@wur.nl

Name: Ken E. Giller
E-mail: ken.giller@wur.nl

Address: Wageningen UR, Plant Production Systems, P.O. Box 430, 6700 AK Wageningen, The Netherlands

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Contents

Preface

This review on the mineral nutrition of cocoa was commissioned by the Scientific Committee of the Cocoa Fertiliser Initiative. In this Initiative, different industrial, governmental and knowledge partners involved in the cocoa sector have joined hands with the aim of *Restoring Soil Fertility in West Africa, for a Rejuvenated and Economically Viable Cocoa Sector*. It is recognised that current yields in West Africa are significantly constrained by nutritional problems. However, discrepancies remain in the current recommendations to improve nutrition in cocoa production, and their scientific basis is often unclear. In order to support the Cocoa Fertiliser Initiative in their action plans and the establishment of their research agenda, this review addresses the following questions:

- What knowledge is currently available about mineral nutrition of cocoa?
- What are the current knowledge gaps?
- What are the key areas for further research?

Published literature on the topic has been reviewed, and relevant findings to date are presented. Collaboration with partners involved in the Cocoa Fertiliser Initiative has added to the completeness and quality of the research. In particular we thank François Ruf and Didier Snoeck (CIRAD), Louis Koko (CNRA), Piet van Asten and Laurence Jassogne (IITA), Keith Ingram (Mars, Inc.), Nicholas Cryer (Mondelez International) and Jürgen Küsters (YARA), for sharing references, for interesting discussions on the topic and for their useful comments on earlier drafts of the report. We thank IDH for facilitating and coordinating the writing of the review and the discussions with the partners of the Initiative. Furthermore, we thank Marius Wessel and Bert Janssen for their independent input.

We aimed to synthesise all relevant scientific knowledge which can assist in understanding how the negative effects of poor crop nutrition are manifested in poor yields of cocoa, and how these negative effects can be overcome. The literature consulted describes research carried out on cocoa nutrition in cocoa producing regions across the globe and includes the establishment of nutrient balances in different cocoa production systems, pot experiments, and short and long term fertiliser field trials on experimental plots or existing farms. We present the current knowledge on nutrient cycling in cocoa production systems, nutrient requirements of cocoa, and yield response to fertiliser 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 fertiliser for closing the yield gap under different production conditions.

Executive summary

This literature review on mineral nutrition of cocoa was commissioned by the Scientific Committee of the Cocoa Fertiliser Initiative to address the following questions:

- What knowledge is currently available about mineral nutrition of cocoa?
- What are the current knowledge gaps?
- What are the key areas for further research?

The results of the review were presented for discussion at the Cocoa Soil & Nutrition Knowledge Forum held in Abidjan, Côte d'Ivoire, on April 30, 2015. Furthermore, the review has been shared with the Scientific Committee of the Cocoa Fertiliser Initiative and is used to guide its knowledge agenda.

Poor yields

Current average cocoa yields in West Africa are around 400 kg/ha although yields of 5,000 kg/ha are achievable. Given the expected increase in global cocoa demand, and the diminishing incomes of cocoa farmers, there is an urgent need to increase cocoa yields. Potential cocoa yields are determined by location and crop specific characteristics, such as climate and the crops natural life cycle, under otherwise optimal conditions. However, the availability of water and nutrients may limit production, and yields may be further reduced by weeds, pests and diseases. The gap between the potential yield and actual yield may be decreased by addressing the limiting and reducing factors with yield increasing and yield protecting measures. As soil nutrient content in many cocoa growing regions is poor, an obvious way to increase yields is to address the nutritional needs of cocoa through fertiliser. However, the response of cocoa trees to fertiliser will remain limited unless the crop is well managed and in a healthy condition.

Potentially strong yield response to fertiliser, but differences in response poorly understood

There is a strong cycling of nutrients within cocoa systems and the amounts of nutrients removed through harvest are relatively small. Yet in the long term cocoa production leads to depletion of soil nutrients. Although the soils upon which cocoa in West Africa was established used to be fertile, many of them are no longer able to provide the nutrients required to obtain good yields. Several trials have shown that cocoa productivity can be more than doubled when fertilisers are applied. However, there is large variability in yields and fertiliser response, and in some cases fertilisers show little effect. The effects of fertilisers depend on the cocoa tree requirements and current nutrient availability from the soil, but also on other environmental conditions, presence of pests and diseases, and the management of shade trees and pruning of cocoa. Most cocoa researchers agree that the largest cocoa yields can be obtained in systems with little shade and high rates of fertilisers under good management, but that yields show a sharp decline after 10 years of full production. Under shade, cocoa yields respond less strongly to fertiliser, but the yield decline is also less severe. These conclusions are derived from Figure 1, based on the results of a trial which is often referred to. Unfortunately, the causal relations between the factors mentioned above and yields and fertiliser response, and the requirements of cocoa for different nutrients, are poorly understood.

Narrow research base

Various lines of research related to mineral nutrition of cocoa have contributed to current understanding, including the establishment of nutrient balances in different cocoa production systems, pot experiments, and short and long term fertiliser field trials on experimental plots or existing farms. Much of the primary research was conducted over 40 years ago. Many variables have not been adequately measured and quantified and only few treatments were compared. Research has been conducted under a restricted range of environments and regions and often for only a few years, whereas the life span of the crop can be 40 years or more. Conclusions drawn from these 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 (fertiliser) recommendations.

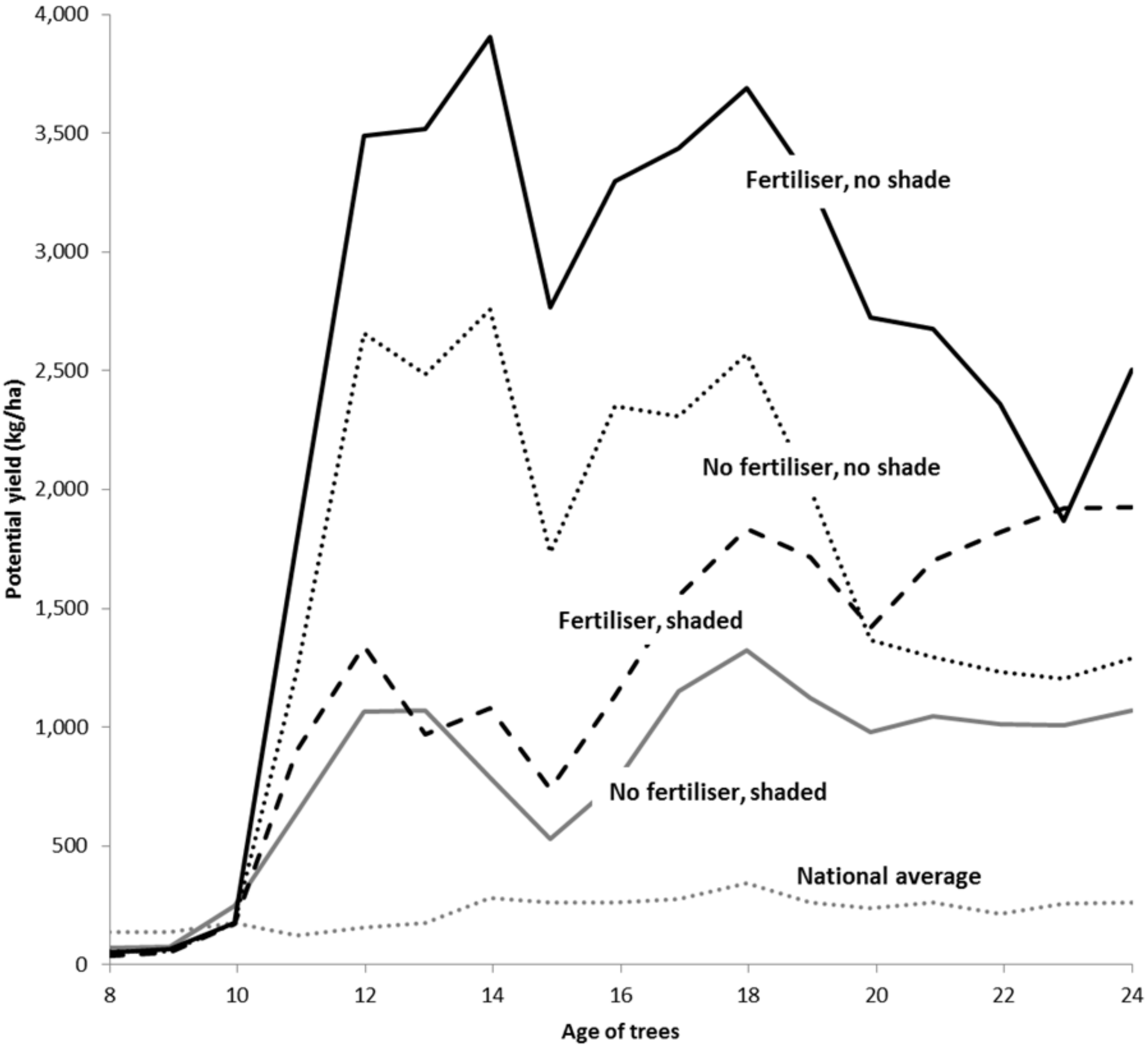


Figure 1. Results of a highly cited shade and fertiliser trial in Ghana, adapted from Ahenkorah, Akrofi and Adri (1974). Treatments started when the trees had reached the age of 10.

Knowledge gaps for the establishment of (fertiliser) recommendations

To date, the knowledge required to come to suitable recommendations under different conditions is limited. Three main themes where knowledge is lacking have been identified.

1 Cocoa tree physiology

A better qualitative and quantitative understanding of cocoa tree physiology is required to understand the mechanisms underlying the constraints to cocoa yield and response of the trees to nutrients. Some examples where further research is required are the uptake and use of nutrients and their interactions, leaf formation and shedding, response to waterlogging and drought stress, cherelle wilt (the discontinuation of development of young cocoa pods), variability in physical traits (including yield) between trees within a single field and production decline and tree mortality.

2 Effects of management practices (especially of shade tree management and pruning) on yields and fertiliser response

Several management practices have an effect on cocoa yield and fertiliser response by influencing nutritional aspects of cocoa production. Highly relevant (and debated) is shade management. Many effects of shade trees are not well understood, including the differences in response to specific nutrients under shade, and the effects on pests and diseases and decomposition. It is not known what degree of shade – and of which trees – is optimal in different climates. The effects of pruning of the cocoa trees on nutrient and biomass allocation and leaf flushing, and the way in which pruning practices interact with shading, are unclear. Similarly, little is known about the interaction of other management practices, such as weeding, the use of organic manure, and the influence of uncontrolled pests and diseases, with cocoa yields and nutrition.

3 Methods available to determine nutrient deficiencies and fertiliser recommendations

Critical values for cocoa leaf and soil nutrient composition to detect nutrient deficiencies are often referred to, but these seem to be based on limited, outdated research. Methods to derive nutrient deficiencies and fertiliser recommendations based on soil and leaf analysis which have been applied to other crops have not been developed for use in cocoa. Given the wide variability in soils and other conditions which affect nutrient requirements across the cocoa production areas, fertiliser recommendations need to be tailored to local conditions. However, as the methods to establish them remain limited, current fertiliser recommendations continue to be highly generalised.

Recommended research

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

On-farm trials

Many variables related to the cocoa tree and its environment can be used as explanatory factors in analysis of yields and fertiliser response. Measurement of these variables can be done on existing farms to capture their wide diversity and allow for simple trials to assess the impact of management practices and fertiliser applications under different conditions. Results can be used to tailor recommendations to site-specific conditions. When conducting on-farm trials to examine fertiliser response, basic sanitation and pruning measures must first be addressed.

Socio-economic analysis

Not only the agro-ecological but also the socio-economic conditions under which the farmers operate are highly diverse. Each farmer has alternative sources of income and options to invest time and money besides cocoa production. It is crucial to understand the trade-offs of (fertiliser) management practices for the farmer and their relative profitability. Key questions are: What increase in cocoa yield is required to justify investment in fertiliser? Which farmers can afford to invest? Only then can fertiliser-ready farmers be identified and recommendations established and taken up by farmers to increase sustainable cocoa productivity.

Long-term fertiliser response trials

Large long-term experiments in which the effects of several factors, such as application rates of N, P and K and degrees of shade, are evaluated in different combinations, are essential to address some of the fundamental knowledge gaps. Such trials would enable the collection of robust data on cocoa yield response to fertilisers in relation to soil type, climatic conditions, degree of shading, etc. They would allow the development of methods to determine nutrient deficiencies and fertiliser recommendations 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.

1 Cocoa tree physiology

1.1 The cocoa tree

The cocoa tree (*Theobroma cacao* L.) originates from the tropical rainforests of the Americas (Almeida & Valle 2007). It has been known to the Mayas since pre-Columbian times, and has been cultivated in agroforestry systems (Almeida & Valle 2007). At the beginning of the 19th century, almost all of the world's cocoa was produced in tropical Latin America and Trinidad (Cunningham & Arnold 1962). Over the last decade, most production has occurred in West Africa (mainly Côte d'Ivoire and Ghana), followed by South East Asia (mainly Indonesia) (FAOSTAT 2015). Cocoa is being grown almost exclusively within 10°N and 10°S of the equator, where the climate is suitable (warm and humid, see also *Temperature and rainfall*, p5) for growing cocoa (Hartemink & Donald 2005). Originally, cocoa is an understorey rainforest tree (Läderach *et al.* 2013). Most cocoa systems have been established as agroforestry systems in the shade of large forest trees, but more recently, monocrop plantations have been introduced and advocated (Cunningham & Arnold 1962; Boyer 1973; Gockowski & Sonwa 2011). Cocoa research began in the mid-1930s, but investigations of the shade and nutrient requirements in West Africa only started in the mid-1950s when control of pests and diseases became effective (Cunningham & Arnold 1962; Lockwood 1976).

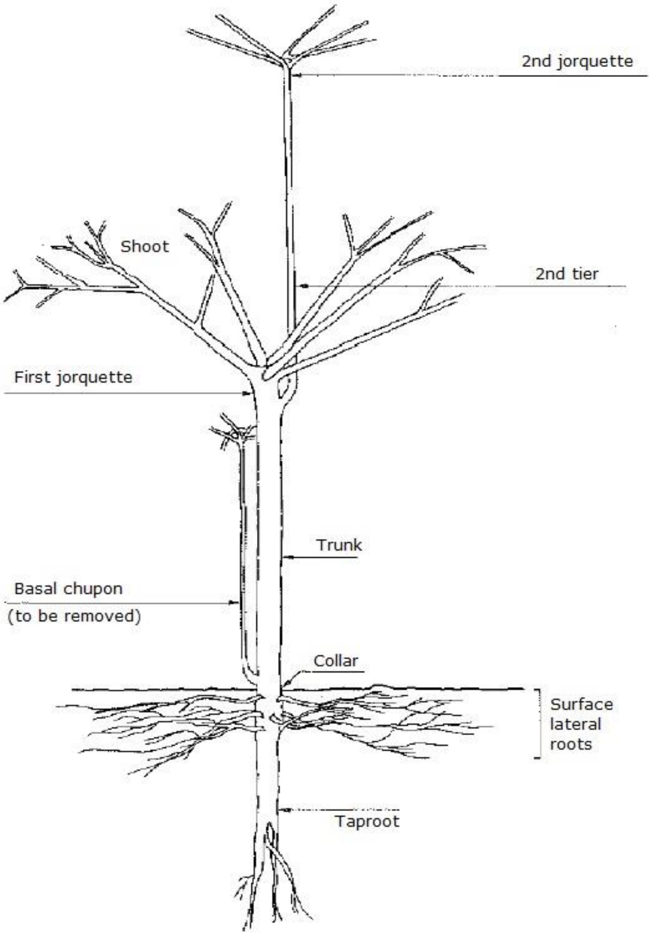


Figure 2. Schematic representation of the cocoa tree (adapted from Mossu 1995).

Under cultivation, cocoa is a rather small tree of about 3-10 m, although under natural heavy shaded conditions, it can be 20-25 m in height (Toxopeus 1985a; Almeida & Valle 2007). Trees grow rapidly during the first 3-4 years after which growth is more steady (Thong & Ng 1978). The tree forms a first 'jorquette' at a height of 1-2 m, where five 'fan branches' grow out sideways (Figure 2) (Toxopeus 1985a). Buds below the jorquette may grow out upward as 'chupons' (labelled as 'Second tier' in Figure

2) and are capable of forming a new jorquette above the previous one, thus increasing the height of the canopy in a step-wise process (Toxopeus 1985a). Basal chupons may also 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 except when the first jorquette is too low. Further pruning may also occur to remove unwanted and diseased shoots and reduce the density of the canopy (e.g. Ahenkorah & Akrofi 1968; Aranguren, Escalante & Herrera 1982; Wood & Lass 1985). The root system consists of a large tap root of 0.8-1.5 m (although it may be deeper in deep soils and may not form in heavy clay soil) and a lateral root system in the topsoil which is responsible for most of the uptake of moisture and nutrients (Wood & Lass 1985; Gerritsma 1995; Hartemink & Donald 2005). Leaf production occurs in flushes in which terminal branches produce 3-6 pairs of leaves after which the bud remains dormant for a period until a new flush occurs (Toxopeus 1985a; Gerritsma 1995). A flush usually coincides with leaf fall of older leaves as the nutrient demand of the new flush is partly met by translocation of nutrients and photoassimilates from the older leaves (Toxopeus 1985a; Almeida & Valle 2007). Although flowers are also formed on secondary branches, pods form mostly on the trunk and main branches (Almeida & Valle 2007; Groeneveld *et al.* 2010). Trees come into bearing after 2-6 years depending on the variety and location (see *Cocoa varieties*, p2) (Wessel 1971; Wood & Lass 1985). From a study including various cocoa varieties (though all but one were Amazon hybrid crosses, see *Cocoa varieties*, p2), Glendinning (1960) concluded that cocoa trees come into bearing when they have reached a stem diameter of about 6 cm. Amelonado cocoa may continue to bear fruits for 40 years or more, while hybrid trees should be replaced every 15-20 years (see *Cocoa varieties*, p2) (Wessel 1971; Gockowski *et al.* 2013). The start of the decline of production varies depending on factors such as variety, productivity of the tree, pest and disease incidence, and soil nutrient status.

1.2 Cocoa varieties

There are many different varieties of cocoa. Cocoa varieties are often classified into three groups: Criollo, Trinitario and Forastero, which, although the distinctions are inadequately defined, are supposed to vary according to morphology and genetic and geographical origins (Bartley 2005; reviewed in Almeida & Valle 2007). The Criollo varieties, which are thought to have originated in Venezuela and were the first to be cultivated in Trinidad (Bartley 2005), have been praised for their fine flavour, however, they lack vigour, yield poorly and are reported to be extremely susceptible to pests and diseases (Toxopeus 1985a; reviewed in Almeida & Valle 2007). Although they dominated the market until the middle of the 18th century, today few populations remain (Toxopeus 1985a). Trinitario is generally assumed to have originated as a cross between Criollo and Forastero, and many of its features are intermediate between the two (Toxopeus 1985a). The Forastero varieties now account for about 80% of global production and include both the Amazon and the Amelonado varieties (Toxopeus 1985a; reviewed in Almeida & Valle 2007). Amelonado was first introduced from Brazil on Príncipe in 1822, expanding from there to most of West Africa where, as in Brazil, it is still widely cultivated (Toxopeus 1985a; Bartley 2005). The Amazon populations, as the name suggests, were first described and collected in the vast Amazon river basin (Toxopeus 1985a). Forastero varieties are much more vigorous and hardy than Criollos. They are often referred to as 'bulk' cocoa as opposed to 'fine' cocoa, although the Ecuadorian 'Cacao Nacional' with its distinctive fine flavour is an Amelonado type (Toxopeus 1985a). 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; Toxopeus 1985b; Thresh & Owusu 1986). Indeed, hybrids are now available which, compared to Amelonado, show superior vigour, early canopy closure, easier establishment, early and high yields, disease resistance and greater tolerance to environmental stress (Asomaning, Kwakwa & Hutcheon 1971; Lockwood 1976; Thresh & Owusu 1986). According to Gockowski *et al.* (2013), hybrid tree stocks should be replaced every 15-20 years rather than the 30-40 year cycles commonly practiced with traditional Amelonado varieties 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. According to him, hybrids require different management methods (*unfortunately not specified*) than those traditionally used for Amelonado (Lockwood 1976). 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 & 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 & Ofori-Frimpong 2013).

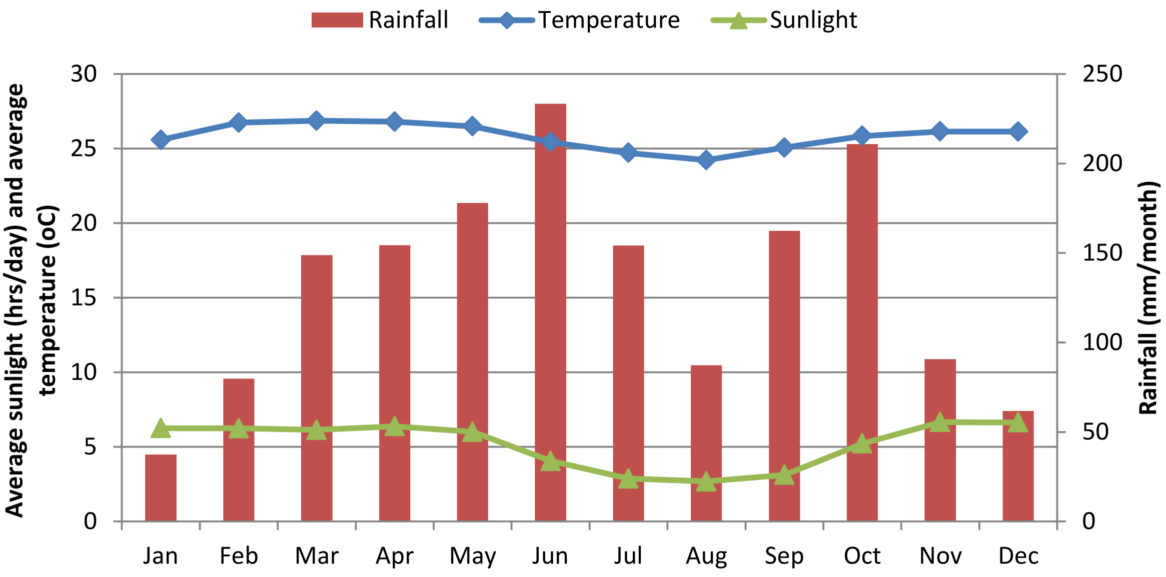
It should be noted that differences in yields between varieties may only be visible when other conditions such as nutrient and water availability and occurrence of pests and diseases do not substantially limit yields (see *Productivity*, p4) (Ofori-Frimpong, Afrifa & Appiah 2002).

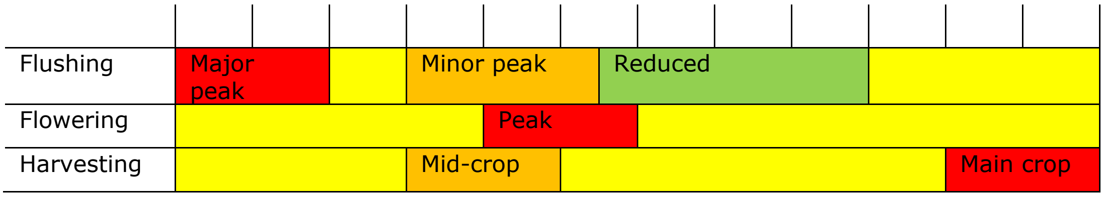
1.3 Annual production cycle

Whether the annual production cycle of cocoa follows a distinct seasonal pattern depends on 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. This is hardly the case in other production regions, where, as a result, cocoa growth and pod production is more continuous (Wood 1985a; Wood 1985b). Therefore, only the annual cropping cycle of Ghana is shown (Figure 3) while, for comparison, climatic data is also presented for Brazil and Malaysia (Figure 4). The annual cropping cycle in other regions than Ghana follows a similar though less distinct pattern, with the main harvest six months after the start of the wet season (Wood 1985b).

Especially in regions with distinct seasons, cocoa tree flushing follows a seasonal variation with reduced flushing during the cool season in which radiation is low (which in Ghana is around June-September, Figure 3), a major peak of flushes in the dry season before the main rainy season (January-February) and a minor peak of flushes in the main rainy season (April-June) (Asomaning, Kwakwa & Hutcheon 1971; Gerritsma 1995). Amelonado is thought to show more distinct seasonal variation than Amazon cocoa (Asomaning, Kwakwa & Hutcheon 1971). Flushing usually occurs in cycles of 6-8 weeks (Asomaning, Kwakwa & Hutcheon 1971). However, there is a lack of clarity on the factors which determine the length 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 (reviewed in Almeida & Valle 2007), which could be related to the effects of environmental conditions such as radiation, temperature and soil moisture (Asomaning, Kwakwa & Hutcheon 1971; Almeida & Valle 2007). The flush cycle, though influenced by environmental factors, is internally regulated, and also occurs under constant environmental conditions (Asomaning, Kwakwa & Hutcheon 1971; Almeida & Valle 2007). Although it seems that flushing is relatively uninfluenced by other aspects of growth, contrary some degree of control over flushing may lead to more efficient pod production (Asomaning, Kwakwa & Hutcheon 1971).

Like leaf flushing, pod production shows a seasonal pattern, especially in regions with distinct seasons. Pod production starts with flowering. According to Asomaning, Kwakwa and Hutcheon (1971), the seasonal pattern is again more distinct for Amelonado than for Amazon cocoa, which supports the notion that Amazon cocoa produces pods throughout the year (Aneani & Ofori-Frimpong 2013). Flowers are mostly pollinated by tiny midge species (Toxopeus 1985a). Flowers which are not pollinated abscise 24-36 days after opening (reviewed in Asomaning, Kwakwa & Hutcheon 1971). If pollinated, pod formation follows. The percentage of flowers that set pods in cocoa is usually small at 0.5-5% (reviewed in Almeida & 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) (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 (Valle, De Almeida & De O. Leite 1990; Gerritsma 1995). This process is known as cherelle wilt. Asomaning, Kwakwa and Hutcheon (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, Kwakwa & Hutcheon 1971; Valle, De Almeida & De O. Leite 1990). This process would be regulated by assimilate production (Valle, De Almeida & De O. Leite 1990). Competition for carbohydrates and minerals has been suggested to induce cherelle wilt, but for minerals this is not supported by data on cherelle wilt after fertiliser application (Asomaning, Kwakwa & Hutcheon 1971). Wessel (1971) found increased wilting at the time of or immediately following leaf flushing, supporting the suggestion that nutrient competition is a cause of cherelle wilt. Cherelles may also wilt as a result of infestation with microorganisms (Asomaning, Kwakwa & Hutcheon 1971). Those pods which pass the wilting stage take about 5-6 months from flowering to develop (Wessel 1971; Toxopeus 1985a; Gerritsma 1995). In West Africa, the main crop can be harvested following the minor rainy season (November-December, starting slightly earlier for Amelonado according to Gerritsma (1995)), while the much smaller mid-crop is harvested during the main rainy season (April-May) (Asomaning, Kwakwa & Hutcheon 1971; Wessel 1971; Ahenkorah, Akrofi & Adri 1974). During these harvesting seasons, harvesting in experimental settings is usually performed every two weeks (Ahenkorah, Akrofi & Adri 1974; Ahenkorah *et al.* 1987; Groeneveld *et al.* 2010). In Ghana, 25% of the annual harvest occurs in the peak month (November), while in Malaysia, where there is no true dry season, harvest in the peak month is only 12% of the annual crop (Wood 1985b).





Flushing	Major peak			Minor peak		Reduced						
Flowering					Peak							
Harvesting				Mid-crop							Main crop	

Figure 3. Annual cocoa cropping cycle (for references, see text) and climate (adapted from Wood 1985a) in Ghana (Tafo).

1.4 Productivity

Potential yields of crops are determined by location and crop specific characteristics under otherwise optimal conditions. These defining characteristics include local temperature, CO_2, sunlight radiation and the crop physiology and phenology. The availability of water and nutrients may limit production, and yields may be further reduced by weeds, pests and diseases and pollutants. Actual yields are likely to be smaller than the potential yields at a given location as a result of the limiting and reducing factors, giving rise to a yield gap. This yield gap may be decreased by addressing the limiting and reducing factors with yield increasing and yield protecting measures. The principles of theoretical production ecology are discussed in Rabbinge (1993), van Ittersum and Rabbinge (1997) and van Ittersum *et al.* (2013). Variability in actual yields is caused by differences in defining, limiting and reducing factors, and the management practices affecting them. Cocoa yields vary widely. For instance, within Ghana, Cunningham and Arnold (1962) report average yields in 53 plots that varied between 112-1,345 kg/ha. Yields of around 3,360 kg/ha have been achieved in on-station trials in Ghana, while the national on-farm average is around 400 kg/ha (Aneani & Ofori-Frimpong 2013). Zuidema and Leffelaar (2002), through simulating annual yields over 10 years, found water-limited yields in Ghana without nutrient limitations and without pests and diseases under 10% shade to be as large as 5,000 kg/ha, and yields of 6,100 kg/ha were achievable in Malaysia. 70% 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). The difference between average simulated yields and average actual yields on a hectare basis is likely to be caused mainly by nutrient limitations and pests and diseases. The difference between simulated yields and the largest reported yields for the same region are much larger in Ghana than in Malaysia (Zuidema *et al.* 2005), which is probably related to the differences in management practices. Furthermore, large variability in productivity can be found between years and among trees of the same population (Bartley 1970; Lockwood 1976; Ahenkorah *et al.* 1987). Part of the variability between trees may be explained by large but localised differences in soil fertility (Cunningham & Arnold 1962; Wessel 1971). Variability may be reduced by providing optimal growing conditions (Bartley 1970). Indeed, Wessel (1971) found fertiliser application to increase yields mainly of poorly-bearing trees, thus reducing yield variability among trees.

1.4.1 Temperature and rainfall

Climatic conditions are important in determining attainable yields (Rabbinge 1993; Zuidema *et al.* 2005). According to Snoeck *et al.* (2010), the optimal mean monthly temperature is about 26°C-27°C for cocoa production. These temperatures are based on the Ghanaian climate. Higher temperatures may be suitable for growing cocoa when rainfall patterns are different, as the increase in temperature will mostly affect cocoa through increases in evapotranspiration potential (ETP) and hence water availability (reviewed in Läderach *et al.* 2013). For instance, the rainforest zone of Malaysia, which can be about 2°C hotter than that of West Africa, is very suitable for growing cocoa as rainfall is well distributed with no dry months (Figs 3 and 4, Läderach *et al.* 2013).

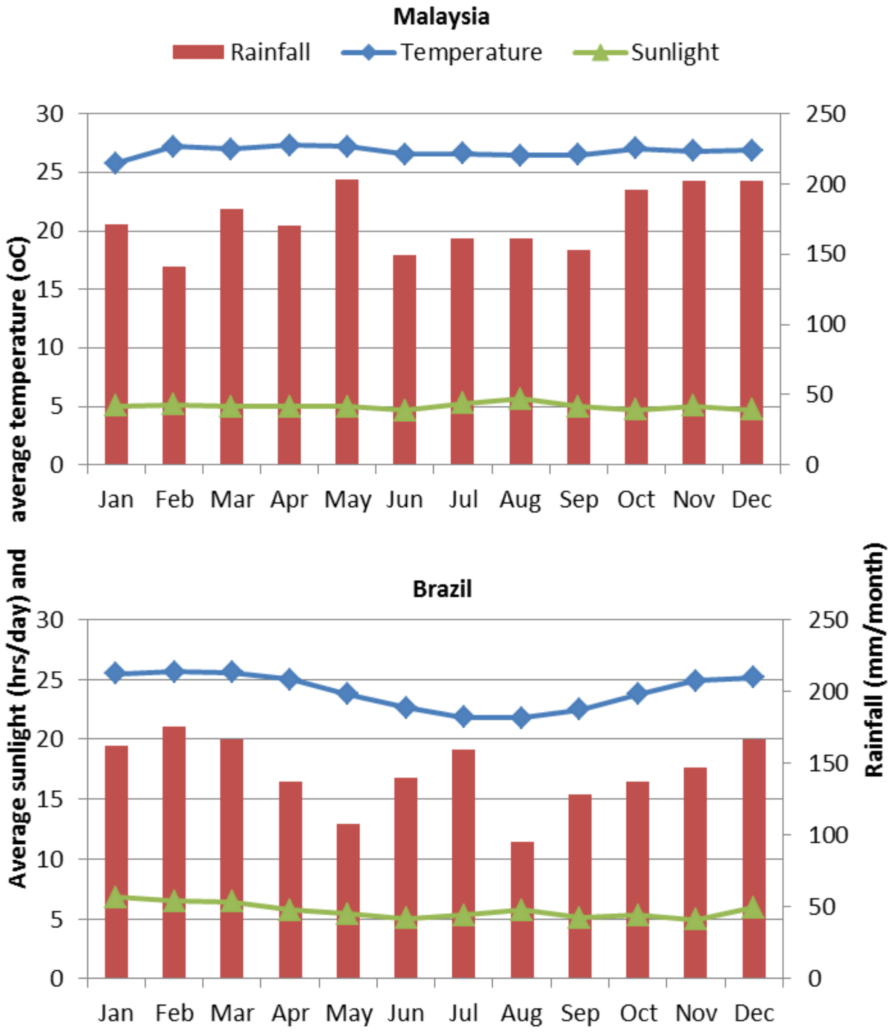


Figure 4. Climatic data of Malaysia (Sabah) and Brazil (Bahia). Adapted from Wood (1985a).

Wood (1985a) indicates that annual rainfall in most cocoa-growing countries is between 1,250 and 2,800 mm. Where rainfall is below 1,250 mm, it is likely that evapotranspiration induces greater moisture losses than precipitation can compensate and cocoa can only be grown here successfully if it can be irrigated (a practice hardly ever used in cocoa production) or if the groundwater table is high (Wood

1985a). Annual rainfall higher than 2,500 mm is likely to increase incidence of fungus 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). To be more precise, soil moisture availability should not fall below adequacy for prolonged periods (Zuidema & Leffelaar 2002). As soil moisture availability also depends on soil conditions and evapotranspiration, it is difficult to establish generally applicable rainfall requirements for cocoa (see *Soil moisture*, p10).

2 Soil properties in cocoa production systems

2.1 Variability in soil suitability criteria

In Table 2, some chemical properties for soils under shaded, unfertilised 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).

Some authors mention certain ranges of soil characteristics which cocoa needs in order to grow. Wessel (1971) set lower limits of adequacy of several soil characteristics according to Table 1.

Table 1. Lower limits of adequacy of soil characteristics at 0-15 cm according to Wessel (1971). For references used, see Wessel (1971).

			Available P (mg/kg)		Exchangeable bases (cmol/kg)		
pH	C (g/kg)	% total N	Sandy soil	Clayey soil	K	Ca	Mg
5.5	17.5	0.150	12	24	0.20	8.0	2.0

When comparing these values with those in Table 2, it can be seen that cocoa is grown under circumstances thought to be inadequate for cocoa production (red values in Table 2), for instance with much lower pH values in Costa Rica, and much smaller available P in Ghana. Some of the low values may be the consequence of long-term cocoa cultivation (see *Soil nutrient content*, p7; *pH*, p9 and *Organic matter*, p10). Inadequate chemical soil fertility may lead to suboptimal growth and yield of the cocoa trees. Indeed, yields in many regions are far below potential yields (Zuidema & Leffelaar 2002; FAOSTAT 2015). However, criteria of suitability may be applicable in one country but not in another (Wood 1985a). Different chemical soil characteristics interact not only with each other and with other soil characteristics, but also with factors such as shade management and climatic factors, which makes it difficult to set general standards. This is exemplified by the fact that available P, according to Wessel (1971), needs to be twice as much in clayey soils as in sandy soils. The environments in which the cocoa is to be grown needs to be assessed as a whole to adapt the method of cultivation to the local environment (Wood 1985a).

2.2 Soil nutrient content

To achieve high productivity, cocoa requires a soil abundant in nutrients (Wessel 1971). The importance of other soil characteristics, such as pH, is largely due to their influence on the availability of nutrients. In many cocoa growing regions, soil nutrient content without fertiliser application is poor, especially if the soil has been under cultivation for a long time (Hartemink & Donald 2005; Baligar *et al.* 2006, see also Table 2). 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. Annual nutrient requirements to replace nutrients exported from the system can be calculated using nutrient balances (see *Nutrient balances*, p17). However, there is little consensus regarding the requirements of the presence of nutrients in the soil for cocoa production. Some authors give lower limits of adequacy (Wessel 1971). However, others stress optimum ratios between nutrients and employ extremely small absolute minimum amounts of nutrients (Snoeck *et al.* 2010). See also *Application of methods to establish fertiliser recommendations in cocoa*, p41.

Without fertiliser application, more nutrients are removed from the system than are imported (see *Nutrient balances*, p17). Although cocoa established from virgin forest on fertile soils may not require fertilisers for many years (Charter 1953 in Appiah, Ofori-Frimpong & Afrifa 2000), eventually, cocoa production, especially without fertilisers, will deplete the soil of nutrients (Gockowski *et al.* 2013). This has been found both directly in long-term cocoa trials (e.g. Ahenkorah, Akrofi & Adri 1974) and indirectly in comparative research of forests and cocoa production systems in various stages following forest conversion (e.g. examples in Hartemink & Donald 2005; Ofori-Frimpong *et al.* 2007). Ahenkorah, Akrofi and Adri (1974) in Ghana found significant reductions of N content after 15 years of cocoa production, regardless of fertiliser application or shading (means of -44.3% N for the 0-5 cm layer and -39.0% N for the 5-15 cm layer).

Table 2. Chemical soil properties in some shaded cocoa production systems without fertiliser application. Values below and above lower limits of adequacy in the 0-15 cm soil layer (Wessel 1971, Table 2) are in red and blue respectively, values of other soil layers (below a depth of 20 cm) or for which no lower limit is given are in black. For available P, the lower limit of adequacy of sandy soils is used, for clayey soils the lower limit has a larger value. Note that the age of the cocoa plantation is not taken into account although long-term cocoa cultivation without application of fertiliser will gradually deplete nutrient stocks.

					Exchangeable bases (cmol/kg)					
Soil depth (cm)	pH	Organic C (g/kg)	% total N	Available P (mg/kg)	K	Ca	Mg	CEC	Source	Country
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	7.98	1.81		Appiah, Ofori-Frimpong and Afrifa (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, Isaac and Quashie-Sam (2010)	idem
0-5	6.7	23.3		0.7	0.34	13.31	2.21		Ahenkorah, Akrofi and Adri (1974)	idem
5-15	6.6	10.9		0.3	0.28	7.50	1.20		idem	idem
0-15	6.1	8.6	0.12	27.3	0.17	13.4	2.93		Ofori-Frimpong, Afrifa and Appiah (2002)	idem
0-20			0.12	17	0.06	5.1	1.58		Boyer (1973)	Cameroon
20-40			0.073	18	0.05	2.8	1.42		idem	idem
0-20	6.7				0.8	11.3	2.2		Duguma, Gockowski and Bakala (2001)	idem
0-20	7.4	15	0.62						Aranguren, Escalante and Herrera (1982)	Venezuela
20-40	7.1	2.9	0.47						idem	idem
0-15	3.8		0.22	*583*[1]	0.57	2.4	0.95		Alpízar *et al.* (1986)	Costa Rica
15-30	3.9		0.19	*616*[1]	0.27	2.65	0.98		idem	idem
30-45	4.1		0.11	*559*[1]	0.17	3.27	1.03		idem	idem

[1] Values are given for total P instead of available P in the soil layer (in mg/kg).

The rate of nutrient depletion depends largely on the productivity of the cocoa (see *Nutrient inputs and outputs*, p13). Nutrient reserves will be more rapidly depleted with increased production, for instance when agronomic practices are improved and/or shading is reduced (Cunningham & Arnold 1962; Appiah, Ofori-Frimpong & Afrifa 2000). Even the most fertile forest soils will not be able to support vigorously growing, unshaded cocoa for more than a few years unless fertiliser is used. This is supported by the positive interaction between increased light and fertilisers which is seen in many trials (Cunningham & Arnold 1962; Ahenkorah, Akrofi & Adri 1974; Ahenkorah *et al.* 1987) (see also *Influence of shade on fertiliser response*, p24).

2.3 pH

The pH of the soil influences uptake and availability of nutrients (Baligar *et al.* 2006). Many nutrients become less available with increasing acidity while others become more available, which can lead to toxicity of these nutrients (Wood 1985a). See Figure 5.

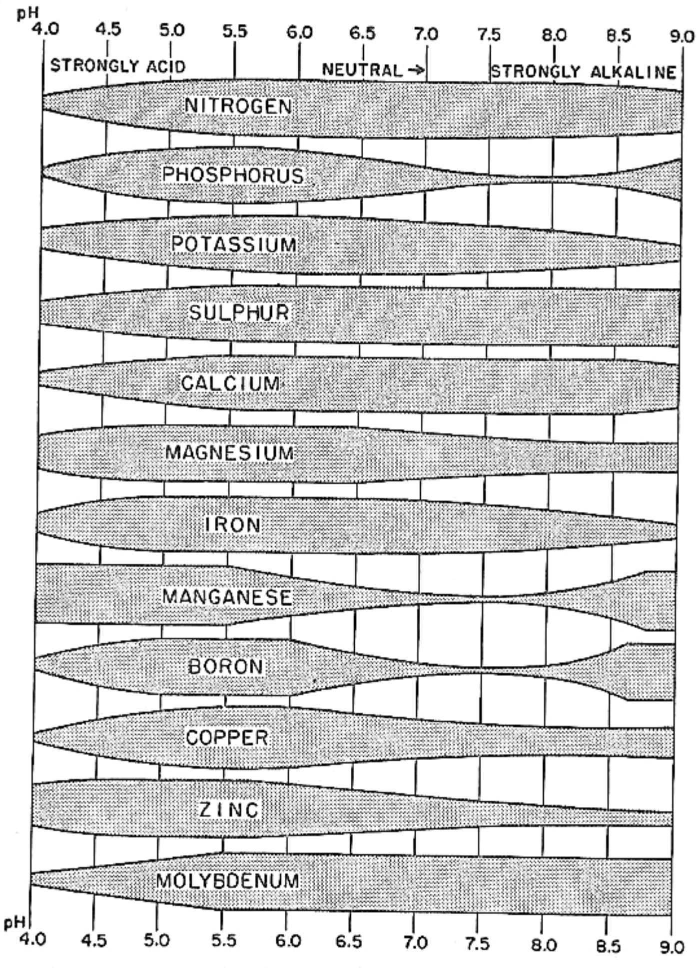


Figure 5. The influence of soil pH on the availability of plant nutrients. The widest part of the bar indicates highest availability (from Lucas & Davis 1961).

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 2). 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.

High rainfall can lead to nutrient leaching and acidity of soils (Snoeck *et al.* 2010). In the Nigerian cocoa belt, the annual precipitation of 1,150-1,650 mm can be considered to be less than ideal for cocoa production. However, this low rainfall is also the main reason why the Nigerian soils have not lost all their bases by leaching (Wessel 1971).

Generally, cocoa production will cause acidification (a lowering of pH) of the soil (although this was not found by Ofori-Frimpong *et al.* 2007). Examples are decreases from pH 6.8 under forest to 5.5 after 10-15 years of cocoa cultivation in Nigeria (reviewed in Hartemink & Donald 2005), from pH 6.7 to 6.2 in 16 years of cocoa cultivation in Ghana (Ahenkorah *et al.* 1987), and 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 in Ghana (Ahenkorah, Akrofi & Adri 1974). A low pH can lead to toxicity of various elements, especially Al toxicity which may in turn cause P fixation, stunted growth and poor yields (Delhaize & Ryan 1995; Shamshuddin *et al.* 2004; Baligar *et al.* 2006). In some cocoa producing regions, e.g. Malaysia and Brazil, pH is especially low and liming is a common practice (Delhaize & Ryan 1995; Shamshuddin *et al.* 2004; Baligar *et al.* 2006).

2.4 Soil moisture

Cocoa is sensitive to both drought and waterlogging (Carr & Lockwood 2011; Gattward *et al.* 2012). Even brief drought episodes can lead to decreases in stomatal opening, photosynthesis, and transpiration of cocoa leaves (Wessel 1971), and reduce yields significantly (Gattward *et al.* 2012). Waterlogging, which may occur during the wet season in some regions, leads to inadequate soil aeration (Evans & Murray 1953). Waterlogging may prevent the initial growth and establishment of cocoa, and will reduce pod production in mature cocoa (Almeida & Valle 2007). Both waterlogging and drought may lead to nitrogen deficiency symptoms in cocoa (Evans & Murray 1953). The amount of water which can be stored in the soil (at field capacity, F.C.) depends on the structure, texture and organic matter content of the soil (Wessel 1971). Soil requirements for cocoa production related to moisture depend on climatic conditions. For instance, where there are dry periods, as in West Africa, and/or where radiation is high, as in Malaysia, a poor water holding capacity can lead to temporary water deficits. In turn this causes large decreases of photosynthesis and yield reductions while this would be much less of a problem with well-distributed rainfall and low radiation, as in Costa Rica (Zuidema & 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 (see also *Box 1: Shade in cocoa production,* p27) (Wessel 1971). It is difficult to quantify yield reductions caused by water stress, as we lack physiological insights on the response of cocoa to water shortage (Zuidema *et al.* 2005).

2.5 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 can play 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 content of total N, organic P, CEC, and the sum of exchangeable bases (within certain pH limits) are all strongly positively correlated with the organic matter content of the soil. This does not hold true for all soils, as we can see in Table 2 (N.B. the amount of organic C being a measure of total organic matter).

Cocoa is usually established on soils cleared from forest, which causes a disturbance of the organic matter equilibrium which exists between forest and soil (Wessel 1971). The soil organic matter initially declines rapidly as a result of erosion, decreased litter supply and increased mineralisation 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 & Arnold 1962; Wessel 1971).

Ahenkorah, Akrofi and Adri (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 layer) within 15 years of cocoa production in Ghana. Losses were larger when C concentrations in mature cocoa plots were compared with plots at planting after forest clearing (Ahenkorah *et al.* 1987). Ofori-Frimpong *et al.* (2007) found losses in a similar range when comparing forest to unshaded cocoa (4.0 to 1.7% in the 0-15 cm layer), also in Ghana. Ahenkorah *et al.* (1987) found that about 44.5 t/ha of soil organic matter was lost in 16 years, and Ahenkorah, Akrofi and Adri (1974) found losses of 55 t/ha in 15 years from the topsoil (0-15 cm) 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 & Donald 2005).

Ahenkorah, Akrofi and Adri (1974) concluded that the rates of loss of soil C do not depend on shade. Yet their results show that without fertilisers, carbon losses were higher without shade, while with fertiliser application, losses in the top soil layer (0-5 cm) were larger under shade (Ahenkorah, Akrofi & Adri 1974). Shade was not quantified. Ofori-Frimpong *et al.* (2007) also found medium shade (15-18 forest shade trees/ha) to reduce C loss in the absence of fertiliser application, Beer *et al.* (1990) in Costa Rica found no significant changes in topsoil C in shaded cocoa systems in Costa Rica and Dawoe, Isaac and Quashie-Sam (2010) found larger carbon concentrations under 30 year old shaded cocoa systems than under 3 year old shaded systems. 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, carbon storage under cocoa is often still higher than in comparable soils under annual cropping (reviewed in Hartemink & Donald 2005).

2.6 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 & Beare 1997), which increases the vigour of the trees (Wessel 1971). Sandy soils are more susceptible to leaching (Aranguren, Escalante & Herrera 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 and 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.

2.7 Soil depth

Cocoa trees usually form a thick tap root 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 roots tend 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, but 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 trees lack physical support and may fall over (Wood 1985a).

3 Nutrient cycling in cocoa

In order 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, 4, 5; Hartemink & Donald 2005; Fontes *et al.* 2014). 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 & Donald 2005).

3.1 Nutrient inputs and outputs

The main sources of nutrient input in cocoa production systems are (in)organic fertilisers, rainfall deposition and nitrogen fixation (Table 3). Fertiliser use will be discussed under Section 4: *The use of fertilisers in cocoa,* p19. Nutrients in rainfall differ per region, depending for instance on nearby industrialisation (Howarth *et al.* 1996). Dinitrogen (N_2) fixation by leguminous trees, if included in the cocoa system, may provide a considerable source of N (Santana & Cabala-Rosand 1982; Hartemink & Donald 2005; Kähkölä *et al.* 2012) or be of limited importance (Beer *et al.* 1998). See also *Nitrogen fixation*, p34. The N contribution of the trees will depend on factors including shade tree density, fertilisation, pruning management and choice of species/clones (Beer *et al.* 1998). The transfer of fixed N from the shade tree to the soil occurs both through aboveground pruning residues and litter fall and through belowground root and nodule turnover (Santana & Cabala-Rosand 1982; Beer *et al.* 1998), as is discussed under *Nutrient transfer* (p14).

Table 3. Nutrient inputs into and removal from cocoa systems. All units are in kg/ha/yr unless otherwise indicated.

		N	P	K	Ca	Mg	Source	Country
INPUTS	Rainfall deposition	5.0-12	0.2-3.0	2.5-12[1]			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)[2]	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, Ofori-Frimpong and Afrifa 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

[1] 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.

[2] Thong and Ng (1978) found export of Mn to be 0.11 and Zn to be 0.09 kg/1000 kg dry beans

The main source of nutrient export is offtake through harvesting (Table 3). In the table, this is given as kg of nutrients per 1,000 kg of dry beans. Of course, annual harvest may be more or less than 1,000 kg/ha, and thus annual nutrient removal will vary. For instance, Zuidema and Leffelaar (2002) found average annual nutrient removal to be 100, 20 and 45 kg/ha of N, P and K respectively for simulated yields varying from 3,800 to 6,100 kg/ha/yr. With average annual yields in Ghana amounting to only about 400 kg/ha (Aneani & Ofori-Frimpong 2013), it is clear that nutrient removal here will be much less.

Most of the variability of nutrient content of the harvest between studies (which is especially large in the case of K, see *Potassium*, p30) can be attributed to differences in the nutrient content of the husks rather than that of the seeds. Husks demonstrate a much larger variation as a result of environmental conditions than do seeds (Hartemink & Donald 2005; Fontes *et al.* 2014). Regardless of variability between studies, nutrient content of husks is large. According to Boyer (1973), the husks contain 44% of the N, 29% of the P, 86% of the K, 90% of the Ca and 54% of the Mg exported by harvest (see Thong & Ng 1978; Hartemink & Donald 2005 for similar conclusions). Returning of husks to the soil thus decreases the rates of nutrient export in cocoa systems (Boyer 1973; Thong & Ng 1978; Fontes *et al.* 2014). This is common practice in many Latin American cocoa plantations (Santana & 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 (Ahenkorah & Akrofi 1968; Boyer 1973; Adejumo 2005). To prevent sanitary problems, cocoa husks can be burned or composted prior to application, but this is not a common practice. Through burning only the P and K is recycled, as N is lost during burning, so composting is preferable.

Except on steep slopes and bare soils, runoff and erosion are considered negligible in mature cocoa plantations (Boyer 1973; Hartemink & 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 & Donald 2005). Losses due to leaching may occur during intense rainfall, especially on bare soils (Boyer 1973; Santana & 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 (Santana & Cabala-Rosand 1982; Hartemink & Donald 2005), others suggest they are considerable, although much smaller than under annual crops (Hartemink & Donald 2005). Deep rooting shade trees may recycle N from deeper soil layers than cocoa and hence reduce leaching (Aranguren, Escalante & Herrera 1982; Hartemink & Donald 2005). However, according to Beer *et al.* (1998), the majority of the roots of shade trees in the humid tropics are found near the soil surface and will hence induce competition with the cocoa trees rather than prevent leaching. Nutrient leaching of nitrogen may be decreased through fertilisation with P and K as they increase root development and thus the nutrient uptake capacity of the cocoa (Santana & Cabala-Rosand 1982; Hartemink & Donald 2005). However, leaching may be intense when inorganic fertilisers are applied on light-textured soils (Aranguren, Escalante & Herrera 1982).

The nutrients captured in the woody parts of trees (Table 5) 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 amount 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. This amounted to 3-4 kg N/ha/yr, 100 g P/ha/yr, 4-5 kg K/ha/yr, 4.5-6 kg Ca/ha/yr and 1-1.5 kg Mg/ha/yr in his study in Cameroon (Table 3).

3.2 Nutrient transfer

Large amounts of nutrients are cycled within the cocoa system. They are taken up from the soil by both shade and cocoa trees, but are returned to the soil through litter fall, root turnover, and rainwash. These transfers are not adding to the total amounts of nutrients present in the system. However, they play a major role in sustaining the availability of the nutrients in the soil (see also *Soil nutrient pools*, p18).

3.2.1 Litter

Considerable amounts of carbon and nutrients are returned to the soil through litter production of both cocoa and shade trees (if present) (Hartemink & Donald 2005; Dawoe, Isaac & Quashie-Sam 2010; Fontes *et al.* 2014). The amount of litter fall in a shaded cocoa system usually lies between 5 and 10 t/ha/yr of dry matter (Hartemink & Donald 2005; Dawoe, Isaac & Quashie-Sam 2010; Fontes *et al.* 2014), most of which consists of leaves (Boyer 1973; Dawoe, Isaac & Quashie-Sam 2010; Fontes *et al.* 2014). Different factors influence the amount of litter returned to the soil. Climate plays a major role. For instance, trees drop more leaves during drought (Boyer 1973; Hartemink & Donald 2005; Dawoe, Isaac & Quashie-Sam 2010), while 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 as more trees will produce more litter and different tree species produce different amounts of litter (Hartemink & Donald 2005; Fontes *et al.* 2014). The amount of litter produced also depends on the age of the plantation as older systems have more litter fall (Hartemink & Donald 2005; Dawoe, Isaac & Quashie-Sam 2010). Soil conditions also 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 the cocoa system, although it is unclear what the effects of pruning are on the natural litter fall of the trees (Alpízar *et al.* 1986).

Table 4. Nutrient transfer. 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
Nutrients 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), Hartemink and Donald (2005)	Range of several studies around the world
Nutrients in standing litter (kg/ha)	122.0-271.9	7.1-13.7	22.8-76.7	145.6-344.7	38.2-67.5	Fontes *et al.* (2014)	Brazil
idem	60.3-64.9	5.2-6.5	16.8-31.3	87.0-96.8	27.1-30.2	Dawoe, Isaac and Quashie-Sam (2010)	Ghana
Nutrient transfer from fine root turnover of shade trees[1] (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	Boyer (1973)	idem
idem	8.0	<1.0-8.0	38.0-47.0			Hartemink and Donald (2005)	Malaysia and Costa Rica

[1] *Erythrina poeppigiana* and *Cordia alliodora*

The concentrations of nutrients in the litter fall of cocoa and shade trees combined are given in Table 4. Fallen cocoa leaves have smaller concentrations than fresh leaves as nutrients are transported from old to young leaves and/or nutrient uptake of old leaves is reduced (Wessel 1971; Toxopeus 1985a; Hartemink & Donald 2005). The amount of nutrients returned to the soil through litter fall (Table 4) depends on these concentrations and the amount of litter fall. According to Hartemink and Donald (2005), the 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, 15% of total K in the vegetation and 10-20% of exchangeable K in the soil. Litter stock, including nutrient stock (Table 4), will build up over time as litter fall increases and litter quality changes (Dawoe, Isaac & Quashie-Sam 2010). Fontes *et al.* (2014) found that the standing litter stock of cocoa production systems ranged from 7.7-16.8 Mg/ha in Brazil, while Dawoe, Isaac and Quashie-Sam (2010) found stocks varying from 3.6 Mg/ha in 3 year old systems to 5.9 Mg/ha in 30 year old systems in Ghana.

Variability in nutrient concentrations and amounts between the different studies reviewed is large, especially for K (see *Potassium,* p30).

The nutrient stock in litter in Ghana was much smaller than in Brazil (though less so for K, Table 4). Although this concurs with the differences in the amount of litter stock (see above), it seems to be contradictory to the difference in calculated decomposition coefficients (*k*-values, per year) found by both authors, which were smaller in Ghana (0.221-0.224, Dawoe, Isaac & Quashie-Sam 2010) than in Brazil (0.51-1.11, Fontes *et al.* 2014). This is perhaps related to more pronounced annual dry spells in Ghana, as the pattern of decomposition largely follows the rainfall pattern with slower decomposition rates during dry periods (Boyer 1973; Dawoe, Isaac & Quashie-Sam 2010). However, the main determinant for annual decomposition rates is litter quality (Cadisch & Giller 1997; Fontes *et al.* 2014). Litter quality may vary strongly among the systems (Fontes *et al.* 2014), which results, at least in part, in the large differences between *k*-values calculated in different regions. Unfortunately, Hartemink and Donald (2005) do not calculate *k*-values for the systems they analyse from different locations around the world. Especially N and lignin concentrations and ratios are highly related to decomposition, with positive correlations between decomposition rate and N concentration and negative correlations with lignin and lignin:N ratio (Dawoe, Isaac & Quashie-Sam 2010; Fontes *et al.* 2014). Negative correlations were also found with polyphenols and cellulose, while positive correlations were found with P (Dawoe, Isaac & Quashie-Sam 2010; Fontes *et al.* 2014). According to Hartemink and Donald (2005), decomposition is most rapid if the N:P ratio is around 10. Dawoe, Isaac and Quashie-Sam (2010) reported larger concentrations of polyphenols and lignin and lower N:polyphenol ratios 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 larger N concentration in fallen shade leaves than in cocoa tree leaves, and Osman, Nasarudin and Lee (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 forest systems (Dawoe, Isaac & Quashie-Sam 2010).

The rate of release differs among nutrients. Boyer (1973) found K 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 one year. Ca and Mg showed a more gradual release, following leaf decomposition rates, while N and P were released more slowly as they are mostly present in organic form.

Shade trees increase the humidity of the microclimate (Beer *et al.* 1998). Although Boyer (1973) found this to have little effect on decomposition rates, and Ahenkorah, Akrofi and Adri (1974) also did not find shading to affect decomposition rates, Ofori-Frimpong *et al.* (2007) found decomposition rates and nutrient release to be faster in shaded than in unshaded farms. However, as discussed above, this could also be caused by the enhanced litter quality of shaded systems. Cocoa drops less leaves under shade trees (Evans & Murray 1953; Boyer 1973; Ofori-Frimpong *et al.* 2007). Shade trees more than compensate for this difference, often contributing around 2-3 t litter/ha/yr or more (Boyer 1973; Aranguren, Escalante & Herrera 1982; Fontes *et al.* 2014). 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. Hence, shade trees may increase both the quantity and the quality of the litter (Dawoe, Isaac & Quashie-Sam 2010), thus increasing nutrient availability. However, quantity and quality of the shade tree litter will depend on the tree species (Aranguren, Escalante & Herrera 1982). Moreover, little quantitative data is available about the effect of the shade trees on the litter quality and quantity of the cocoa trees, and whether this will have a net positive or negative effect on the nutrient cycling (e.g. through increasing the decomposition rate).

Fertiliser application seems to have no influence on the amount of litter but increases the concentration of P, K, Ca and Mg in the litter. By contrast, accumulation of N in fertilised plots is less than in unfertilised plots (Fontes *et al.* 2014). Acquaye (1963) suggested that application of NP fertilisers increases mineralisation of organic P.

3.2.2 Root turnover

Fine root turnover can contribute substantially to return of nutrients to the soil (Table 4, Hartemink & 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 aboveground 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 (Santana & Cabala-Rosand 1982; Beer *et al.* 1998). Other authors suggest that aboveground litter is generally a stronger source of N return in agricultural systems (Ledgard & Giller 1995).

Kähkölä *et al.* (2012) suggested that although the amount of leaf litter was much smaller than the amount of root litter from *Inga* shade trees, uptake of N from root litter was greater than that from leaf litter as the root litter decomposed significantly faster than the leaf litter. However, again, this will depend on the choice of the shade species (Beer *et al.* 1998).

3.2.3 Rainwash

Rainwash transfers nutrients which are leached from the leaves back to the soil (Table 4, Hartemink & Donald 2005). Although the transfer of N and P is limited, transfer of bases, and especially K (related to its solubility, see *Potassium*, p30), is highly important (Boyer 1973; Hartemink & 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).

3.3 Nutrient stocks

Nitrogen accumulation in the above- and belowground biomass of cocoa ranges from about 100 to over 400 kg/ha (Table 5). This variation is explained by the age of the trees, differences among cultivars, and environmental conditions (Hartemink & Donald 2005). Aranguren, Escalante and Herrera (1982) found the total N store in cocoa plants in Venezuela to be 302 kg/ha. Branches, stems and roots contributed 30%, 20% and 29%, respectively, of this total. Shade trees may also contain considerable amounts of N: up to 250 kg N/ha (Table 5). Some 91-94% of the N in cocoa systems is found in the top soil. Total N content in the upper 30 cm of the soil varied from about 4,800 to 6,700 kg/ha (Table 5). N content of soils with leguminous shade trees can be larger than with non-leguminous shade trees, and a difference of 1,000 kg N/ha was found between the two systems in Costa Rica (Hartemink & Donald 2005). The accumulation of P in cocoa ecosystems is small. The P stored in the soil amounted to 30-79 kg/ha (Table 5, Hartemink & Donald 2005). Variability of accumulated K in cocoa systems is extremely large. Stocks of exchangeable K in the top soils of mature cocoa varied from about 100-560 kg/ha, which was between 27 and 61% of total exchangeable K accumulated in the cocoa systems (Table 5, Hartemink & Donald 2005).

Table 5. Nutrient stocks in shaded cocoa systems. All values are based on Hartemink and Donald (2005), who review a range of several studies around the world. Not all values were measured in each study included in Hartemink and Donald (2005), so the number of studies on which the ranges are based (*n*) differs per value range.

	N total	P available	K exchangeable
Vegetation (cocoa trees) kg/ha	103-438	10-57	52-633
Vegetation (shade trees) kg/ha	245-263	20-32	140-258
Top soils 0-30 cm kg/ha	4,782-6,699	30-79	103-557
Total kg/ha	5,171-7,367	39-136	417-1,304

When assuming a typical soil bulk density of 1,300 kg/m^3 and a required N content of 0.15% (Wessel 1971), required N stock in the top soil for cocoa production would be equivalent to 5,850 kg/ha. Hence, less than half of the soils in the study of Hartemink and Donald (2005) contain sufficient N. Assuming a required available P content of 12-24 mg/kg (Wessel 1971), required available P in the top soil for cocoa production would be equivalent to 47-94 kg/ha. At least one of the soils in the study of Hartemink and Donald (2005) does not contain enough P, the other two values are only adequate if the soils are sandy rather than clayey. When assuming a required exchangeable K content of 0.20 cmol/kg (Wessel 1971), required exchangeable K in the top soil for cocoa production would be equivalent to 304 kg/ha. Two of the five soils in the study of Hartemink and Donald (2005) did not contain sufficient K, whereas the other three did.

3.4 Nutrient balances

Without added fertiliser, the nutrient balance in cocoa systems is negative for all nutrients considered when assuming a yield of 1,000 kg/ha/yr. N_2-fixation by leguminous shade trees could compensate fully for the export of N and hence make the balance for N positive. Furthermore, returning the cocoa husks to the soil after harvest and composting would decrease the nutrient export considerably (see also *Nutrient inputs and outputs*, p13 and *Alternative fertilisers*, p33). In order to prevent nutrient depletion of cocoa soils, fertiliser application of especially P and K (and N in the absence of leguminous shade trees) is required.

The removal of nutrients from the systems is small compared with the amounts of nutrients present in the nutrient stock and the amounts of nutrients transferred within the system (Tables 3, 4, 5; Hartemink & Donald 2005). Especially N reserves in the soil are large (Table 5). However, this N is largely unavailable as the net mineralisation from soil organic matter and plant biomass is slow (Boyer 1973). P, especially in soils in West Africa, is at the largest risk of shortage, as available P is present in small amounts in the soil (Boyer 1973). The K cycle in cocoa systems is very fast (Boyer 1973). Large amounts of K (half of the exchangeable soil K reserve in Cameroon, Hartemink & Donald 2005) present in the system are mobilised and returned to the soil through litter and rainwash, while also relatively large amounts of K are being exported through harvest, especially when husks are removed (Table 3, 4, 5).

3.5 Soil nutrient pools

Nutrients in the soil exist in different forms. N is usually measured as total N, however, most of this N has to be mineralised before it becomes available to plants. P and K are usually measured as available P and exchangeable K, respectively. These values give a more realistic measure of availability of these nutrients to the plants. For both P and K, there also is a large amount present in the soil which is unavailable to plants. In the soil, both labile (available) and stable (unavailable) pools of nutrients are present. Nutrients may move between these pools in different time frames. Nutrients taken up from the labile pool may deplete this pool in the short term, but the labile pool may be restored from the stable pools over a longer period. Similarly, those nutrients which are returned or added to the soil may at first (or after decomposition) be present in the labile pool, but can be fixed into the stable pool in the longer term. The transfer of nutrients between the pools complicates the interpretation of nutrient balances and affects the fertiliser use efficiency. However, the studies reviewed here regarding nutrient balances and transfers do not take these fluxes between nutrient pools into account, except for the transfers related to litter decomposition.

4 The use of fertilisers in cocoa

4.1 Cocoa fertiliser trials

Many cocoa fertiliser trials have been conducted, often including treatments of both shade and fertilisers. Perhaps the most cited shade-fertiliser trials are the long-term trials conducted at the Cocoa Research Institute in Ghana (CRIG), two of which are described by Ahenkorah and colleagues. The first, K1 (described in Ahenkorah, Akrofi & Adri 1974), involving 3 ha of uniform West African Amelonado cocoa, was terminated in 1971, 24 years after planting. Treatments involved presence and absence of fertilisers and shade in all four combinations, with fertiliser application as stated in Table 6. Shading was not quantified. Initially, the soil had a high nutrient status and a good buffering capacity.

Table 6. Nutrient application in several trials. All values in kg/ha/year, on an elemental basis (own calculations based on values in sources). Yields are not included in this table as the number of treatments receiving (combinations of) these nutrient application rates in the trials is large. For general yield results of trials K1 and K2-01, please refer to Figure 7 (p22) and Figure 8 (p23).

Source	Experimental year/series	Rate	N[4]	P[5]	K[6]	Ca[7]	Mg[8]
Ahenkorah, Akrofi and Adri (1974)[1]	1956		15	45	84		30
	1957		112	15			
	1958		112	49	69		34
	1959-1961		112	49	93		34
	1962-1964		112	49	140		34
	1965-1971			49	140		
Ahenkorah *et al.* (1987)[2]	1963-1971	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, Ofori-Frimpong and Afrifa (2000)				56	63		
Santana and Cabala-Rosand (1982)			40	39	50		
Evans and Murray (1953)[3]			448	224	224		

[1] Experiment K1, started by Cunningham and Lamb. After 1965 N and Mg application was discontinued following the results obtained from NPKMg factorial experiments (Ahenkorah & Akrofi 1969 in Ahenkorah, Akrofi and Adri 1974). No significant responses to Mg or NMg were noted, the response to N was sometimes significant but usually negative. Similarly the increase in the amount of K applied was in response to findings reported by Acquaye, Smith and Lockard (1965, in Ahenkorah, Akrofi and Adri 1974) and Ahenkorah and Akrofi (1968).

[2] 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, Kwakwa and Hutcheon (1971) give different values still (same N as Ahenkorah and Akrofi (1968), but P about twice as high and K also higher). Here we present the values as given in Ahenkorah et al. (1974), as this was published later than the other two studies.

[3] Very high rates. Calculations based on the assumption that values given in the paper are on an elemental basis, which is not entirely clear. Murray (1975) refers to the results of the continuation of this same experiment (fertiliser application unknown).

[4] N was applied as urea, except in 1956 in the trial described by Ahenkorah, Akrofi and Adri (1974), when it was applied as ammonium phosphate, and in the trial described by Evans and Murray (1953) when it was applied as ammonium sulphate.

[5] P was applied as triple superphosphate, except in 1956 in the trial described by Ahenkorah, Akrofi and Adri (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.

[6] K was applied as potassium chloride in the trial described by Santana and Cabala-Rosand (1982), as sulphate of potash in the trials described by Ahenkorah, Akrofi and Adri (1974) and Wessel (1971), and as muriate of potash in the trials described by Ahenkorah *et al.* (1987), Appiah, Ofori-Frimpong and Afrifa (2000) and Evans and Murray (1953).

[7] Ca was applied as calcium sulphate.

[8] Mg was applied as magnesium sulphate.

The follow-up of this trial, K2-01 (described in Ahenkorah & Akrofi 1968; Asomaning, Kwakwa & Hutcheon 1971; Ahenkorah *et al.* 1987), was planted with Amazon hybrid cocoa in 1959. It included three levels 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 6) in all combinations, leading to 81 treatments. This trial was terminated in 1982. In K2-01, trees in all treatments also received NPK fertilisers upon planting and 1 and 2 years later. Fertiliser treatments were started four years after planting, while in the K1 trial, they were initiated in the tenth year after planting. This difference in the start of treatments is likely to be related to the onset of fruit bearing, which occurs earlier in Amazon than in Amelonado cocoa (Lockwood 1976). However, this cannot be deduced from the data given in the papers consulted (Ahenkorah & Akrofi 1968; Asomaning, Kwakwa & Hutcheon 1971; Ahenkorah, Akrofi & Adri 1974; Ahenkorah *et al.* 1987).

Wessel (1971) describes several trials conducted in Nigeria. Series I, II and III trials were not planted for this purpose, but sites with 25 to 35 year old cocoa were selected on farms. The cocoa had been planted randomly and grown under irregularly spaced shade trees. Yield recording began at least two years prior to the introduction of fertiliser treatments to obtain pre-treatment data to be used to correct the treatment yields for existing yield differences, considerably reducing variability. Fertiliser treatments with different fertiliser application rates of the nutrients as stated in Table 6, including a zero-application for each nutrient, lead to 128 treatments in Series I (all nutrient rates in all combinations), 27 treatments in Series II (rates of N, of P, and of KMg together in all combinations) and 8 treatments for Series III (all nutrient rates in all combinations). Treatments were from 1962 to 1968 in Series I, from 1964 to 1969 in Series II, and from 1965 to 1969 in Series III.

Appiah et al. (2000) evaluated the effect of fertiliser application (application rate as stated in Table 6) on peasant farms in Ghana for four years. Most farms had reduced degrees of shade.

Santana and Cabala-Rosand (1982) used 30-40 year old shaded plantations in Bahia, Brazil and compared fertilised plots (application rate as stated in Table 6) with unfertilised plots for one year. Their research did not include yield response, but was focused on nutrient cycling.

Evans and Murray (1953) conducted experiments in Trinidad, where they planted cocoa cuttings under 5 degrees of artificial shade using bamboo slats. Upon planting, the cocoa cuttings each received 130 g of N as ammonium sulphate, 65 g of P as superphosphate, 65 g of K as muriate of potash, and a basal dressing of 6.8 kg pen manure. The trial included 8 fertiliser treatments (presence and absence of N, P and K at the application rates given in Table 6, in all combinations). Half of the fertiliser was applied in January, ¼ in June and ¼ in August. All applications were done by applying fertiliser to each individual plant. Results of the trial described by Evans and Murray (1953) are only from the first 2 years after planting, but the trial was continued after that and results described in Murray (1975).

4.2 Some notes on fertiliser research data

Prior to discussing the results of different cocoa fertiliser research papers in detail, it is important to note some failings of this type of research. Results of some papers have been excluded from this review due to inadequacies in research methods and/or data presentation.

First, it is not always clear how much nutrients are added with fertilisers, and in which form. In research involving farm surveys, often a dummy variable is used indicating presence or absence of fertiliser use. In further analysis of the impact of fertilisers, only this dummy variable is used without taking into account the amount of fertiliser applied. In their survey, Gockowski and Sonwa (2011) found that fertiliser use (number of farmers applying fertiliser) in Côte d’Ivoire and Ghana was 13% and 17% respectively. One would not expect a large difference in yields caused by the difference between these percentages. However, the quantity of fertiliser applied by those who used it was 27 kg/ha in Côte d’Ivoire but close to 222 kg/ha in Ghana. When taking this quantity into account, one would expect a large influence on yield, which, indeed, was the case.

Second, initial soil fertility is often not accounted for, while fertiliser response will depend on soil fertility. For instance, a limited response of cocoa to fertilisers (i.e. little difference between fertilised and unfertilised plots at the same site) may be explained by the fact that the trees were sited on relatively fertile soils (Appiah, Ofori-Frimpong & Afrifa 2000). On the other hand, application of a particular nutrient may not be effective as long as other nutrients are limiting, while once these other nutrients are adequately replenished, application of this particular nutrient will increase yields.

Thirdly, many trials are conducted under optimal management conditions. This must be taken into account when applying these research results to the average smallholder farm where most cocoa production takes place. Especially when trials are conducted on research stations, management will be better than average and this may also be true for trials on smallholder cocoa farms. For instance, Appiah, Ofori-Frimpong and Afrifa (2000) selected plots for their trials 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. It is known that fertiliser application will be most successful when other management practices are adequately performed (Cunningham & Arnold 1962; Appiah, Ofori-Frimpong & Afrifa 2000). Ahenkorah *et al.* (1987) state: "*With proper farm maintenance practices*, the need for fertilizers to increase Amazon cocoa yields, whether the farm is with or without shade, is obvious" (own emphasis). As this may not be the case in actual field situations this may lead to overestimations of the impact of fertiliser application for farmers. On the other hand, the control yields in these experiments may be overestimations compared with the average farmer situation as a result of above average management practices, especially when in combination with fertile soils (as often is the case on research stations).

It is known that there are interactions between the applications of different nutrients, that is, the effect of the application of one nutrient depends on the availability of another nutrient (e.g. Ahenkorah & Akrofi 1968; Wessel 1971; Ahenkorah *et al.* 1987). Despite the possibility of such interactions, results are often given per nutrient, even when interactions between nutrients were observed within the same trial (Ahenkorah & Akrofi 1968; Ahenkorah *et al.* 1987). In these cases, it is often unclear whether data shown are results only of plots with application of different rates of the single nutrient, or of all plots where the nutrient was applied regardless of the rates of the other nutrients (see for instance Figure 6).

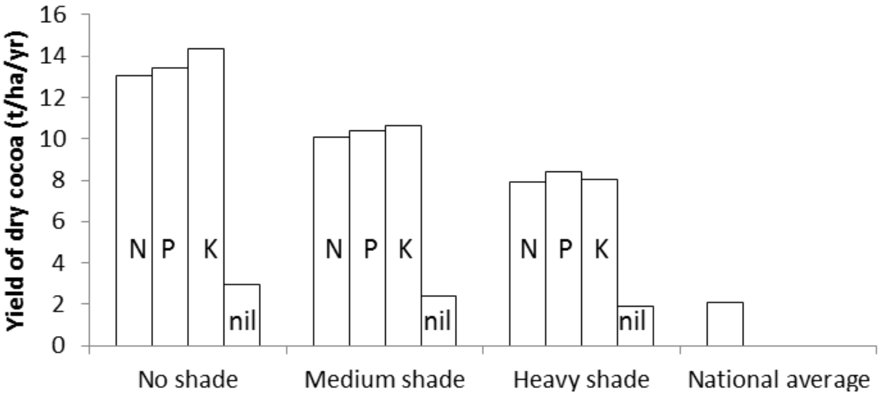


Figure 6. Results of application of fertilisers under different shade levels in trial K2-01, adapted from Ahenkorah *et al.* (1987). It is not clear what is presented: the original caption reads '*Cumulative mean effect of shade and fertiliser on Amazon cocoa yield over the 20 year period*', whereas the text states '*The dominant influence of overhead shade and the effect of the various fertilizer treatments under different shade regimes are shown (…)*'. For application rates, see Table 6. Interactions between nutrients do not seem to be taken into account, while Ahenkorah and Akrofi (1968) clearly showed nutrient interactions at least during the first years of the trial. Moreover, it seems that the yields are not given in t/ha as stated, but rather in hectogram/ha.

In trials, the results of plots or periods which may have suffered from suboptimal conditions, such as bad management, poor climatic conditions or disease incidence, may be discarded. This leaves the trial data with only the results of the more optimal plots/periods, which are usually also the plots/periods which show the largest yields and the best responses to fertilisers. Also, of the plots and periods taken up in the data, pods which are damaged by insects or diseases, or otherwise not suitable for commercial use, are sometimes still part of the 'yield' of the trials through correction for disease losses by extrapolating yields with the potential weight of diseased/attacked pods (e.g. Asomaning, Kwakwa & Hutcheon 1971; Ahenkorah *et al.* 1987; Groeneveld *et al.* 2010), even though the beans of these pods are worthless and disease or pest incidence may be influenced by the treatments.

4.3 General yield effects of fertiliser application

Below, some general effects of fertiliser application, sometimes in combination with shade effects, on cocoa yields in several trials are given. However, it must be kept in mind that these results are based on average yields in fertiliser research trials, while fertiliser response may vary greatly between farms and regions (Ruf & Bini 2012).

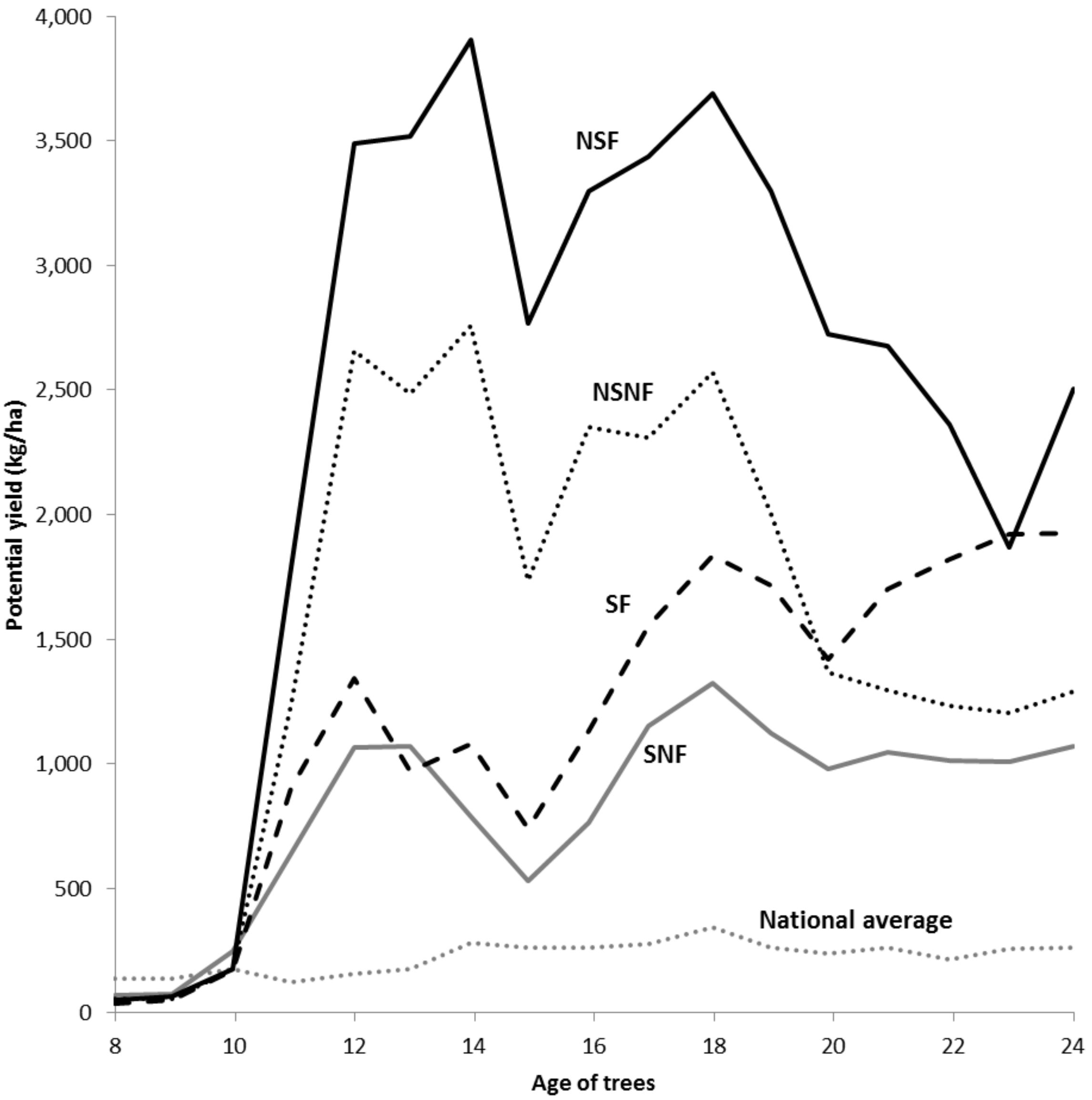


Figure 7. Results of application of fertilisers with and without shade in trial K1, adapted from Ahenkorah, Akrofi and Adri (1974). Treatments started when the trees had reached the age of 10.

Figure 7 shows the results of trial K1. According to Ahenkorah, Akrofi and Adri (1974), in the no shade with fertiliser (NSF), no shade no fertiliser (NSNF) and shade with fertiliser (SF) treatments it took 5, 7 and 10.5 years, respectively, to reach the same cumulative yield as was achieved in the shade no fertiliser (SNF) treatment after 17 years. Yields of NSF, NSNF and SF in the entire period of treatment were on average 3.2, 2.2 and 1.3 times greater than SNF (Ahenkorah, Akrofi & Adri 1974). No shade treatments yielded three times more than shaded treatments over 17 years, but the shade effects tended to decrease with the age of the trees. During the last 5 years, SF outyielded the NSNF and showed a moderate upward trend in yield while yields in all other treatments, but especially the no shade treatments, declined (apart from the yield of NSF in the last year). SNF, which is comparable to the usual Ghanaian practice, gave the smallest yields, though far exceeding the estimated national average (Ahenkorah, Akrofi & Adri 1974). Within the last years of production, the yields of NSF and SF in some years seem aberrant. Fluctuations in the earlier years were also large, however, these were normally apparent in all treatments while these later aberrations 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 cannot be explained and may be artefacts. Unfortunately, the trials were ended before trends in yields in these later years could be established with certainty.

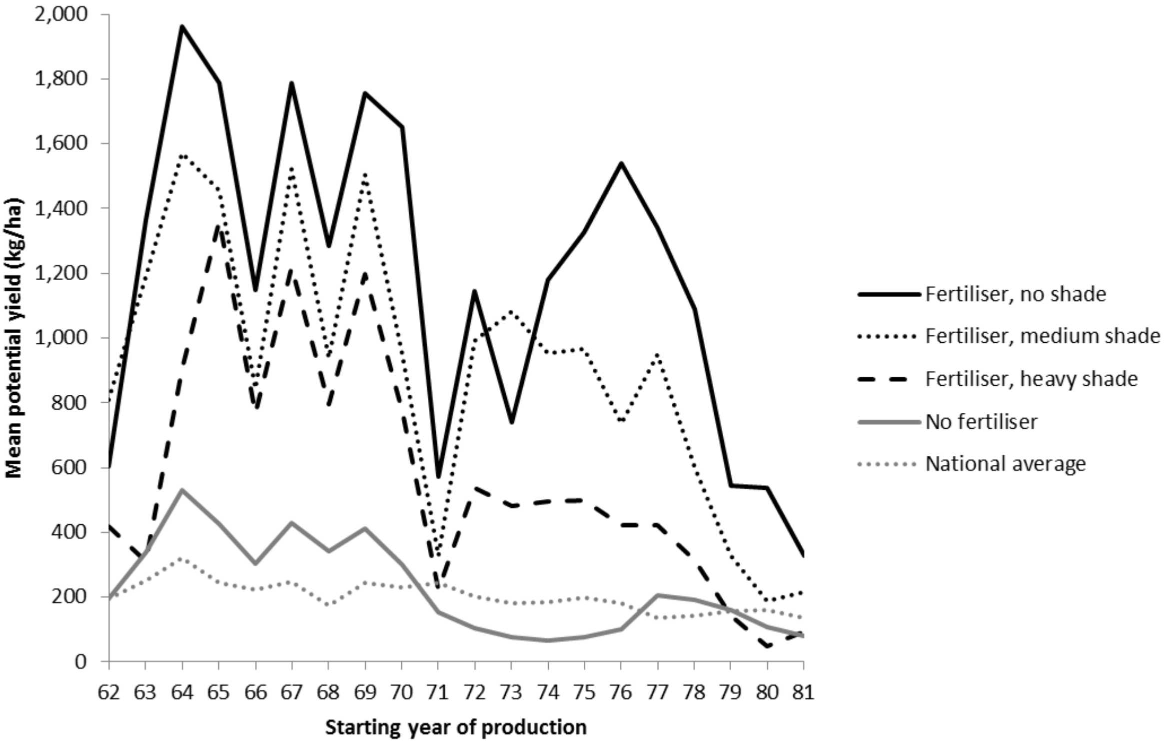


Figure 8. Results of application of fertilisers under different shade levels in trial K2-01, adapted from Ahenkorah et al. (1987). For application rates, see Table 6. Of the unfertilised plots, only average yields for all three shade treatments are given. Of the fertilised plots, average yields of both fertiliser rates are given for each shade level. No distinction between the effects of different nutrients, nor between the effects on the main and the minor crop are given. Interactions between nutrients as described for this trial by Ahenkorah and Akrofi (1968) are not taken into account.

In the K2-01 trial (Figure 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. One very bad year (1971/'72), in which especially the fertilised plots showed a large yield dip, was followed by 5-6 years of gentle fluctuations and either a rise in yield (for the fertilised no shade treatment) or a yield plateau, ending with a period of rapid decline in yield, in which the decline was more intense with increasingly reduced shade. Ahenkorah *et al.* (1987) claim that the decline rate was larger on unfertilised than on fertilised plots, yet this does not appear to be supported by the data presented.

Jadin and Snoeck (1985) applied fertilisers to smallholder farmers' fields in Côte d'Ivoire. The amounts of nutrients added differed among the fields and were calculated through the soil diagnostic method (see *Application of methods to establish fertiliser recommendations in cocoa*, p41). It is clear that the application of fertilisers increased the yields in these fields (Figure 9).

From Figs 7, 8 and 9, it is clear that fertiliser application can greatly increase cocoa yields. However, from the data presented 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. Others have also found large yield increases due to fertiliser application.

Appiah, Ofori-Frimpong and Afrifa (2000) found yields in fertilised farmer plots to be 97%, 296%, 243% and 169%[1] larger in years 1, 2, 3 and 4 of treatments respectively, compared with unfertilised plots. 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 fertiliser use in Ghana. Wessel (1971) reported positive responses to fertiliser application, although the degrees of response varied from site to site, with no response at some sites. Responses to fertiliser also varied throughout the year. In

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[1] 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 fertilisers instead of averaging the relative yield increases per site.

Ghana, where there is a minor and a main harvesting season, some fertiliser 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 & Akrofi 1968; Ahenkorah *et al.* 1987).

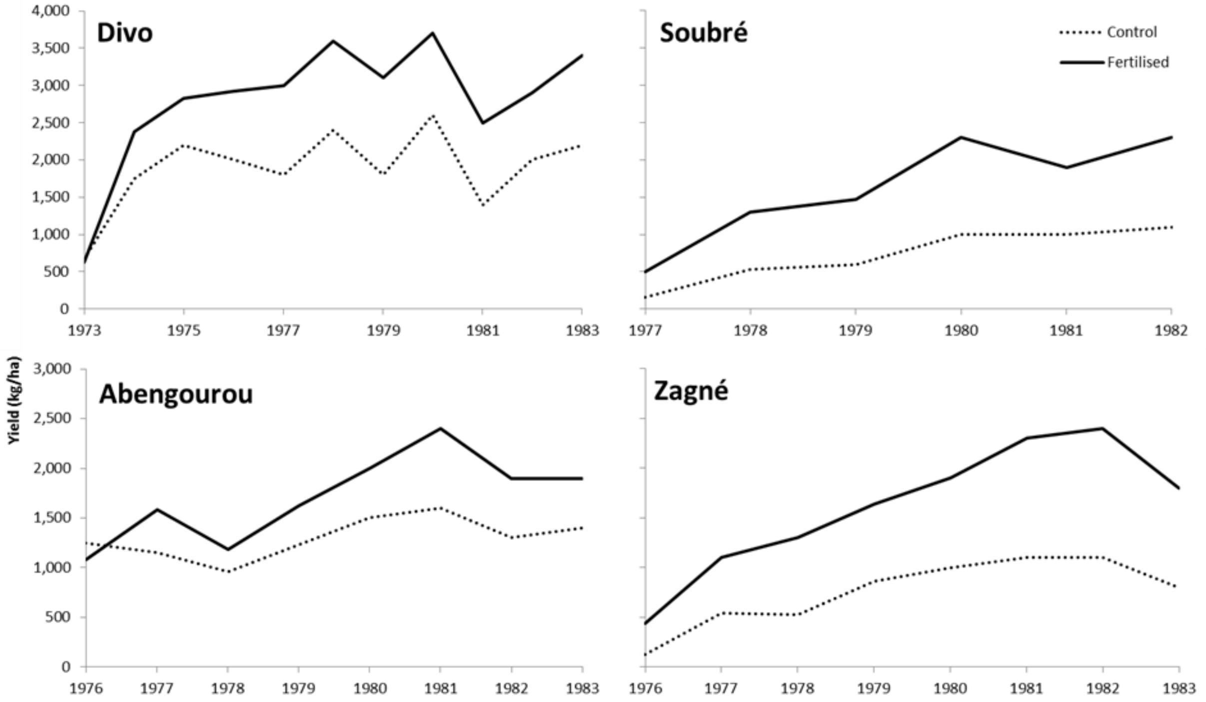

Figure 9. Results of application of fertilisers in several regions in Côte d'Ivoire based on data from Jadin and Snoeck (1985). Applied amounts of fertilisers are not specified in the paper but are based on calculations following the soil diagnostic method (see above).

According to Wessel (1971), yield increases due to fertilisers resulted from increases in the number of pods rather than the pod content. Others also found increased pod counts (Asomaning, Kwakwa & Hutcheon 1971). Although Asomaning, Kwakwa and Hutcheon (1971) found fertiliser application to result in slight increases in flower production and slight decreases of cherelle wilt, they attributed increased yields mostly to increased pod setting.

4.4 Influence of shade on fertiliser response

4.4.1 Optimal shade level

As seen in some of the figures above (Figs 6, 7 and 8), the degree of shade has an influence on the response of cocoa to fertiliser. Generally speaking, fertilisers result in stronger impacts on cocoa growth and yield without shade (see also Cunningham & Arnold 1962; Asomaning, Kwakwa & Hutcheon 1971; Wessel 1971). However, this effect depends on the degree of shade, which is not always quantified. A graph frequently used to illustrate the interaction between the degree of shade and fertiliser effects from Murray (1975) is depicted in Figure 10.

From Figure 10 we can conclude that NPK fertiliser application increased cocoa yields. However, under heavy shade, yields will remain small irrespective of fertiliser application. With fertiliser application, yields increased with increasing light intensity, although 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 fertiliser 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 fertiliser application and light intensity. However, this trial was performed using only one rate of fertiliser, and on a single soil. With different rates of fertiliser and soil fertility, and hence differing availability of nutrients for the trees, the optimal shading density may shift. Moreover, the shading density is expressed as percent of full daylight transmitted. As radiation intensity at 'full daylight' will vary between regions (and was not quantified in this experiment), 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 light levels. Also, the interaction between light intensity and fertiliser application may change during the lifetime of the cocoa trees. It seems that when the cocoa is still young, it needs at least some shade for the fertiliser application to be most effective, but once the cocoa has matured, fertiliser application effectiveness in the absence of shade increases (Asomaning, Kwakwa & Hutcheon 1971) (see also *Box 1: Shade in cocoa production*, p27).

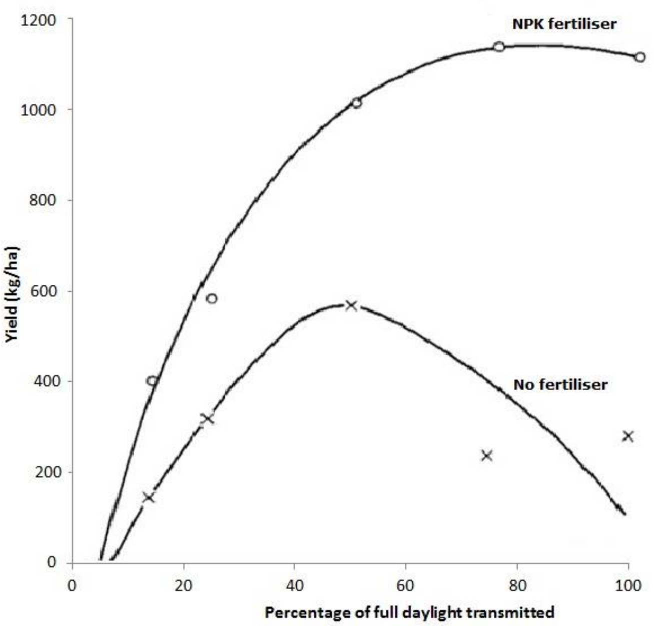

Figure 10. The interacting effect on cocoa yields of shade and fertiliser, adapted from Murray (1975). These results are from the continuation of the experiment by Evans and Murray (1953), when trees came into bearing in their third year. Nutrient application rates unknown.

4.4.2 Long term effects

In experiment K1 (Figure 7), yields were spectacularly greater in the non-shaded treatments over the first 8 years of treatment. However, after this period they also exhibited a spectacular decline in yields. When the trial was terminated, yield differences between the shaded and unshaded plots without fertiliser (SNF and NSNF) were small. Yields of the shaded fertilised plots (SF) had exceeded those of the unshaded unfertilised plots (NSNF) for several years, and even exceeded those of the unshaded, fertilised plots (NSF), although not in the final year as a consequence of a sudden yield increase in the NSF plots. Ahenkorah, Akrofi and Adri (1974) call the relatively stable yields of both NSNF and SNF in these last years 'yield plateaus', but for NSNF this plateau is small compared with the earlier yields. Ahenkorah, Akrofi and Adri (1974) also maintain that the fertiliser effect without shade tends to last longer and is hence comparatively more economic, while it can clearly be seen that the yield increase due to fertiliser declined over time under shade while it increased without shade (compare NSF with SF).

4.4.3 Superior experimental conditions

Yields in the K1 experiment, even in the SNF treatment which is suggested to resemble farmers practice, were much larger than the national average. 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 favourable (Cunningham & Arnold 1962; Mossu 1995; Beer *et al.* 1998). These factors include not only soil fertility (nutrient availability), which can be improved through fertiliser applications, but also climatic factors and pest and disease management. It is likely that the large yields achieved without shade in the K1 experiment, both with and without fertiliser application, are not easily achieved without the good initial soil fertility and the management practices allowed under experimental conditions. Nevertheless, the yields of the unfertilised plots in the K2-01 experiment were similar to the national average and even fell below it in some years, suggesting 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 fertiliser on cocoa yield is much larger than the overall effect of shade, although increased shading reduced the response to fertiliser.

4.4.4 Physiological processes

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

Like coffee, cocoa occurs naturally as an understorey species. Full sunlight in absence of fertiliser application leads to reduced yields (see also *Box 1: Shade in cocoa production*, p27). Fertiliser application under full sunlight stimulates vegetative growth leading to self-shading of the canopy, which reduces the negative effects of full sunlight. The cocoa benefits from increased photosynthesis, leading to increased yields. If fertilization is not sustained, leaf die-back is likely to occur as the cocoa tree can no longer support the nutrient demand of a large canopy and the high yield leads to substantial removal of nutrients (as is the case in coffee, DaMatta 2004). This phenomenon may also occur under shade in absence of fertiliser, reducing photosynthesis.

Competition between the shade and cocoa trees for the applied nutrients and the moisture needed to achieve good yields may play a role (Wessel 1971). The effect of shade trees on nutrient cycling, which can influence the availability of nutrients and hence the fertiliser use efficiency, may contribute to differences in fertiliser response (see also *Litter*, p14). Part of the explanation may be found in the greater production often seen in the absence of shade. As the amount of photosynthetically active radiation (PAR) is greater with less shade, so is the rate of photosynthesis. To achieve good yields, more nutrients and water are also needed. Thus, if nutrients are limiting, fertilisation will increase yields when shade is removed. If yields are larger in absence of shade, nutrient requirements to compensate for the nutrients taken off through harvest also increase, contributing to increased fertiliser requirements in absence of shade. Some authors suggest that increased production in the absence of shade in combination with fertiliser application, especially when varieties with good yield potential are used, may increase physiological stress and hence contribute to the more early and rapid deterioration of the cocoa trees (Beer *et al.* 1998; Gockowski *et al.* 2013). Direct sunlight and consequent high leaf temperatures (Boyer 1973; Beer *et al.* 1998), lack of wind protection (Cunningham & Arnold 1962; Beer *et al.* 1998), increased pest and disease incidence (Cunningham & Arnold 1962; Wessel 1971; Beer *et al.* 1998), and increased soil moisture evaporation in absence of shade trees (Cunningham & Arnold 1962; Wessel 1971; Beer *et al.* 1998; Ofori-Frimpong *et al.* 2007) may also cause physiological stress to the trees, contributing to accelerated tree deterioration in absence of shade.

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 for shaded systems, and large rates of K especially for unshaded cocoa. N fertiliser is recommended for unshaded systems but not for shaded systems (Wessel 1971; Ahenkorah *et al.* 1987). See also the different paragraphs on specific nutrients below, p28. No explanation is given by these authors for the differences in fertilisation for shaded and unshaded cocoa with N, P and K. The difference in recommendations for N fertiliser is readily understood as increased N stimulates leaf production and increases N concentration of leaves. This results in greater photosynthetic efficiency due to the larger concentration of chlorophyll and Rubisco in the leaves, so that better use can be made of the increased radiation in absence of shade. Other possible causes include competition for different nutrients with the shade trees, the nutrient content of the litter produced by the shade trees, or direct and indirect effects of the shade trees on the mineralisation of nutrients.

4.5 Box 1: Shade in cocoa production

Under full sunlight, cocoa leaves develop differently than when shaded. For mature trees, these differences can also occur within the canopy of a single tree (self-shading), while in seedlings, any shade will have to come from an external source. Shaded leaves usually have a larger surface, but are thinner and hence have a larger LAI than leaves in full sunlight (Evans & Murray 1953; Gerritsma 1995; Almeida & Valle 2007) 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. In full sun, excessive transpiration may cause water stress, which may explain the reduced leaf expansion compared with shaded leaves (Almeida & Valle 2007). In shaded conditions, cocoa leaves may have an increased chlorophyll content (Evans & Murray 1953; Almeida & Valle 2007). Unshaded leaves age faster, presumably as a result of increased leaf temperature and transpiration (Wessel 1971; Gerritsma 1995).

Cocoa is normally established under temporary shade, which is gradually removed as the trees grow and after a few years form a canopy and hence start to provide self-shading (Evans & Murray 1953; Ahenkorah & Akrofi 1968; Wessel 1971). 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 & Valle 2007). Wessel (1971) in Nigeria found that establishment of cocoa in drought-susceptible soils to be 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.) (Evans & Murray 1953; Ahenkorah & Akrofi 1968; Wessel 1971). 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 (Evans & Murray 1953; Cunningham & Arnold 1962; Boyer 1973; Santana & Cabala-Rosand 1982; Beer *et al.* 1998; Hartemink & Donald 2005; Snoeck *et al.* 2010).

Once cocoa has formed a good canopy cover and a dense root network, some of the benefits of shade species become less prominent. The risk of soil degradation becomes negligible (Boyer 1973; Santana & Cabala-Rosand 1982; Hartemink & Donald 2005; Snoeck *et al.* 2010). Through self-shading, individual leaves lower in the canopy are more protected against the harmful effects of full sunlight related to higher temperatures, excessive transpiration and moisture stress. However, other benefits remain. Besides reducing light intensity directly affecting the leaves, including those 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 (Evans & Murray 1953; Cunningham & Arnold 1962; Beer *et al.* 1998). Channels in the soil, left by dead roots, may improve aeration and drainage (Evans & Murray 1953). Shade trees may also reduce soil degradation and increase nutrient availability through litter cycling (see *Litter*, p14) and nitrogen fixation (see *Nitrogen fixation*, p34) (Evans & Murray 1953; Cunningham & Arnold 1962; Ahenkorah, Akrofi & Adri 1974; Beer *et al.* 1998; Isaac, Timmer & Quashie-Sam 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 (Evans & Murray 1953; Cunningham & Arnold 1962; Wessel 1971; Ahenkorah, Akrofi & Adri 1974; Ahenkorah *et al.* 1987; Beer *et al.* 1998; Zuidema *et al.* 2005). 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, Gockowski & Bakala 2001; Dawoe, Isaac & Quashie-Sam 2010; Gockowski & Sonwa 2011). However, shade trees have also been shown to decrease yields and reduce the benefits of fertiliser application (Wessel 1971; Ahenkorah, Akrofi & Adri 1974; Ahenkorah *et al.* 1987; Beer *et al.* 1998; Ofori-Frimpong *et al.* 2007; Gockowski & Sonwa 2011). This may be related to reduced light interception and hence reduced photosynthesis, but also to increased competition for water and nutrients (Evans & Murray 1953; Wessel 1971).

The effects of shade trees depend on the tree species (Isaac, Timmer & Quashie-Sam 2007). Once cocoa has been established, removal of large forest trees is likely to cause mechanical damage to cocoa trees and is not recommended (Glendinning 1966). 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 agro-ecological 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 ecological factors which are emphasised in this review, but also the resources and objectives of the farmer (Evans & Murray 1953; Wessel 1971; Beer 1987; Duguma, Gockowski & Bakala 2001).

4.6 Effect of fertiliser on pest and disease incidence

Pests and diseases are estimated to cause cocoa yield reductions of 20-40% globally, and losses may exceed 75% on individual farms (Adejumo 2005; CacaoNet 2012). The effect of fertiliser application on the incidence of pests and diseases in cocoa is unclear with positive, negative, and no effects found by different authors (Asomaning, Kwakwa & Hutcheon 1971; Ahenkorah *et al.* 1987; Appiah, Ofori-Frimpong & Afrifa 2000). It is sometimes argued that increases in pest and disease incidence in fertilised plots is primarily a consequence of higher yields and vegetative production in these plots (Ahenkorah *et al.* 1987). On the other hand, lack of adequate nutrition may reduce the strength of cocoa trees, hence making them more susceptible to pests and diseases (Ofori-Frimpong *et al.* 2007).

4.7 Nitrogen

As with most crops, nitrogen (N) is the nutrient required in the largest quantities by cocoa. About 90% of the N in soil is found in the soil organic matter in the topsoil (Hartemink & Donald 2005), and Santana and Cabala-Rosand (1982) found soil N contents to be higher under shade trees than without shade trees in Brazil. This N has to be mineralised before it becomes available to plants, and as a result, measurements of total soil N are a poor predictor of response to N fertilisers.

N stimulates leaf flushing, resulting in increases in leaf area and canopy formation, and mature trees may only respond to N when they are pruned and thinned (Jadin & Snoeck 1985). Wessel (1971) found that N additions stimulated growth of young seedlings and jorquette formation (in interaction with K and Mg application), stimulating early closure of the cocoa canopy.

In some experiments in Ghana, young seedlings responded positively to N application, while mature cocoa showed no response regardless of shading (Appiah, Ofori-Frimpong & Afrifa 2000). Wessel (1971) in several experiments with mature Amelonado in Nigeria found that yields increased steadily with increasing rates of N. 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 & Akrofi 1968; Wessel 1971; Ahenkorah *et al.* 1987). 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 fertiliser demand (Wessel 1971).

In some cases, a negative response of cocoa to N application has been observed. Wessel (1971) found NPK application at planting of young seedlings to have a depressive effect on growth of the plants in the first year, especially when the fertilisers were applied in the planting hole instead of on the surface. Later, when fertilisers were applied in split dosages and in bands around the plants, this gave no negative effects (Wessel 1971). Wessel (1971) reviewed a few trials in Ghana which showed young cocoa to be sensitive to N and K fertilisers, especially when placed in the planting hole. The negative effect of N was related to a reduction of P uptake. High rates of NP also depressed early growth of cocoa seedlings if K and Mg were not applied (Wessel 1971).

In mature cocoa, a negative response to N was observed especially in shaded and/or closely spaced plots (Wessel 1971; Ahenkorah *et al.* 1987). Wessel (1971) found dense shade to reduce response to N, while 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 production of high yields, while in Ghana, where cocoa was heavily shaded, cocoa failed to respond to N.

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 usually start to appear only after two to three years, as first the general nutritional status and vegetative growth of the trees has to be improved before more pods can be produced.

The Cocoa Research Institute of Ghana (CRIG) and the Centre National de Recherche Agronomique (CNRA) of Côte d’Ivoire do not currently include N application in their national fertiliser recommendations, although both institutes are involved in research to assess its relevance. 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, explaining the lack of response to N application. N deficiencies and the need for N fertiliser are difficult to diagnose using soil analysis. Plants absorb N from soil as the mineral ammonium and nitrate ions. The soil concentrations of ammonium and nitrate at any given time are the net result of many processes: the dynamic equilibrium of mineralization and immobilization of N from litter and soil organic matter, plant uptake and losses through leaching, volatilization and denitrification. This means that soil concentrations of mineral N can fluctuate rapidly making it difficult to derive a soil test to indicate N deficiency. Jadin and Snoeck (1985) indicated that total N concentrations are 'low' when they are 1.0-2.0‰. However, they state N application is only needed in case of large concentrations of bases (when Total Exchangeable Bases (TEB[2], cmol/kg) > 8.9*N (‰), which is the case in 11% of Ghana's cocoa production regions (Snoeck *et al.* 2010)). See also *Application of methods to establish fertiliser recommendations in cocoa*, p41. Wessel (1971) suggested 1.5‰ Total N as the lower limit of adequacy, while Snoeck *et al.* (2010) only deemed soils inadequate where Total N was below 0.6‰. In both of these latter examples, the thresholds given for Total N are minimal requirements, and hence will not be adequate for optimum production. Currently, if N is applied in cocoa, this is done in the form of calcium nitrate as it has been suggested that application of urea increases incidence of black pod disease. However, the reduction of black pods when calcium nitrate is applied may also be caused by the added calcium rather than the form of N.

4.8 Phosphorus

The availability of phosphorus (P) is determined using a range of extractants. Much of the total P present in the soil is unavailable for plant growth, particularly in strongly acid or strongly alkaline soils (Figure 5, p9), so available P is a more useful indicator of P deficiency. P is generally lacking in West African soils and in cocoa soils in most cocoa-producing regions (Wessel 1971). Although only small amounts of P are exported through harvest, depletion of soil available P has been claimed to be relatively most substantial (Wessel 1971; Ahenkorah, Akrofi & Adri 1974) (see also *Nutrient balances*, p17 and *Soil nutrient content*, p7). Generally, only 10-20% of P applied as fertiliser 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 (Wolf *et al.* 1987; Sattari *et al.* 2012). Some acidic tropical soils (notably Nitisols) can fix P strongly into unavailable forms. Application of P close to the roots of the cocoa tree can increase uptake in the first year after application (Wolf *et al.* 1987).

P response of cocoa was suggested to be hampered by excessive competition for P with shade trees by Wessel (1971). By contrast, Ahenkorah *et al.* (1987) observed a large P response under heavy shade. 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 5, p17) (Hartemink & Donald 2005). P application increases flowering (Asomaning, Kwakwa & Hutcheon 1971; Jadin & Snoeck 1985) and dry matter production (Ofori-Frimpong, Afrifa & Appiah 2002) in cocoa. Ahenkorah *et al.* (1987) found that P gave the strongest cocoa yield response in trials in Ghana compared with N and K. Wessel (1971) also found positive responses to P, often in interaction with N (P was required for N to have an effect). The yield increase was mostly due to increased yields of the poorly-bearing trees within the plantation.

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. Perhaps soil P reserves had still not 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. While the soil available P of unfertilised, unshaded plots decreased throughout the experiment, with shade and P fertilisation the soil available P continued to increase, although yield responses to P fertilisation continued to be observed (Ahenkorah *et al.* 1987). Contrary to N, large rates of P application have been recommended especially under shaded conditions (Ahenkorah *et al.* 1987).

According to Snoeck *et al.* (2010), P fertilisation is likely to increase cocoa growth and yield in almost all soils in the cocoa producing regions of Ghana, based on the soil diagnostic method of Jadin and Snoeck (1985). The lower limit of adequacy used by Wessel (1971) for available P in cocoa soils was 12 mg/kg for sandy soils and or 24 mg/kg for clay soils (determined in Truog's extractant). Jadin and Snoeck

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[2] Total Exchangeable Bases (TEB) is the total of the base cations Ca, Mg, K and Na in exchangeable form. The cation-exchange capacity (CEC) divided by the TEB gives the base saturation of a soil.

(1985) mention that available P[3] (using Olsen-Dabin analysis) should not be below 130 mg/kg. However, they stress that the N/P ratio, expressed in Total N and Total P_2O_5, is more important than the absolute quantity of (available) P, and should be 2.0. Wessel (1971) indicated that P responses were observed only with superphosphate in Ghana and not with rock phosphate. However, the source of rock phosphate is not specified, and availability of P from rock phosphate is highly variable depending on the hardness and solubility of the phosphate rock (Wolf *et al.* 1987). Jadin and Snoeck (1985) suggest that the best form of fertiliser P depends on the pH and the ratio of K-Ca-Mg in the soil, as some P fertilisers are rich in CaO and could create an undesirable cation ratio (see *Potassium*, p30 and *Other nutrients*, p30).

4.9 Potassium

In soil analysis, potassium (K) is determined as exchangeable K, commonly using ammonium acetate or ammonium chloride as extractants. Much of the total K is present in minerals that weather slowly to replenish the exchangeable K pool (Hartemink & Donald 2005). A large part of the K in cocoa ecosystems can be found in the biomass of cocoa and shade trees rather than in the soil (Hartemink & Donald 2005). Large amounts of K are exported in the harvest, especially when the husks are not returned to the field (see *Nutrient inputs and outputs*, p13). 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 & Akrofi 1968). Exchangeable K persisted to decline regardless of K applications (Ahenkorah *et al.* 1987). Wessel (1971) did not find cocoa to exhaust exchangeable K in Nigeria, and concluded that the soils had large K reserves. However, he also mentions that K availability may be too poor for production of Amazon cocoa (which he found to be more K demanding than Amelonado cocoa), especially without 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, where K fertilisers increased yields in general but especially in absence of shade where the largest yields in the experiment were reported (Ahenkorah & Akrofi 1968; Ahenkorah *et al.* 1987). By contrast, under heavy shade, P fertilised plots yielded more than K fertilised plots (Ahenkorah *et al.* 1987). Also, 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 (Ahenkorah *et al.* 1987).

Although Wessel (1971) in Nigeria found that K application did not raise K leaf concentration on soils with an adequate K status, 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 (see *Nutrient inputs and outputs*, p13 and *Litter*, p14). Boyer (1973) emphasised that the K in leaves is highly soluble, as it is largely present in the cytoplasm of cells, which further explains the large concentrations of K transferred to the soil by rain wash and the rapid release of K from litter as also concluded by Hartemink and Donald (2005).

K is important for translocation of carbohydrates (Boyer 1973), and is thought to increase tolerance to water stress (reviewed in Almeida & Valle 2007). K comprises some 70% of the minerals in the xylem sap of cocoa (reviewed in Almeida & Valle 2007). Gattward *et al.* (2012) have found that Na could partially replace K in cocoa nutrition, with significant beneficial effects on photosynthesis and water use efficiency. They suggest that Na is more efficient than K in the osmotic function of stomatal closure, which leads to decreased susceptibility to drought (Gattward *et al.* 2012).

Jadin and Snoeck (1985) state that the optimum proportion of K of the exchangeable bases Ca, Mg and K in soil should be 8%. Using the minimum recommended Total Exchangeable Bases of 0.6 cmol/kg soil proposed in Snoeck *et al.* (2010), this would be only 0.048 cmol/kg K. Wessel (1971) uses 0.2 cmol/kg as the lower limit of adequacy for K which is a value commonly used for other crops.

4.10 Other nutrients

Some fertiliser trials examined response to application of calcium (Ca) and magnesium (Mg) (see e.g. Table 6), and the fertiliser formula most used and recommended for cocoa in Ghana, Asaase Wura, and fertiliser blends on the market in Côte d'Ivoire, such as SuperCao, also contain these elements. However,

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[3] In the paper it is not clear if this is P or P_2O_5. However, 130 mg/kg available P is very high as critical values of Olsen P are normally given as 15 mg/kg.

little data regarding the response to these elements has been published. Ca is said to be especially important for establishment of cocoa, while Mg is favourable to the retention of leaves and delays leaf senescence (Thong & Ng 1978; Jadin & Snoeck 1985), presumably due to its role in chlorophyll. According to Jadin and Snoeck (1985), optimum proportions for cocoa are 68% Ca, 24% Mg and 8% K of the total of these exchangeable bases in the soil. They found a strong Mg deficit in soils in Côte d'Ivoire. Wessel (1971) did not detect Ca and Mg deficiencies in leaves, but soil analyses and fertiliser trials suggested that Mg may become a limiting factor in some sites in Nigeria, especially when N and P supply is increased. The lower limits of adequacy Wessel (1971) used for these elements based on the work of other cocoa researchers were Ca 8.0, Mg 2.0 and K 0.2 cmol/kg soil. Ahenkorah *et al.* (1987) found no appreciable changes in exchangeable Ca and Mg over the last 15 years of trial K2-01. Ahenkorah, Akrofi and Adri (1974) found that exchangeable Ca, Mg and K fell by 10, 22 and 23% in absence of shade and fertilisers and some depletion in shaded, unfertilised plots. No declines were observed in the other treatments in the last 15 years of trial K1. However, comparison of exchangeable bases under bush fallow and under cocoa cultivation suggested strong depletion of Ca, Mg and K with cocoa soils only containing about one third of the amount of these bases in bush soils (Ahenkorah, Akrofi & Adri 1974). These 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 *Organic matter*, p10). Part of the depletion could be due to erosion. According to Thong and Ng (1978), when compared with other nutrients, the requirement of Ca is high in the nursery and immature stage and less in the mature stages.

In the trials described above, Ca was applied as calcium sulphate. 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 sulphate, as also used in several trials, Table 6) (Jadin & Snoeck 1985).

The Ghanaian fertiliser Asaase Wura and the Ivorian fertiliser SuperCao also contain sulphur (S), but even less information is available on the requirements and application of this element although S deficiencies have been reported across Africa, more commonly on sandy soils. Cocoa fertiliser formulas may also contain micronutrients such as boron and zinc (e.g. Teractiv). 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, but highlighted 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 increasing worldwide, although they occur not only because of their scarcity in the soil but also because of factors such as pH which affect their availability, see *pH*, p9 (Baligar *et al.* 2006). 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, although 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 which tend to occur especially at low pH (e.g. aluminium (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. A problem particularly associated with soil acidity is Al toxicity which is a major limiting factor in plant production on acid soils. Cocoa is an Al-sensitive crop (Delhaize & Ryan 1995; Shamshuddin *et al.* 2004). What is known as the "soil acidity complex" is the combined impact of deficiencies cations such as Ca and Mg, of P due to fixation onto iron and aluminium sesquioxides and toxicity of Al. These combined effects can result in stunted growth of cocoa 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 Zn deficiency. As 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% which is sufficient to overcome Al toxicity and provide Ca for crops. Chicken dung, green manure and basalt applications also increased soil pH, reduced Al toxicity and had 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). In some extreme soils, however, the amount of lime needed to sufficiently reduce Al toxicity is too high for practical use as is the case in acid sulphate soils in Malaysia (Shamshuddin *et al.* 2011).

4.11 Recommendations on method and timing of fertiliser application

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

Once the cocoa has matured, fertilisers are either broadcast or applied in a circle around the stem. Since mature cocoa forms a dense layer of lateral roots in the topsoil broadcasting seems appropriate. 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 fertilisers into the top soil is not advised as in mature trees the roots come to the surface under the litter (Jadin & Snoeck 1985). Application of ammonium or urea forms of N and covering by litter was recommended to prevent volatilization of ammonia (Jadin & Snoeck 1985), but currently, if N is applied, this is done in the form of nitrate. For most 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 (De Geus 1973; Wichmann 1992; Ahn 1993). In general, macronutrients are not suitable for foliar application as the quantities to be applied are too high (De Geus 1973; Wichmann 1992; Ahn 1993). An exception is foliar application of N in the form of urea, which in some crops is sometimes combined with foliar spraying of insecticides or fungicides to save application costs (De Geus 1973; Wichmann 1992). Although in cocoa, foliar spraying of fungicides and insecticides is recommended, the use of foliar urea fertiliser might be limited as most fruit crop leaves do not tolerate high concentrations of urea (De Geus 1973). Urea sprays can boost leaf-N content to overcome temporary N shortages, but it cannot substitute for the usual soil application of N-fertilisers (De Geus 1973). Foliar application of micronutrients may be suitable for use in cocoa production.

In both the K1 and the K2-01 experiments, the fertiliser treatments started only when the trees had started to bear. Ahenkorah and Akrofi (1968) suggest that Amazon cocoa does not respond significantly to NPK fertilizer until it is over five years old. However, this result appears specific to the WACRI (West Africa Cocoa Research Institute, the predecessor of CRIG) soil series on which their experiment was performed, which Ahenkorah, Akrofi and Adri (1974) reported to have a good initial nutrient status and good buffering capacity. Wessel (1971) recommended increasing rates of fertilisers until the trees are six years old after which recommendations remain equal. Thong and Ng (1978) proposed increasing annual nutrient requirements to sustain growth, however, their calculations appear to be based on nutrient stocks in the cocoa biomass rather than annual requirements. It is likely that nutrient requirements will increase until the tree has reached maximum biomass, after which requirements will vary depending on amounts of production. Ahenkorah et al. (1987) suggested that requirements of Amazon cocoa for P and K increase with age especially under reduced shade (dosages of P and K were increased in experiment K2-01, leading to better yields), but it is unclear whether this is related to specific soil characteristics influencing the availability of these nutrients. If soils are already depleted upon planting, larger initial fertiliser rates may be required which may be reduced once a reserve has been built up (Wessel 1971; Jadin & Snoeck 1985). Appiah, Ofori-Frimpong and Afrifa (2000) found no significant relationships between the age of cocoa trees and fertilizer response.

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 fertilisers are usually applied at once in April/May (Wessel 1971; Ahenkorah *et al.* 1987; Appiah, Ofori-Frimpong & Afrifa 2000). 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). Although Jadin and Snoeck (1985) suggest that further splits would lead to better uptake (e.g. Mg is best applied in November, at the end of the second rainy season in West Africa), they acknowledge that this is not economically feasible and 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 two to three months later (Jadin & Snoeck 1985).

Little is known about the differences in fertiliser requirements between cocoa varieties. Wessel (1971) found Amazon to be more K-demanding than Amelonado. Other differences in fertiliser demand most likely arise from the fact that Amazon hybrids under good circumstances give greater yields, which increases nutrient demand. Further, Amazon hybrids show less seasonality in the annual production cycle, reducing fluctuations in nutrient demand throughout the year. However, fertiliser application is largely determined by seasonality of climate, especially of rainfall patterns, so if this is the case in a region, the recommended timing to add fertiliser will be the same for all varieties.

4.12 Increasing soil fertility through alternative fertilisers and nitrogen fixation

The use of organic fertilisers and the inclusion of N_2-fixing trees can greatly contribute to nutrient availability in cocoa production. This may be important especially for farmers for whom it is difficult to access inorganic fertilisers, due to problems with supply and/or cost (Smaling *et al.* 1992; Agbeniyi, Oluyole & Ogunlade 2011). Off course, the use of alternative soil amendments must be feasible and profitable, as is the case for instance with (farm) waste materials produced close to the cocoa production site (Wichmann 1992).

4.12.1 Alternative fertilisers

Organic residues have the advantage over standard NPK fertilisers of adding other nutrients such as Ca, Mg, and micronutrients. They also assist in maintaining soil organic matter. A larger soil organic matter content is considered to be favourable for cocoa production (see *Organic matter*, p10). A number of organic fertilisers are used in cocoa. Commonly mentioned is the scattering of (burnt or composted) pod husks and residues in the fields (Boyer 1973; Thong & Ng 1978; Fontes *et al.* 2014) (see *Nutrient inputs and outputs*, p13). Adejobi *et al.* (2014) obtained good responses in leaf nutrient content and growth measurements of cocoa 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 volatilisation during burning (Adejobi *et al.* 2014). Agbeniyi, Oluyole and Ogunlade (2011) found cocoa pod husk to increase yields and profitability of cocoa production in Nigeria. Recycling of cocoa pod husks appears to be a sensible option as long as they are burned or, preferably, composted.

Other organic fertilisers studied by Adejobi *et al.* (2014) which enhanced cocoa seedling growth are kola pod husk and cowpea pod husks (Table 7) but these are unlikely to be available in any significant quantity.

Table 7. Chemical analysis of the organic manures used for the experiment of Adejobi *et al.* (2014).

Treatment	pH (H_2O)	C/N ratio	OM (%)	N (%)	P (mg/kg)	K (mg/kg)	Mg (mg/kg)	Ca (mg/kg)	Na (mg/kg)
Cow pea husk	7.0	6.0	4.0	2.6	22.9	3.9	8.3	5.0	4.2
Cocoa pod husk ash	7.2	9.5	2.0	1.0	40.2	5.3	1.1	3.6	3.1
Kola pod husk	7.0	5.6	3.2	2.7	6.5	3.3	1.1	2.7	2.6

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, and can be seen as a slow-release fertiliser as it may take more than 9 months for basalt to react effectively in soils and after 27 months, still not all basalt has 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, and farmers report significant increases in yield as a result (Ruf *et al.* 2015). Cooke (1982) gives nutrient and organic matter content of some animal manures based on analyses from Britain and the USA (Table 8). Composition of manure may vary widely depending on the diet, health and type of animal and the nutrients transferred to the soil further depend strongly on the handling, storage and application of the manure (Ahn 1993; Rufino *et al.* 2007).

In oil palm plantations, Palm Oil Mill Effluent (POME) and Empty Fruit Bunches (EFB) are likely to be available in large quantities. Both products have a high nutrient content and can enhance yields and reduce expenditure on chemical fertilisers (Sharifuddin & Zaharah 1991). Similarly, in rubber plantations

Rubber Factory Effluent (RFE) may be applied (Sharifuddin & Zaharah 1991). When available, these products may also increase cocoa production.

Table 8. Nutrient content of several animal manures (from Cooke 1982).

	Percentage based on fresh weight				Percentage based on dry weight		
	Moisture	N	P	K	N	P	K
Poultry-droppings compost	75	1.2	0.4	0.4	4.8	1.6	1.6
Cattle farm yard manure	76	0.6	0.1	0.5	2.5	0.4	2.1
Pig slurry	97	0.2	0.1	0.2	6.7	3.3	6.7
Sheep manure	65	1.4	0.2	1.0	4.0	0.6	2.9

4.12.2 Nitrogen fixation

Some of the trees commonly used for shade in cocoa plantations are N_2-fixing legumes that may contribute N to the plantation (Giller 2001). Estimates of N input through leguminous trees vary considerably and depend on the tree species, shade tree density, fertilisation and pruning management (e.g. Santana & Cabala-Rosand 1982; Beer *et al.* 1998; Hartemink & Donald 2005). Beer *et al.* (1998) found N_2-fixation in unfertilised coffee and cocoa plantations ranged between 35-60 kg/ha/yr for *Inga jinicuil*, *Gliricida sepium* and *Erythrina poeppigiana* (although much larger estimates have been recorded, see below, these seem to be reasonable estimates for average conditions), which they consider 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 fertilisers, which indeed seems likely when comparing N input through N_2-fixation with N exports (Table 3) (Santana & Cabala-Rosand 1982; Hartemink & Donald 2005; Kähkölä *et al.* 2012). The N_2 fixed by the trees is for a large part transferred to the soil by aboveground litter fall (Beer *et al.* 1998). Pruning the trees may enhance this process considerably (pruned trees could provide up to 340 kg N/ha/yr, but this seems to be exceptional) (Beer *et al.* 1998). Another part of the fixed N is released belowground through nodule senescence and decomposition (up to 66 kg/ha/yr) (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 & Cabala-Rosand 1982). *Gliricidia sepium* (syn. *G. maculata*) on the other hand is an evergreen tree (Ahenkorah & 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, Cadisch & Giller 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 *Litter*, p14). These and other attributes should be taken into account when choosing among different leguminous shade species (see *Box 1: Shade in cocoa production*, p27).

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, p260). Shade trees may also compete with cocoa for nutrients and water (see *Box 1: Shade in cocoa production*, p27).

5 Fertiliser recommendations for cocoa

5.1 Various fertiliser recommendations

Based on his research in Nigeria, Wessel (1971) set preliminary fertiliser recommendations for cocoa (Table 9). In the first 3 years, the fertilisers 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 1st to 3rd year after planting, one half is applied in April and one half in August. From the 4th year onward, the fertilisers are broadcast every year with one half being applied in April and one half in August.

Table 9. Preliminary fertiliser recommendations for cocoa on soils derived from metamorphic igneous rock (from Wessel 1971).

Young cacao (established according to modern planting and maintenance methods)

Year	Soils cleared from forest: only N		Soils cleared from cacao and arable crops: N as soils cleared from forest, with additional P		
	g N/tree	kg N/ha	g P_2O_5/tree	kg P_2O_5/ha	kg P/ha
Year of planting	10	13[1]	10	13[1]	6
1st to 3rd year after planting	20-30	27-40[1]	20-30	27-40[1]	12-17
4th and 5th year after planting		50-67		34	15
6th and following years[2]		67-101		50	22

Existing mature Amelonado cacao

Cacao	Nutritional status		Recommended fertiliser rate	
	Soil	Leaf[3]		
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 fertiliser	
P deficient	Available P<10 mg/kg	%P (dm)<20 %P (fm)<0.070	50-67 kg P_2O_5/ha	= 22-29 kg P/ha
Not P deficient	Available P>12 mg/kg	%P (dm)>20 %P (fm)>0.070	No P fertiliser	

[1] Assuming a tree density of 1,333 trees per hectare

[2] These rates have to be adjusted according to the criteria given for mature cacao and N fertilisers should be omitted in heavily shaded cacao

[3] 5-10 weeks old leaves sampled in April/May. Dm is dry matter, fm is fresh matter.

For Côte d’Ivoire (Table 10), several fertilizer treatments were recommended in three different regions during the 1956 campaign to promote the general application of fertilizers to cocoa (Loué 1961):

Table 10. Fertiliser recommendations in Côte d’Ivoire based on Loué (1961).

	g/tree			kg/ha[1]				
	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

N.B. it is unclear why there are several recommendations per region, and on what the decision between them should be based.

[1] Assuming a planting density of 1,333 trees per hectare.

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 ha. However, good-yielding cacao 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 6th 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 & Walmsley 1961 in De Geus 1973) recommended applications were 60 g N, 120 g P, 90 g K and 500 g Ca per tree.

Recommendations for cocoa in Bahia, Brazil (Cabala Rosand *et al.* 1966a; Cabala Rosand *et al.* 1966b; Cabala Rosand *et al.* 1967 in De Geus 1973) are 65-100 g of a mixture of 50% ammonium sulphate, 30% triple superphosphate and 20% KMg sulphate 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 sulphate (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 $MgSO_4$ (ca. 33% MgO). For unshaded cocoa, they are 24, 6, 10 and 3 g/tree, respectively, of the same substances.

The above recommendations were recalculated and summarised for comparison in Table 11.

Table 11. Various fertiliser recommendations from 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[1]	Upon planting	9-14	12-18	4-6	5-8	3-5	Cabala Rosand *et al.* (1966ab, 1967; all in De Geus 1973)
	After 1st year	18-28	23-36	8-12	10-16	6-10	
	After 2nd 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	

When rates were given in g/tree, rates in kg/ha were calculated assuming a planting density of 1,333 trees/ha

[1] Rates were calculated assuming ammonium sulphate contains 21% N, triple superphosphate contains 45% P_2O_5, and KMg sulphate contains 22% K_2O.

Based on their knowledge at that time, Von Uexküll and Cohen (1980) estimate the following recommendations for young, mature, unshaded cocoa:

Table 12. Recommended fertiliser rates for young, mature, unshaded cocoa (Von Uexküll & Cohen 1980).

Targeted yield (dry beans[1]/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

[1] Although this is not indicated in the original text, it is assumed here that dry beans is given in tonnes

Wyrley-Birch (1972, in Von Uexküll and Cohen 1980) presents fertiliser recommendations of different authors from various cocoa producing countries (Table 13).

Table 13. Rates of application of nutrients to cocoa (after Wyrley-Birch 1972, in Von Uexküll and Cohen 1980).

Author	N (kg/ha/yr)	P (kg/ha/yr)	K (kg/ha/yr)	Remarks
Wyrley-Birch (1972)	37	41	100	Light shade, yields 450 kg. East Malaysia
Maliphant (1965)	105	30	167	Unshaded cocoa
Cunningham and Smith (1963)	-	50	-	Shaded Upper Amazon
Quartey-Papafio and Edwards (1963)	58	33	-	Smallholder cocoa in Ghana
Cunningham (1963)	115	26	198	Unshaded cocoa, yield 2.5 t/ha
Verliere (1967)	-	37	133	P applied as rock phosphate
Wessel (1967)	132	13	-	Smallholder cocoa in Nigeria
Jacob and von Uexküll (1963)	22-34	18-22	28-37	Cocoa up to 3 years old
idem	34-68	13-26	56-84	Mature cocoa over 3 years old
Van Dierendonck (1959)	100-156 or 150-233	44-68	83-129	Planting density 1,100 trees/ha
idem	97	25	61	Trinidad, young trees
idem	195	50	123	Trinidad, old trees
idem	16	68	69	Bahia Brazil, shaded
idem	23	6	19	Jamaica, shaded, 1st and 2nd years
idem	47	12	37	Jamaica, shaded, 3rd year
idem	31	12	75	Jamaica, shaded, 4th year
idem	16-37	5-11	11-28	Côte d'Ivoire, 2-6 year old trees, P as rock phosphate

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 per tree per year. In Ghana, an annual application of 3 bags per acre, or 300-400 grams per tree, 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 tardy (YARA 2012). It is recommended to be applied at 1 bag per acre, or 100-150 grams per tree.

Table 14. Current fertiliser recommendations in Ghana and Côte d'Ivoire, per tree and in kg/ha at recommended tree densities.

	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[1]	*15-23*[3]	66-88	54-72	*17-26*[3]	73-97	59-79	32-42	49-66
Côte d'Ivoire[2]	0	69-92	57-76	0	92-123	76-101	40-54	63-84

[1] Asaase Wura (0-22-18) at 300-400 g/tree, 1,100 tree/ha
[2] 0-23-19 at 2 x 150-200 g/tree, 1,333 trees/ha
[3] If Nitrabor is included at 100-150 g/tree.

More fertiliser recommendations from different authors of different regions exist, but from the above it can already be concluded that the amounts of fertiliser recommendations 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 fertiliser recommendations are discussed.

5.2 Establishing fertiliser recommendations

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

1. Nutrient balance analysis
2. Soil analysis
3. Leaf analysis
4. Fertiliser response trials

Below, these methods and their uses are discussed. In section 5.3, the application of these methods to establish fertiliser recommendations in cocoa is discussed.

5.2.1 Nutrient balance analysis

The use of nutrient balance analysis in establishing fertiliser recommendations is based on the principle of replacement: the nutrients added in fertilisers should replace the nutrients leaving the system. Nutrient balances may take into account all nutrient flows into and out of the system. Often only the nutrients removed in the harvested crop are taken into account. In the case of perennials, sometimes nutrients immobilised in the tree for growth are also included in the balance (see e.g. Goh 2005).

To calculate the nutrients being removed from the field, the harvested parts of the crop are analysed for their nutrient composition so that crop offtake can be calculated. Once the nutrient concentrations of harvested products have been established all that has to be known is the yield of that field of the previous year, or the projected yield of the coming year. Due to its simplicity, this is an attractive approach.

Yet the method has several shortcomings:

1. The nutrient composition of a crop varies depending on climate, soil, and management conditions. Thus the nutrient composition must be established at least for each major production situation.
2. Nutrient losses such as leaching, as well as nutrient inputs through nitrogen fixation or atmospheric deposition, may be considerable, so that partial balances based only on fertiliser 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 & Giller 2006), and applying fertilisers 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 fertiliser applied based on this method will be too small (De Geus 1973).

5.2.2 Soil testing

This method assumes that a crop needs a certain amount of available nutrients in the soil for it to produce an optimal yield. The current amount of available nutrients can be estimated through the soil test. The soil may not contain enough nutrients to supply the crop, and the portion that cannot be supplied by the soil should be applied as fertiliser (Hochmuth, Mylavarapu & Hanlon 2014b). The process of soil testing consists of several steps, all of which influence the final result.

Usually, the topsoil is sampled, but for some nutrients (especially mobile elements like N) and crops (especially perennials) subsoil nutrient reserves may be important and deep sampling is then recommended (De Geus 1973; Olson *et al.* 1982).

Different extractants are used to estimate the amount of each nutrient available to the crop in the soil sample. The suitability of an extractant may vary between soils, climatic conditions, and crops. The concentration of available nutrients is compared with established critical nutrient concentrations for a specific crop and soil combination. The results may be expressed as an index of the nutrient-supply capacity of the soil, for instance low, medium or high. Based on this index, a certain rate of fertiliser is recommended. Substantial research has been done to select appropriate extractants for varying conditions, to correlate nutrient levels according to the extractant to crop response and define the nutrient indices, and to calibrate how much fertiliser is required for each index to obtain satisfactory yields for major food crops. 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. But without it, it is impossible to use soil analyses to establish fertiliser recommendations. For more details about the research required, see for instance Van der Paauw (1956), Smilde (1985) and Bruulsema (2004).

Soil testing is most applicable to nutrients that are less mobile in soil such as P, K, Mg, Ca and micronutrients. N is a highly mobile soil nutrient, which may rapidly transform or leach from the soil (Hochmuth, Mylavarapu & Hanlon 2014b). 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 mineralisation have been sought, but finding a useful measure of N availability using soil analysis remains problematic (Geypens & Vandendriessche 1996; Smethurst 2000).

To interpret the results of soil analyses, information on the soil, the crop, the climate, and management factors is needed (e.g. Van der Paauw 1952; De Geus 1973; Posner & Crawford 1992). With adequate data available from trials, calibrations with yield response can be made for specific (soil) factors, which increase the applicability and accurateness of the soil test results (Smilde 1985; Posner & Crawford 1992; Bruulsema 2004). If such factors are not adequately taken into account, the nutrient indices may explain only a small percentage of the variation seen in fertiliser response (e.g. 16-29% according to Posner and Crawford (1992) and 13-17% according to Bruulsema (2004)). A weak correlation of a soil test with yield weakens the reliability of applying a calibration to new areas.

Even when there is agreement on nutrient indices, there are different philosophies on how to translate this into a fertiliser recommendation. A main difference is whether fertilisers should only be added when the current nutrient availability is insufficient to meet crop requirements (the 'sufficiency level' or 'crop nutrient requirement' (CNR) approach), or whether additional fertiliser should be added to replace nutrients projected to be removed by the crop (thus combining soil testing with the nutrient balance approach, also referred to as the 'build-up and maintenance' approach). According to some, the additional fertiliser added in the latter approach will lead to excessive nutrient build-up, is economically unfavourable as the additional nutrients do not increase yields, and lead to environmental risks (Olson *et al.* 1982; Hochmuth, Mylavarapu & Hanlon 2014a). Others, however, maintain that it is beneficial to invest in nutrient stocks, especially of P, due to residual effects in subsequent years (Godden & Helyar 1980; Smilde 1985; Janssen 1998). Which approach is most sensible no doubt depends on which nutrient is considered. Whilst is would be foolish to apply more N than the crop needs due to the likelihood this will be lost (Giller, Cadisch & Palm 2002), building up soil reserves of P may be sensible on some soils that are not strongly P-fixing (Janssen, Lathwell & Wolf 1987; Wolf *et al.* 1987).

Often, fertiliser recommendations based on soil tests are made independently for each nutrient. However, nutrients have interactive effects on crop growth (Fitts & Nelson 1956; Anderson & Nelson 1975) and the expected response to a specific nutrient will only occur if there is no limitation of other nutrients (Janssen 1998; Johnston 2005).

Sometimes the base cation saturation ratio approach is used. Fertiliser requirements of the nutrients K, Ca and Mg are determined based on the deviation from their desired ratio in the soil instead of their individual content. However, according to some authors there is little to no relationship between the cation ratio and fertiliser response, although the method may have relevance for soils that fall within a narrow soil cation exchange capacity range (Johnston 2005; Jones Jr 2012; Hochmuth, Mylavarapu & Hanlon 2014a).

The Quantitative Evaluation of the Fertility of Tropical Soils (QUEFTS) system (Janssen 1990) is based on the results of soil analyses and crop response trials with fertiliser. Once calibrated this method can predict fertiliser requirements based solely on soil analyses. It compares the potential supply and the actual uptake of each nutrient under consideration, and results in a yield estimate for the soil under consideration. This system can be calibrated to different crops and growing conditions (Sattari *et al.* 2014), including plantation crops such as banana (Nyombi *et al.* 2010) and coffee (Maro *et al.* 2014) and can be used to establish fertiliser recommendations.

5.2.3 Plant (leaf) analysis

Plant analysis may be used to determine fertiliser requirements, especially for perennial tree crops (Smilde 1985; Ahn 1993; Jones Jr 2012). Usually leaves are used in the analysis, although other tissues may also be used (e.g. the rachis in oil palm, Foster & Prabowo 2002). The amount of nutrients in the leaf is a measure of the actual nutrient uptake of the plant, and may show a strong correlation with yields (Ahn 1993; Foster & Prabowo 2002). In perennials, nutrient deficiencies can be detected and corrected before they have an effect on production (Smilde 1985; Ahn 1993). As the amount and mass fraction of nutrients in leaves varies depending on factors such as season, physiological leaf age, and position on the plant, standardised sampling techniques are required for each crop, and sampling needs to be done by experienced persons (De Geus 1973; Smilde 1985; Walworth & Sumner 1987). In leaf analysis the total nutrient content is determined (Smilde 1985).

There are different approaches to determine nutrient deficiencies using the results of leaf nutrient analysis. These approaches are based either on the mass fractions of individual nutrients or on the ratios between the nutrients. In the first approach, the mass fractions of each nutrient are compared with established critical values or sufficiency ranges of that nutrient in the crop under study. These values or ranges have been established and calibrated in pot experiments (e.g. the double pot design, Janssen 1974; Smilde 1985) and field trials in a similar way as soil test nutrient indices through analysing the relation between leaf nutrient content and plant response in terms of deficiency symptoms, growth and/or yield (Loué, Verlière & Lay 1960; De Geus 1973; Smilde 1985). In the latter approach, instead of mass fractions per nutrient, the ratios between nutrients are compared to established norms to calculate nutrient indices which indicate the deficiency of each nutrient relative to the other nutrients under consideration. The norms are based on the leaf nutrient ratios of a high-yielding sub-group of a large population. Examples of this approach are the Diagnosis and Recommendation Integrated System (DRIS) method, first developed by Beaufils and using dual ratios (Walworth & Sumner 1987), and the Compositional Nutrient Diagnosis (CND) method developed by Parent and Dafir using multi-elemental ratios (Parent & Dafir 1992).

There is much discussion regarding the use of both methods. The critical value or sufficiency range approach is easy to apply and requires no calculations to determine nutrient deficiencies. However, nutrient mass fractions are influenced by environmental conditions and change as a result of aging. Some nutrient concentrations increase while others decrease under similar conditions, depending on their mobility in the plant and ‘dilution’ effects. This limits the use of foliar analyses for diagnostic purposes, and critical values or ranges can only be applied to plants growing in similar conditions and particular leaves of the same physiological age. However, the ratio of two nutrients which both either increase or decrease in mass fraction will show much less variation, and so will the product of two nutrients when one of them increases and the other decreases under similar conditions. This argues for using indices based on multiple nutrients rather than sole nutrients despite the more complicated method of calculation (Walworth & Sumner 1987).

Both approaches give a direct indication of the nutritional status of the plant. This status is the net effect of variables related to soil, plant, climate and management, hence, it may have a cause not related to soil fertility (Ahn 1993) which will hence not be solved by fertiliser application. As with soil testing, extensive research is needed to go from the results of leaf analysis to fertiliser recommendations, as “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.

Some authors argue that plant analysis is indispensable in calibrating soil tests (Smilde 1985), while similarly, others maintain that plant samples should always be accompanied by soil samples so that results of both analyses can be combined in interpreting them (Jones Jr 2012). In practice, plant samples may also be used in case soil testing facilities are lacking (Smilde 1985; Ahn 1993).

5.2.4 Fertiliser response trials

The most direct way to establish fertiliser recommendations is to test different rates and compositions of fertiliser on the crop under the conditions for which the recommendations are meant, and determine the optimum fertiliser application (which is expected to result in the highest yield or the largest economic benefit). This approach is required to arrive at reliable fertiliser recommendations. Fertiliser trials are required in any case to calibrate the soil and leaf testing methods. Results of fertiliser trials and subsequent fertiliser recommendations are only valid for the conditions under which the trial has been executed. But when combined with soil or plant testing the results of the trials can be extrapolated more widely, for instance using QUEFTS (see *Soil testing*, p38). As trials need to be executed over multiple years to account for residual effects and soil fertility changes and conducting the trials requires heavy investments, the number of sites where trials are executed will usually be limited compared with the need to serve different agroecologies (Ahn 1993).

In order to determine the optimum fertiliser 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 & Nelson 1975; Neeteson & Wadman 1987).

5.2.5 Discussion and alternatives

Objectives of the establishment of fertiliser recommendations for particular crops and regions will be weighed against the costs of achieving these objectives. Often several methods are combined to gain maximum benefit of each method (e.g. Goh 2005). Modelling may be used to reduce research trials required. The cost of trials may be reduced by making use of on-farm research rather than fully controlled trials on agricultural stations. This increases the number of trials feasible to execute and increases the representativeness of the results to farmer field situations, although trials will be less controlled and results will be more variable (Posner & Crawford 1992; Ahn 1993).

Finally, regardless of which method is used to establish a fertiliser recommendation, the actual fertiliser application will be influenced by the farmers' objectives and constraints, and the economics of fertiliser use which must be taken into account when establishing the recommendation.

5.3 Application of methods to establish fertiliser recommendations in cocoa

As seen in *Various fertiliser recommendations*, p35, the amounts and composition of fertiliser recommended in cocoa production vary widely. It is not always clear on what these recommendations were based.

Recommendations 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 & Cohen 1980). Nutrient balances for cocoa systems have been discussed in *Nutrient cycling in cocoa*, p13. Estimates of various nutrient flows differ widely depending on the flow and nutrient under consideration, while some flows have been inadequately quantified. Hence, it is difficult to quantify the amount of nutrients leaving the system. Moreover, as mentioned above, the use of nutrient balances in establishing fertiliser recommendations is highly questionable.

The method used by Jadin and Snoeck (1985) as developed by Jadin (Jadin 1972; Jadin 1975) is primarily based on soil analysis. The fertilisation philosophy used is a combination of the base cation ratio approach and the build-up and maintenance approach, thus also making use of the nutrient balance approach. It is assumed that the optimal ratio in the soil for Exchangeable bases/total N is 8.9, with actual amounts in the soil depending on pH (higher amounts at pH 6 than at pH 5), the optimal ratio between K-Ca-Mg is 8%, 68% and 24%, and the optimal N/P ratio is 2.0. After soil analysis, the amounts of fertiliser which are needed to reach the desired ratios are calculated. The calculation is based on soil volume and density, the difference between the current soil analytical value and the desired value, the amount of oxides needed to overcome this difference, etc. Different factors may be applied to the calculated amounts of nutrients to account for the utilisation efficiency, immobilisation and migration of each nutrient in the soil. For instance, Jadin and Snoeck (1985) set fertiliser use efficiency at 50%. Application per year is set to a maximum, so that it may take several years to reach the desired ratios. Once the desired nutrient balances have been obtained in the soil, these are maintained through replenishment of the offtake of nutrients by harvest. Although part of the calculations are implemented in Excel, using this programme requires substantial agronomic knowledge. Final recommendations are based not only on the theoretically calculated fertiliser required to reach the desired balance, but also on site-specific variables (as derived from the soil analysis), base saturation and presence of P in the soil. The desired ratios used 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. The full data sets from the trials used to establish the ratios are not available in any of the publications cited. The fertiliser trials used to verify the suitability of the Jadin and Snoeck method have made use of different fertiliser regimes at each location (applying the amounts as established according to this method based on soil analyses per plot). Although these fertiliser regimes led to significant yield increases, they were not compared with other fertiliser regimes in the same locations. Hence, it cannot be established whether the fertiliser regimes used were indeed optimal. The research on which the method is based was conducted in Côte d'Ivoire, and the same method has been applied to establish fertiliser recommendations for Ghana (Snoeck *et al.* 2010) and Togo (Jadin & Vaast 1990). More generally speaking, the use of cation ratios is disputable (see above), as is the use of total N and total P (whether used in ratios or as individual mass fractions) to assess soil nutrient availability.

Several authors refer to various critical soil nutrient concentrations for cocoa production (e.g. Wessel 1971; Ling 1990), based on old publications (e.g. numerous authors refer to Wessel (1971), who refers to publications from 1939-1966). It is unclear what research has been conducted to establish these critical soil nutrient concentrations. Even if research at that time was extensive, these critical soil nutrient concentrations need to be re-examined as soil testing methods, cocoa varieties used, cocoa production management and soil conditions have changed. Ling (1990) mentions that there is a lack of data from fertiliser trials, and that there is a 'need to carry out more complete long-term fertiliser experiments to define more precisely the nutritional needs of older cocoa under various environmental conditions.' Little has changed since.

Critical values for leaf nutrient analysis are also referred to (*Box 2: Cocoa leaf analysis: sampling and critical ranges*, p43). These values are nearly always based on the research of Loué and Murray (publications 1961-1966). 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. Wessel (1971) established preliminary fertiliser recommendations depending on leaf nutritional status, but suggested they are only valid for mature Amelonado cocoa on soils derived from metamorphic igneous rock in Nigeria. 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 high 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. 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.

Both the application of DRIS and of CND in cocoa production are currently under research (personal communication Didier Snoeck (February 2015) and Laurence Jassogne (March 2015)), but its relevance has yet to be affirmed. A major drawback of the use of foliar analysis in cocoa is the importance of the timing and procedure of sampling. As long as there is no agreement on a standard sampling procedure results across studies cannot be compared. Currently, leaf analysis cannot be used to derive fertiliser recommendations for cocoa, although it may be useful to give an indication of prevalent nutrient deficiencies.

5.4 Box 2: Cocoa leaf analysis: sampling and critical ranges

The first part of this text is primarily based on Wessel (1971)

The nutrient content of the cocoa leaf depends on many factors besides the adequacy of availability of the nutrient in the soil, so conclusions regarding nutrient deficiencies may be misleading when only based on soil analysis. Leaf nutrient content depends, amongst others, on leaf age, the development of new leaves and fruit bearing, light intensity and seasonal effects.

The leaves sampled should be of the same age to derive nutrient norms. 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 colour is also unsuitable. The petiole colour may be the most useful for age determination, but only for young leaves of the last flush. Generally, the absolute content of N, P and K increases in the first weeks of leaf growth after which there is a progressive decrease, while when expressed as a percentage of fresh weight, N and Ca increase with age while P and K are more or less constant, although this depends on light conditions. The changes in leaf nutrient content over time may be influenced by the development of new leaves and fruit bearing. The decrease in nutrients after the first weeks (9-10 weeks) may be caused by the transfer to the leaves of new flushes which started to develop around that time and/or reduced uptake of the nutrients for the same reason. Wilting of young pods at the time of or immediately following leaf flushing, and nutrient 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 influences the nutrient content of leaves, as 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. For instance, 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, while Ca concentrations varied inversely, and Mg either varied little (Ghana) or followed the Ca trend (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 and to a lesser extent from mid-December to mid-January.

Drawing conclusions based on leaf analysis is further complicated by the fact that a deficiency in one nutrient may also affect the uptake and concentration of other nutrients. For instance, increases in soil N depress leaf K content, increases in soil P and K depress leaf N content (but only at high light intensities) and increases in soil N and K depress leaf P.

Based on his findings, Wessel (1971) suggested norms for cocoa leaf N and P content at different ages and times of year. Young leaves sampled are second and third fully green leaves of the last flush below the apex of fan branches, older leaves are leaves directly adjacent to these.

Nitrogen

April/May	Young leaves	N <1.8%	very N deficient trees
		N 1.8-2.0%	moderately and non-N deficient trees
	Older leaves	N<1.6%	N-deficiency
August/September leaves		N<1.7%	N-deficiency

A low N:P ratio can also indicate N-deficiency:

N:P ratio <9: severe N deficiency
N:P ratio 9-10: moderate N deficiency
N:P ratio 10-11: no N deficiency

Phosphorus

April/May	Young leaves	Of dry weight	<0.16%	severe P deficiency
			0.16-0.20%	moderate P deficiency
			>0.20%	no P deficiency
		Of fresh weight	<0.060%	severe P deficiency
			0.060-0.070%	moderate P deficiency
			>0.070%	no P deficiency

Old leaves	Of dry weight	<0.11%	severe P deficiency
		0.11-0.13%	moderate P deficiency
		>0.13%	no P deficiency
	Of fresh weight	<0.040%	severe P deficiency
		0.040-0.050%	moderate P deficiency
		>0.050%	no P deficiency

For August/September and January leaves, no distinct critical values were found, but no deficiency is likely to occur if P concentrations are 0.18-0.19% of fresh weight or 0.060-0.065% of dry weight.

N:P ratio > 11 on non-N-deficient sites indicates P deficiency in all sampling periods. In older April/May leaves the N:P ratio should be above 14.

Wessel (1971) concludes that leaf analysis is mainly useful for detecting and identifying pronounced nutrient deficiencies. A range of optimum concentrations has to be established for different leaf ages and shade intensities. Even then it will be difficult to use the analysis to establish a quantitative fertiliser recommendation, especially in small farms where trees are highly variable.

Acquaye (1964) acknowledges that the variability in nutrient concentrations of leaves arises from many other factors besides the supply of nutrients in the soil (similar to those pointed out by Wessel 1971). However, he remains 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, the experiment did not include soil and yield analyses, and no critical concentrations were derived or applied, hence the results cannot be used to establish fertiliser recommendations. 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 such a publication.

Table 15. Normal, low and deficient concentrations (%dm) of nutrients in cocoa leaves as stated in De Geus (1973).

Nutrient	Normal according to Murray	Normal according to Loué	Low according to Murray	Moderately deficient according to Loué	Deficient according to Murray	Severely deficient according to Loué
N	>2.00	2.35-2.50	1.80-2.00	1.80-2.00	<1.80	<1.80
P	>0.20	>0.18	0.13-0.20	0.10-0.13	<0.13	0.08-0.10
K	>2.00	>1.2	1.20-2.00	1.00-1.20	<1.20	<1.00
Ca	>0.40		0.30-0.40		<0.30	
Mg	>0.45		0.20-0.45		<0.20	

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 if a marked deficiency exists, the small concentration in the leaf will override problems of sampling and indicate the type of fertilizer required to correct the deficiency. Apart from the concentrations found by Wessel (1971), De Geus (1973) in his book presents critical levels established by Murray (1966) and Loué (1961) which are also referred to by Wessel (1985), see Table 15. Both De Geus (1973) and Wessel (1985) note that the concentrations set by Loué are probably for somewhat older leaves than those of Murray, although these authors did not specify the age of the leaves.

Von Uexküll and Cohen (1980) refer not only to the difficulty of obtaining representative and reproducible leaf samples, but also to the problems with varying 'critical' values depending on nutrient capacity/intensity factors, soil moisture, evapotranspiration, the amount of climatic and artificial shade, etc. The general guidelines for leaf nutrient content they proposed were the same as those of Murray (1966) (see Table 15).

More recently, various authors have mentioned the use of leaf analysis for detecting nutrient deficiencies in cocoa. Nelson *et al.* (2011) for their research in Papua New Guinea refer to Wessel (1985) as their source of critical values, which are most likely the values of Table 15. They base their conclusions regarding the nutritional status of cocoa in Papua New Guinea on comparison of nutrient content of their samples with these values, in combination with similar comparisons for soil samples. For P and K there was a reasonable relationship between soil and leaf nutrient concentrations, although the K concentrations in leaves were often not below the critical concentrations while those of the soils for the same site were. For other nutrients, no relationship was found between soil and leaf nutrient concentrations. A possible explanation for the discrepancy for K given by the authors is that widespread N deficiency may have been more limiting and masked the expression of K deficiency in the leaves. However, Pushparajah (1994) argues the opposite: that uptake of K in crops can be reduced by lack of N. In the same article by Pushparajah (1994), it is stressed that to obtain best results, analytical data of soil and leaf samples should be used together with other criteria, in particular the environmental and growing conditions (soil type, slope, rainfall, soil cover etc.), physiology of growth and productivity, yield, nutrient requirements of the crop, experimental data from fertilizer trials, and nutrient balances. The ranges of values of N, P and K in cocoa leaves and soil and guides to fertilizer rates referred to in this article (Table 16) are based on Ling (1989). Unfortunately this publication is not accessible, but in a different publication than the one referred to (Ling 1990), a similar table with only slightly different critical nutrient values is presented. Desired leaf N concentrations are somewhat higher than those in Table 15, while concentrations for P and K are similar.

Table 16. Range of values of N, P and K in cocoa leaves and soil, and guide to fertilizer rates (from Ling 1989 in Pushparajah 1994).

	Nutrient content		
Nutrient	In leaf (%)	In soil[1]	Fertilizer rate (kg/ha)
N	<2.0	-	100-150
	2.0-2.6	-	60-80
	>2.6	-	Nil
P	<0.2	<15 mg/kg	40-70
	>0.2	<15 mg/kg	15-30
		>15 mg/kg	Nil
K	<2.0	<0.3 cmol/kg	100-150
	>2.0	<0.3 cmol/kg	70-80
		>0.3 cmol/kg	Nil

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

Aikpokpodion (2010) also uses both soil and leaf samples to analyse nutrient dynamics in cocoa soils. The critical values used for concentrations of nutrients in leaf samples are 0.9% N, 0.2% P, 2.0% K, 0.6% Ca and 0.5% Mg, which is much less for N but larger for Ca and Mg compared with Table 15. Critical values are based on Egbe, Olatoye and Obatolu (1989, unpublished but cited by Aikpokpodion 2010). Again, a discrepancy is found between soil and leaf K concentrations, this time with K concentrations in leaves nearly always being below the critical value, while those of the soils had K concentrations well above the critical concentration of K in cocoa soil used (the opposite of what Nelson *et al.* (2011) found). For other nutrients, the results for comparison of both leaf and soil concentrations with critical values were comparable, with N and Ca concentrations being adequate in both leaf and soil, and P and Mg concentrations being mostly inadequate.

Of numerous fertiliser regimes recommended by various authors, countries and organisations, it is unclear what scientific research has been conducted to arrive at them. It seems the this research is limited. In some cases, there is differentiation among regions or soils, but often recommendations are generalised for a whole country, despite the diversity of conditions under which cocoa is produced (Table 17).

Table 17. 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. From the 2001/2002 IITA STCP producer survey in Gockowski and Sonwa (2011) ***Note: 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 tree/ha), or changes in the production systems over time.***

	Cameroon	Côte d'Ivoire	Ghana	Nigeria
	Proportion of farms			
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%

Table 14 (p37) shows the official national fertiliser recommendations in Côte d'Ivoire by CNRA (Centre National de Recherche Agronomique) and in Ghana by CRIG (Cocoa Research Institute of Ghana). According to Snoeck et al. (2010), and based on the Soil Diagnostic Method, the recommendation is optimal for only 6% of the cocoa soils in Ghana, although it would have a positive impact on about 55% of the soils (Figure 11). This application is recommended for hybrid cocoa planted at 1,111 trees/ha with a maximum shade density of 12-15 trees/ha, but adoption of the full package including low shade and hybrids is limited (Gockowski & Sonwa 2011). According to a Ghanaian field survey, there was no difference in the fertiliser use between type of production system (largely based on shade tree management) (Gockowski & Sonwa 2011) while this should be taken into account when establishing fertiliser needs.

Some of the specific gaps in knowledge which may help in establishing farm-level recommendations are discussed in Section 6: *Knowledge gaps and recommended research*, p47.

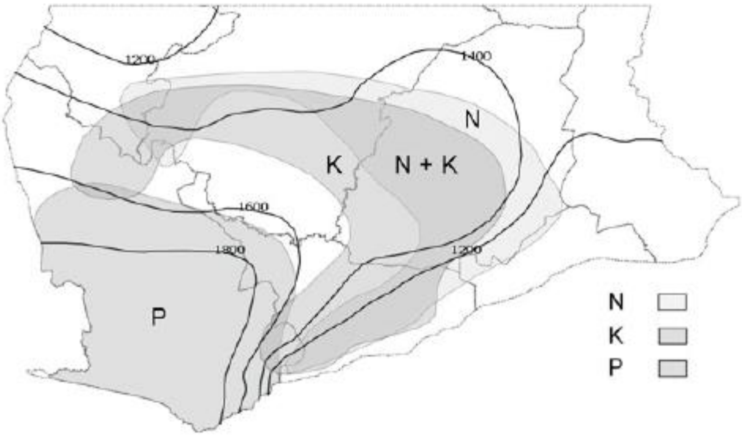

Figure 11. Areas in Ghana where N, P, K needs are greater than the current recommendation when computed by the soil diagnostic model. From Snoeck *et al.* (2010).

6 Knowledge gaps and recommended research

6.1 Current understanding

Cocoa yields much less than what we know to be attainable in most of the cocoa producing regions. A main aim of the cocoa sector is to increase yields in a sustainable way to meet the growing global demand for cocoa. As for all crops (van Ittersum & Rabbinge 1997), several factors together determine the actual yield of cocoa. 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. For instance, although yields of cocoa in Ghana can be as high as 5,000 kg/ha when nutrient limitations are overcome and pests and diseases controlled, the national on-farm average yield is estimated at around 400 kg/ha. This yield gap may be decreased by addressing the limiting and reducing factors with yield increasing and yield protecting measures. As soil nutrient content in many cocoa growing regions is poor, an obvious way to increase yields is to address the nutritional needs of cocoa through fertiliser. However, the effects of fertiliser application will remain limited without good crop management including shade management and phytosanitary measures.

There is a strong cycling of nutrients within cocoa systems and the amounts of nutrients removed through harvest are relatively small. Yet cocoa production still leads to depletion of soil nutrients in the long term. Whereas upon establishment of the cocoa in West Africa, soils were fertile due to the nutrient build-up under forest, many of the soils under cocoa production are no longer able to provide the cocoa with the nutrients required to obtain high yields. Several trials have shown that the application of fertilisers can greatly increase cocoa productivity. However, there are large differences in yields and fertiliser response between different trials, regions, plots and even individual trees. The effects of the application of fertiliser 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 fertilisers 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, fertiliser response is less, but the yield decline is also less severe. However, the causal relations between the factors mentioned above and yields and fertiliser response, and the fertiliser response to different nutrient applications are poorly understood.

6.2 Research base

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 fertiliser 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 fertiliser 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, leaf area index 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 is lacking from many experimental reports. 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. Moreover, the long-term effects of fertiliser 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 (fertiliser) recommendations.

Current fertiliser 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. For instance, current fertiliser recommendations for cocoa production in West Africa omit N. One possible explanation why no N is recommended for cocoa could be that at the time the recommendations were established, cocoa was grown under shade on relatively fertile soils that had not been long under cultivation.

6.3 Knowledge gaps

6.3.1 Cocoa tree physiology

Physiological insights of the mechanisms underlying the constraints to cocoa yield and response of the trees to nutrients under different conditions are lacking. A better qualitative and quantitative understanding of cocoa physiology would allow further development of the cocoa growth model of Zuidema and Leffelaar (2002). The dearth of experimental information prevented these researchers from building nutrient limitations into their model. More fundamental knowledge regarding cocoa tree physiology is crucial to understand how current yields can be increased. Some examples where knowledge is lacking and further research is required are:

- Quantitative understanding of the uptake and use of nutrients, not only of N, P and K but also of secondary macronutrients (Ca, Mg, S) and micronutrients (e.g. Mn, Fe, Cu, Zn, B, Mo)
- Interactions among nutrients throughout the cocoa life cycle
- Effects of nutrients (especially of different forms of N) on pest and disease incidence
- Rooting density and distribution in different soils, and influence of pruning on rooting patterns and density
- Water-responses to both waterlogging and drought stress and their interaction with nutrition
- Causes of production decline and senescence in aging trees, especially in unshaded trees
- Causes of phenotypic variability between trees within a single field
- Conditions affecting leaf flushing dynamics
- Conditions affecting cherelle wilt
- Variation among cocoa varieties in the above processes

6.3.2 General crop management

Besides application of inorganic fertilisers, other management practices have an effect on cocoa yield through influencing nutritional aspects of cocoa production. Fertiliser application will be ineffective and unprofitable as long as correct practices are not in place, as the trees need to be in the best condition to respond to added nutrients. Management practices will influence factors such as radiation and water and nutrient availability, thus affecting several of the physiological processes in the cocoa tree mentioned above. Management can affect soil properties (see *Soil properties in cocoa production systems*, p7) and nutrient cycling (see *Nutrient cycling in cocoa*, p13) in cocoa production systems. The effects of management practices on yields and fertiliser response and their interaction with each other and with other conditions (such as climate and soil characteristics) remain poorly understood.

6.3.2.1 Effects of shade management

Perhaps most relevant in cocoa production is the effect of shade management. It is known that cocoa requires shading at least in the first years of establishment. However, the advantages and disadvantages of shade for mature cocoa are hotly debated. The effects of shade trees are not only caused by a reduction of incident radiation, but through effects on wind, moisture, nutrient availability, etc. These variables also vary with climatic conditions. Examples of some effects of shade trees which are not well understood are the differences in response to specific nutrients under shade, and the effects of shade trees on decomposition. It is not known what is the optimal degree of shade – and of which trees – under different conditions. Pruning of the cocoa tree canopy will to some extent influence the same variables (though usually in the opposite direction), and in addition will influence other variables within the trees such as nutrient and biomass allocation and leaf flushing. In the case of coffee production in full sun, overbearing will lead to a risk of die-back when the trees are not pruned. It is not clear whether this is also the case for cocoa trees.

Measurements of yield-influencing factors under variable shade conditions could assist in unravelling the effects of shade trees and pruning on cocoa production (see also *Research base*, p47). These measurements are likely to be more informative in explaining yield effects than the current ‘quantifications’ of shade levels (expressed for instance in percentage of full sunlight or shade tree density), which are difficult to interpret and compare. Important in this respect is a characterisation of the shade trees used in cocoa production systems. Characteristics such as ability to fix nitrogen, canopy height and density, rooting depth and density, seasonality of leaf and litter production, etc. will determine the effect of the shade trees through their effect on the variables influencing yield.

6.3.2.2 Other management practices

Good crop management to ensure healthy cocoa trees is needed to ensure the efficient use of added nutrients, to reduce the pest and disease pressure, and to prevent loss and damage to the developing pods. Given the wide variability of planting material, age of the trees, past management of the cocoa trees and degree of shade on smallholder farms in West Africa (Table 17), it is not easy to arrive at simple recommendations for practices such as pruning and weeding. Several reasons to prune fruit trees are to obtain the desired tree shape, for sanitary reasons, and to maximise new wood production to support the subsequent crop and prevent overbearing. Optimum pruning practices for cocoa appear not to be well established. By analogy with oil palm management, smallholders often practice clean weeding, whereas especially during the establishment phase, weed cover may be beneficial in preventing soil erosion and in retention and recycling of nutrients. Selective weeding to prevent establishment of highly-competitive weeds is needed. Once the cocoa trees are mature, ground cover is likely to disappear due to shading and is no longer necessary as a litter layer will have formed on the soil surface. A better understanding of the possible impacts on cocoa nutrition of pests, diseases and weeds, and possible interactions among these factors is required.

6.3.2.3 Use of organic manures

Where organic manures are available in sufficient quantity they are likely to be a useful resource for smallholders (see also *Alternative fertilisers*, p33). A better understanding of the nutrient composition and availability of organic fertilisers within the cocoa producing farms and surroundings would be useful to explore whether this is a viable option. In the majority of African farming systems the quantities of organic manures available are usually too small to supply all nutrient demands of crops (Vanlauwe & Giller 2006).

6.3.3 Methods available to determine nutrient deficiencies and fertiliser recommendations

We lack basic information on critical soil or leaf-tissue concentrations for cocoa (*Variability in soil suitability criteria*, p7 and *Application of methods to establish fertiliser recommendations in cocoa*, p41). Attainable yields and the nutrients required to obtain them vary according to different soil, climatic and management conditions and depend on characteristics such as the age of the cocoa tree, but relationships have not been robustly quantified. There is no consensus on the best sampling methods of leaves for nutrient analysis. The nutrient composition of cocoa leaves has shown only weak correlation with yields. ‘Critical values’ for cocoa leaf and soil nutrient composition are often referred to, but these seem to be based on limited and outdated research. Although both soil and leaf analysis can give an indication of the most important nutritional limitations, they cannot be used to derive fertiliser recommendations for cocoa production without calibration using dose-response trials. Methods to derive nutrient deficiencies and fertiliser recommendations based on soil and leaf analysis which have been applied to other crops (e.g. QUEFTS, see *Soil testing*, p38 and CND, see *Plant (leaf) analysis*, p39) have not been developed for use in cocoa. Given the wide variability in soils and other conditions which affect nutrient requirements across the cocoa production areas, it is likely that fertiliser recommendations need to be tailored to local conditions. However, with the methods currently available to determine nutrient deficiencies, fertiliser recommendations are likely to continue to be highly generalised blanket recommendations.

6.4 Research requirements

It is clear that fertiliser application has the potential to greatly increase cocoa productivity. However, with the knowledge currently available, it is not possible to come to suitable fertiliser recommendations for farmers who produce cocoa under a wide variety of conditions. Different types of research are recommended to complement the knowledge currently available.

6.4.1 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 fertiliser response. Variables such as amount of radiation reaching the cocoa trees, cocoa canopy cover, leaf area index, plant nutrient concentrations, temperatures, rainfall and soil description and chemical and physical analysis can be used as explanatory factors in analysis of yields and fertiliser response. Taking measurements of these variables is essential to unravel the effects of 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 fertiliser applications under different conditions. This will be of great use in tailoring recommendations to site-specific conditions. When conducting on-farm trials to examine fertiliser response, basic sanitation and pruning measures must first be addressed to minimise pest and disease problems and ensure that the crop response to fertiliser will be optimal.

6.4.2 Socio-economic analysis

Although this review has focused mainly on the agronomic aspects of nutrition in cocoa production, it is highly important not to lose sight of the socio-economic context in which this cocoa production occurs. The socio-economic conditions under which the farmers operate are highly diverse and are related to the diversity in the methods and management of cocoa production. Each farmer has alternative sources of income and options to invest time and money besides cocoa production. Even if the agronomic effects of different (fertiliser) management practices are understood, it is crucial to understand the trade-offs of these practices for the farmer and their relative profitability. Only then can fertiliser-ready farmers be identified and recommendations established which will be adopted by farmers to sustainably increase cocoa productivity.

6.4.3 Multifactorial fertiliser 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 five years of production. The role of secondary nutrients (S, Ca, Mg) and micronutrients (notably B, Zn) must also be considered. Such trials would enable the collection of robust data on cocoa yield response to fertilisers 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 fertiliser 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.

Concluding remarks

We provide a thorough review of published scientific knowledge regarding the role of mineral nutrition in cocoa production. We hope that the identified knowledge gaps will be an inspiration to (further) develop a joint research agenda of the partners of the Cocoa Fertiliser Initiative and all others who are interesting in increasing the productivity of cocoa. This is clearly required both to secure supply to meet increasing demands and to improve the livelihoods of the smallholder farmers. The research requirements as put forward in this review can serve as a guideline towards the different directions that the research could (and, in our view, should) take in order to be able to derive grounded fertiliser recommendations, suited to different conditions, and support the sustainable production of cocoa.

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