Chapter 4
Cacao Nutrition and Fertilization

Didier Snoeck, Louis Koko, Joël Joffre, Philippe Bastide, and Patrick Jagoret

Abstract Cocoa is globally the third agricultural commodity traded in terms of value. The cocoa world production is relatively stable since 2010, amounting to around 4.5 million tonnes. Eight countries account for 90 % of the cocoa production, of which four West African countries. Under traditional cultivation practices, cocoa yields are poor with an average of ten fruits per cacao (*Theobroma cacao* L.), even though it has a potential to yield more than 100 fruits. As for most tree crops, the yields are depending on many factors, of which the more important are planting material, climate, cultural practices, and soil. Cacao is cultivated on many types of soil, and in various conditions, from agroforestry systems to full sun. Soil degradation and low soil fertility are among the main causes of low cocoa productivity. However, despite this inherent low fertility, most of the cocoa farmers do not use fertilizer because they are not well informed of the agricultural and fertilizers issues.

Here we first review why fertilizers are used and how to optimize their effects, particularly farming practices and soil fertility management in full sun or shaded plantations. Secondly, we describe soil diagnosis and the foliar diagnosis, the two complementary approaches that were developed to assess the nutritional needs of cacao. The soil diagnosis provides a means to improve soil nutrient availabilities, while foliar diagnosis provides information on the cacao health. Third, we review the methods used to design fertilizer formulae and doses, and how they are calculated. Fertilizer inputs and mode of application are determined from the local conditions and farming practices. Finally, we review the effects of nutrients on the characteristics of the cocoa tree and cacao product. Finally, some current issues are discussed, such as the use of advising a single formula for a whole region or country and how to develop adoption of fertilizer by cocoa farmers.

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4.1 Introduction

Cacao (*Theobroma cacao* L.) is a tree native to the Amazonian forest. It is grown for the pods that contain the beans from which chocolate is made. The economic importance of the cocoa sector has been amply demonstrated. For example, World cocoa production today is about 4 million tons yearly, of which 75 % are produced in Africa (ICCO 2015). Cacao is grown in 70 countries, all located in the tropical belt and provides livelihoods for more than 5 million small farmers (Rafflegeau et al. 2015). So this is basically a smallholder agriculture which, since the 1990s and the liberalization of the sector in many countries, suffered the brunt of the fluctuations of the world market. In terms of agriculture, this crop is characterized by relatively low productivity and a displacement of the production areas. Indeed, after 20–30 years of cultivation or even less, cocoa plantations installed after a forest clearing must be regenerated because of the depletion of soil fertility and biological decline of cacao trees in the absence of adequate pest and disease control and mineral fertilizers (Ruf 2009). At the same time, a consequence of the improvement of living standards in emerging countries like India, China, Brazil and Russia, is the increasing demand for cocoa. According to the International Cocoa Organization, experts estimate that around 2020–2025, one extra million tons of cocoa will be needed to meet consumers' demand (ICCO 2015). To achieve this goal, to secure the supplies and increase the sustainability of current cacao growing areas in order to limit the impact of this crop on the environment, recent initiatives have been launched to provide support to farmers, especially in terms of fertilizing cocoa plantations (Adjehi 2014; IDH 2014).

Under traditional cultivation practices, cocoa yields are poor with an average of ten fruits per cacao, which is very low for a crop that has a potential to yield more than 100 fruits per tree (Aneani and Ofori-Frimpong 2013). The yields depend of many factors, of which the more important are environment, climate, cultural practices, and the soil. Among these, management practices have to take into account that the cacao is cultivated on many types of soils, either in agroforestry systems or in full sun. Moreover, after many decades of cacao cultivation and changing generations of cocoa farmers, soil fertility and available cultivation areas per family are shrinking. Finally, soils are getting depleted because of continuous cropping with little or no added inputs.

Both cacao growers and development experts know how much the cacao plots are getting degraded and need fertilisation to replenish the soil nutrients and recover their production levels and income. Conversely, the mechanisms for adopting fertilizers and their impact are widely ignored. Now, after many years with very little use of fertilizer linked to low prices and low income from cocoa, the cacao growers are willing to increase their production, especially in countries where cacao is mostly grown under full sun or very low shade, as it is the case in Côte d'Ivoire and Ghana.

Fertilisation is therefore a major issue for the future of cacao cultivation and cocoa farmers (Ruf 2012).

Being a shade plant, the ecological requirements of cacao are quite adapted to many regions in the humid tropics. Altogether, cacao turns out to be a plant that can adapt easily to various growing conditions and to many soil types (Smyth 1980), as long as the nutrients can be provided to correct the soil nutrient levels and balances (Jadin 1975). Initially, cacao was grown under shade, but scientists quickly realized that productivity was much better when the trees were grown in full sun (Alvim 1965; Beer 1987). Thus, research has favoured intensive models based on the use of selected varieties, vigorous hybrids, conducted on total forest clearings or light shade and high use of inputs. The example of the Cocoa High Technology Program developed in Ghana in the early 2000 has underlined that such systems allow to obtain high yields. With the help of the project, yields of exceeding one ton of cocoa per hectare could be achieved during a period of more than 10 years thanks to good management, improvement of the soil fertility and reduction of parasitic pressure, following a clearing of the number of shade trees.

The objective of this paper is to review research findings from Africa, Asia, Latin America and the Pacific regions with the aim of coming up with suitable answers to the questions raised by cocoa farmers about fertilization, particularly on how to supply the soil nutrients in correct and balanced amounts to improve and maintain optimal yields on the long term.

4.2 Cacao Nutrition and Nutrient Requirements

To provide adequate and balanced nutrient amounts to support the cacao growth and yields, researchers and development agents need to consider the cacao needs, the current available soil contents and how these soil nutrients can be made available to the cacao tree.

Each plant species has its own nutritional needs and ways of taking up nutrients from the soil. Plant tissues are made up of a number of elements, 16 of which are essential for their physiological development. Three of these, carbon (C), oxygen (O), and hydrogen (H), can be supplied by the atmosphere and water or taken up from the soil. The other 13 can only be absorbed as mineral nutrients from the soil through plant roots. These 13 nutrients are divided into macronutrients that are required in large quantities: nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulphur (S) and into micronutrients that are required in micro quantities: manganese (Mn), boron (B), iron (Fe), zinc (Zn), copper (Cu), aluminium (Al) and molybdenum (Mo).

Each soil has different amounts and balances of nutrients. Their availability depends on many factors, but primarily the origin of the parental material and its geological and pedological development. Soil origins are wide ranging, from basaltic soils in Brazil to granitic gneiss and schist soils in Africa or sedimentary or metamorphic soils in Trinidad (Verlière 1981). Consequently, the soil pedology parameter is essential to determine the types of available nutrients and to calculate their amounts to meet cacao requirements. The initial soil fertility may have to be adjusted. More specifically, the soil nutrient availability varies with the type of soils, but also with regard to its ease of being taken up by the cacao in relation with the soil cation exchange capacity (Jadin 1975; Loué 1961). Light, soil moisture and associated crops also influence the soil fertility (Afrifa et al. 2009; Ahenkorah et al. 1987; Somarriba et al. 2001; Wessel 2001). The structure, texture, fertility and nutrient availability of a soil depend also on its history. Some important factors influencing the evolution of soil are described below.

The purpose of fertilization is to feed the crop and refill the missing and exported nutrients and achieve the optimum nutrients balance for maximum, sustainable cocoa production. Once the right balance is reached, fertilization has to be continued to maintain the optimum quantities and combinations of ingredients in the soil to replace the nutrient removed by the cacao. For fertilization to be effective, it is essential that all required nutrients are present in the soil (naturally or introduced) and in an available form that the plant can take up. This requires an adequate choice of fertilizer formula, an healthy root system, and conditions favourable to the uptake, especially climate (Hartemink 2005).

The balance between available nutrients supplied by the soil and the demand of the plant will determine the nutritional quality and thus the extent to which the cacao will benefit in each cultivation system. Indeed, even in case of severe deficiency, the only correction of this deficiency is not sufficient to improve yield and the effects of interactions between nutrients are often superior to the effects of nutrient taken alone (Verlière 1981).

4.2.1 First Research Results

The need to fertilize cacao has been known since the time when high yielding cacao trees were first grown in commercial plantations. The first fertilizer trials are found in Trinidad in the 1930s (Mac Donald 1934), then in Cameroon and other countries (Loué 1961). These first results highlighted the strong interaction between fertilization and shade showing that cacao without shading, but with fertilizer inputs, can give huge returns. In the beginning, the trials focused on the effect of each nutrient supplied separately. Trials in Ghana have shown that, under shade, soluble P can increase yields by 20 %, but no response were found for N, K, Ca, Mg and micronutrients (Cunningham and Arnold 1962). Other trials in Côte d'Ivoire have also found that N has no effect when cacao is grown under shade and that the fertilizer should mainly contain P and K, with K being effective only if P levels are correct. Positive effects of Ca and Mg on yields were also observed, but to a lesser extent (Verlière 1965). Later, Murray (1965) showed that, if K fertilization was not efficient on cacao grown under shade, it was because high K contents under shade are common in Trinidad. However, in full sun, it is the combination of N–K inputs that predominates in the choice of nutrients to be used in the fertilizer formulae.

To determine the nutrients requirements, researchers have started investigating the foliar diagnosis as a mean to assess yield requirements. In 1935, the first article on foliar diagnosis was published by researchers having worked at the Trinidad Imperial College of Tropical Agriculture on a shaded NPK trial (Hardy et al. 1935). The authors observed that best yields were obtained with relatively high levels of leaf K compared to N or P. Later in Costa-Rica, leaf content differences were found between treatments in a fertilizer trial, but only at particular periods of the year (Machicado and Alvim 1957). The correlations between leaf nutrients levels and the cocoa yields were described by Verlière (1965) who could also determine the best period to sample the leaves. His results confirmed previous works done in Trinidad showing that the growth of pods is the most demanding period in nutrients, which are partly derived from the leaves, but no direct correlation is possible. Similar observations were also found in Ghana, Côte d'Ivoire, Nigeria, Malaysia, Colombia, Ecuador, West Irian, DR Congo, São Tome and Brazil (Eernstman 1968; Murray 1965; Wessel 1971).

Verlière (1981) also assessed how ratios between leaf nutrients can be correlated two by two with the plant health or soil nutrients. The studies were done first in a green house on sandy soil receiving various amounts of nutrients, then in fertilizer trials planted in areas of various geological origins. In these trials, the nutrients were added independently one by one. He found that K fertilizer increased significantly leaf K, Ca and Mg, but significantly decreased Cu; Ca fertilizer increased K, Mg but decreased N, P, Cu; Mg fertilizer increased nothing, but decreased K, Ca, Mg; high K/Ca ratio was significantly associated with higher P, Ca, Mg, Cu but low K; high K/Mg ratio was significantly associated with higher Ca, Mg, but low K; high Ca/Mg ratio was significantly associated with higher Mg, but low K, N, Cu.

However, despite the interest of the foliar diagnosis method, Verlière (1981) felt that the method suffers from major limitations that hamper its use. Particularly, he reported that:

– Cacao is very tolerant with respect to the soil. The wide range of soils on which cacao trees are grown obviously implies variations in nutrient absorption, so a broad range of mineral compositions may be observed in cacao trees without major variations in cocoa yields.
– Vegetative and generative activities of cacao trees have very different rates compared to those normally found in many other crops. Equally, the leaf nutrient content is influenced by fertilization, shade, rain, light, temperature, sunlight, evaporation and pod maturation.
– The period when the leaf is sampled is the main factor of variation in leaf mineral composition, even if a leaf of the same age growing in the same position relative to the branch is sampled. It is thus difficult to predict if the tree has enough reserves to produce a large harvest.
– As cacao is cauliflorous, the maximum of pods is located between the roots and the leaves and intercept part of the nutrients before they reach the leaf. Thus, pods may receive sufficient mineral nutrients for their growth while the leaves may not and analysing the leaves may suggest deficiencies that do not influence yields. There may also be serious competition between the cambium of the trunk and branches, pods and leaves for food, growth substances and water. This is

why some researchers have tested using bark as an indicator of pod yields (Humphries 1950; Moss 1964). However the technique had not much success and was abandoned after Verlière (1981) demonstrated good relationships between foliar diagnosis and all other parts of the tree (leaves, branches, trunks, roots) for K, Ca and Mg.

All of this shows that standardization of leaf sampling and its relation with cocoa yield is quite difficult. Particularly, the mineral content of cacao leaves can adapt to light conditions (Cunningham and Burridge 1960; Lachenaud and Oliver 1998). Shaded leaves are able to use very low light while sunlit leaves seem to have an internal resistance to the penetration of light rays. By acting on leaf size, shading causes a dilution effect in the nutrients levels without the total quantity of these necessarily being reduced. Depending on its position on the cacao foliage, a leaf can have diverse foliar density and nutrient levels (Bastide and Jimmy 2003). Cacao leaves also vary greatly with the environment. The leaf chemical content follows the rainfalls distribution and seasons in relation with leaf flushes.

Finally, most researchers found that foliar diagnosis is insufficient to be used as a means to determine the cacao fertilization requirements and that the use of soil testing is preferable For example, Murray (1967) wrote that: “Despite the work that has been done, we must accept the fact that foliar diagnosis is of limited value to plan a cacao fertilizer program”. Similarly, Wessel (1971) wrote that the main advantages of the cacao leaf analysis are the detection and identification of nutritional deficiencies and its assistance in interpreting the results of fertilizer trials.

Researchers then focused on soil diagnosis with the objectives to correct the soil nutrient deficiencies and imbalances, firstly to enhance cacao yields and secondly to adapt the soil before planting cacao in new land envisaged for growing cacao. There is need to add nutrients in order to tailor the soil composition to meet cacao requirements. This generally means increasing the nutrient content and correcting the balance between the main cations. It also entails eliminating the toxic effects of nutrients, such as aluminium, manganese or iron, in acidic soils. Fertilizer trials have been carried out in all cocoa producing countries. They have shown that good correlations exist between cocoa yields and soil nutrients levels, thus confirming that the method is well adapted for cacao growing and production improvement (Appiah et al. 2000; Wessel 1971; Ahenkorah et al. 1987; Bénac and Dejardin 1970; Morais 1998; Ojeniyi et al. 1982; Paviot 1977; Santana et al. 1971; Souza Júnior et al. 1999b; Tossah et al. 2006; Wyrley-Birch 1987).

However, despite the many limitations described above, foliar analysis remains a practical tool for detecting nutrient deficiencies, and particularly in the field through visual diagnosis (Machicado and Alvim 1957). The authors concluded that it is a good option to combine both approaches: (1) the soil diagnosis for soil correction, to assess the need for fertilization and to calculate the most suitable fertilizer formula and dose and (2) foliar diagnosis for information on the cacao status and direct overview of imbalances and fine-tune the fertilizer recommendations.

4.2.2 Soil Diagnosis

The principle is based on the fact that the crop feeds from soil nutrients, which have to be available in the soil in diversity and amounts required by the crop. The required thresholds were previously determined from fertilizer trials setup in different regions of the country.

Three methods are currently used for fertilizer calculations: (1) based on thresholds (most of the cacao growing countries. (2) Based on soil nutrient thresholds and the ratios of some specific nutrients; this method is developed in Brazil, mainly and described below (Sect. 4.2.2.1). (3) Based on soil nutrient thresholds and the ratios of all nutrients; this method is developed in Sect. 4.2.2.2).

A fourth method using a combination of both some soil and leaf nutrients also exist; it has been developed in Malaysia only. It is described in Sect. 4.2.4.

4.2.2.1 Method Based on Soil Nutrient Thresholds and Ratios

The method consists in calculating more or less precise fertilizer formulae that are designed to fill in the missing nutrients due to exportation revealed by soil analysis to compensate for nutrient deficiencies. The required thresholds obtained from fertilizer trials were used to draw up tables giving lower or upper thresholds. The recommendation is then to correct the soil assuming that cacao growth and productivity will be optimum if each of the nutrients (macro and micro) is in between these limits. Standards were developed in Côte d'Ivoire, Ghana, Nigeria, Brazil and Malaysia (Mac Donald 1934; Cunningham and Arnold 1962; Machicado and Alvim 1957; Lockard and Asomaning 1965b; Liabeuf and Lotode 1969; Bartley 1970).

Table 4.1 shows a synthesis of the information given in the literature.

Locally, the thresholds might be slightly different because of the influence of local conditions and cacao genotypes (Ribeiro et al. 2008; Rosand and Mariano 1998; Schroth et al. 2001; Snoeck and Jadin 1992; Obiri et al. 2007).

In a second step, researchers added the imbalances between some of the nutrients to improve the formulae recommended. For example, in Brazil, the decision to fertilize is monitored through soil analysis (Malavolta 1997). As recently recalled (Chepote et al. 2013), the fertilizer formulae are calculated from the critical levels of two soil nutrients, P and K and two sets of formulae are given, one for each of the main cacao growing regions (Table 4.2).

In Brazil, specific recommendations for N and soil acidity correction are given separately in addition to the recommendations given in Table 4.2:

- N applications: they are based on light intensity and field observation regarding possible deficiency symptoms.
- Liming is recommended if the concentration sum of Ca plus Mg is lower than 2.0 $cmol \cdot kg^{-1}$ of soil in Amazonia or below 3.0 $cmol \cdot kg^{-1}$ of soil in Bahia at the dose calculated by the formula: CaO (t/ha) = 1.5 × Al. Otherwise, Ca and Mg are not recommended.

Table 4.1 Average soil macronutrients and micronutrients thresholds for cacao

	Parameter	Unit	Medium
Macronutrients	pH (H_2O)		5.1–7.0
	C org	%	1.7–3.2
	N total	%	0.2–0.4
	C/N		9.5–15.5
	P $_{\text{avail. (Mehlich)}}$	ppm	6.0–15.0
	P $_{\text{avail. (Olsen)}}$	ppm	12.0–25.0
	K $_{\text{(Ac. Am. pH 7)}}$	me/100 g	0.2–1.2
	Ca $_{\text{(Ac. Am. pH 7)}}$	me/100 g	4.0–18.0
	Mg $_{\text{(Ac. Am. pH 7)}}$	me/100 g	0.9–4.0
	Al $_{\text{(Ac. Am. pH 7)}}$	me/100 g	0.1–1.5
	CEC $_{\text{(Ac. Am. pH 7)}}$	me/100 g	12–30
Micronutrients	Fe $_{\text{(Mehlich)}}$	ppm	19–45
	Mn $_{\text{(Mehlich)}}$	ppm	3–12
	Cu $_{\text{(Mehlich)}}$	ppm	0.4–1.8
	Zn $_{\text{(Mehlich)}}$	ppm	0.5–2.2
	B $_{\text{(Hot water)}}$	ppm	0.16–0.90

Soil data below the lower limit are deficient in the corresponding parameter or nutrient
Note: 1 me/100 g = 1 $cmol^{+} \cdot kg^{-1}$ of soil

Table 4.2 Calculation of soil nutrient requirements for cacao in the two main cacao growing region of Brazil based on soil P and K levels

Fertilization criteria		Nutrients (kg/ha)					
P (ppm)	K (ppm)	Amazonia			Bahia		
		N	P_2O_5	K_2O	N	P_2O_5	K_2O
<6	<47	30	90	60	60	90	90
<6	47–117	30	90	30	60	90	45
<6	>117	–	–	–	60	90	–
7–15	<47	30	60	60	60	45	90
7–15	47–117	30	60	30	60	45	45
7–15	>117	15	15	10	60	45	–
>15	>117	–	–	–			

The amounts of N, P, K fertilizers are calculated from the combination of soil P and K limits. The limits are different in Amazonia or Bahia

Realising that it is important to consider both the nutrient levels and their ratios in the soil pool, a more sophisticated model was developed in Côte d'Ivoire (Jadin and Snoeck 1985).

4.2.2.2 Soil Diagnosis Model

Nutrient balances and their levels and ratios measured in many different soils were compared to the vigour and yields of cacao crops in a large number of fertilizer trials. Assumptions were made once the balances were known and classified. They were then implemented and tested in greenhouse and field trials. The results were used to develop a software programme which calculates nutrient levels and the relationship between them with the aim of achieving optimum vigour and yields in the soil concerned (Jadin 1975; Jadin and Snoeck 1985; Snoeck et al. 2006). This method was developed parallel to the other approaches in the four main African cocoa growing countries (Jadin 1975; Loué 1961). The results were satisfactory and the tool has been validated in Côte d'Ivoire (Jadin 1975; Koko et al. 2009, 2011), Togo (Jadin and Vaast 1990) and Ghana (Snoeck et al. 2006).

Required Parameters

Physical The percentage of clay plus fine silt helps agronomists understand the soil type as it is related to the pH and cation exchange capacity (CEC) and can consequently help them choose the right type of fertilizer.

Chemical Analyses The following are necessary (Jadin and Snoeck 1985). The methods are standard laboratory analyses (Blakemore et al. 1987):

- N: total N by the Kjeldahl method.
- C: organic C by the method of Walkley and Black.
- pH: pH in water (pH_{H2O}) is measured at a soil to water ratio of 1:2.5.
- Total phosphorus and available phosphorus: The method used must be appropriate (e.g. the Olsen method, the modified Dabin or Truog method, or the modified Bray2 method).
- Exchangeable cations (K, Ca, Mg, Na) and CEC: Extraction with ammonium acetate at pH 7 is preferred because it gives the real potential of cation levels and CEC in the soil. Therefore, it is best suited for fertilizer determination than methods that give the current levels, but will be modified by the fertilizer applied (e.g. cobaltihexamine).

Calculation of the Nutrients Required for Soil Correction

Acidity: Cacao trees can grow in soil with a pH ranging from 4.6 to 7.5 in the top 20 cm. However, severe production limitations are observed when the pH is below 5.0. Particularly, soils with a pH of less than 5.0 usually lack calcium and should be limed. In acid soils, the amount of lime is computed either to reduce the Al saturation or to increase the base saturation. The two formulae below are possible (Jadin and Snoeck 1985; Kamprath 1970):

– Cao ($kg \cdot ha^{-1}$) = Al × 1.5 × 28.1 × 1.4 × 20, where Al is in $cmol \cdot kg^{-1}$, 1.5 is to obtain the quantity of CaO to neutralize 85–90 % of exchangeable Al (in a soil with 2–7 % SOM).
– CaO ($kg \cdot ha^{-1}$) = CEC×(BS_{corr} – BS_{soil}) × 28.1 × 1.4 × 20, where BS_{corr} is the corrected Base Saturation, BS_{soil} is the actual soil BS.

With 28.1 is the ratio to convert 1 $cmol \cdot kg^{-1}$ of Ca into mg of CaO, 1.4 = soil density in $g \cdot cm^{-3}$, and 20 = soil depth in cm.

Moreover, phosphorus availability starts reducing at pH below 5.5 (Jadin and Truong 1987).

Nitrogen: The N demand is calculated from the ratio of exchangeable bases (EB) to nitrogen (N). The EB:N ratio is pH dependent. For each pH, there is an optimal zone where cacao produces the highest yields. These privileged zones can be joined by a line according to the formula: EB = 89 N + 6.15; where EB is the sum of the exchangeable bases in $cmol \cdot kg^{-1}$ of soil or mili-equivalent per 100 g of soil (me/100 g) and N is the total nitrogen in % (Fig. 4.1).

C:N Ratio: This provides an indication of the type of OM present in the soil and, in particular, the degree of humification. In tropical soils, the C:N ratio is quite low due to high temperatures and intense microbial activity. The incorporation of partially decomposed organic residues can greatly modify the C:N ratio. Non-decomposed straw residues tend to increase the ratio whereas leguminous residues, with high N content, tend to reduce it. This factor should be taken into consideration when applying organic fertilizers because it could lead to N deficiency. The C:N ratios of severa1 materials are equal to 40 for straw, 20 for acid humus, 12 for good soil (including average cocoa plantations), and below ten for soil poor in organic matter. Verlière (1981) reported a positive correlation between the organic matter content and the C:N ratio of the same horizon on the one hand, and the cacao yield on the other. This demonstrates that the C:N ratio of soil can be a useful indicator of soil fertility in cocoa production.

Available Phosphorus: Critical level of 10 ppm (Olsen-Dabin method) or 5 ppm (Truog or Mehlich extraction). The optimal P value is calculated from the N:P ratio. The value of the regression coefficient will depend on the extraction method used. The optimum ratio is equal to 100 mg/kg with Olsen-Dabin analytical method and 50 mg/kg with the Truog 2 method (Jadin and Snoeck 1985).

By default, the software program proposes an immobilization factor of 50 % if the soil pH is <5. The agronomist can accept or adjust this value.

Similarly, if the soil already has sufficient N and extra N-based fertilizer is added, this may have a negative effect (Ofori-Frimpong et al. 2003; Wyrley-Birch 1987). In such a case, further addition of P will likely improve yields.

Total Phosphorus: The N:P ratio is more important than the threshold level of P. The best yields are obtained with an N total (%):P_2O_5 total (%) ratio of 2.0 (Fig. 4.2). P becomes a limiting factor if this ratio is higher than 2.0. For example,

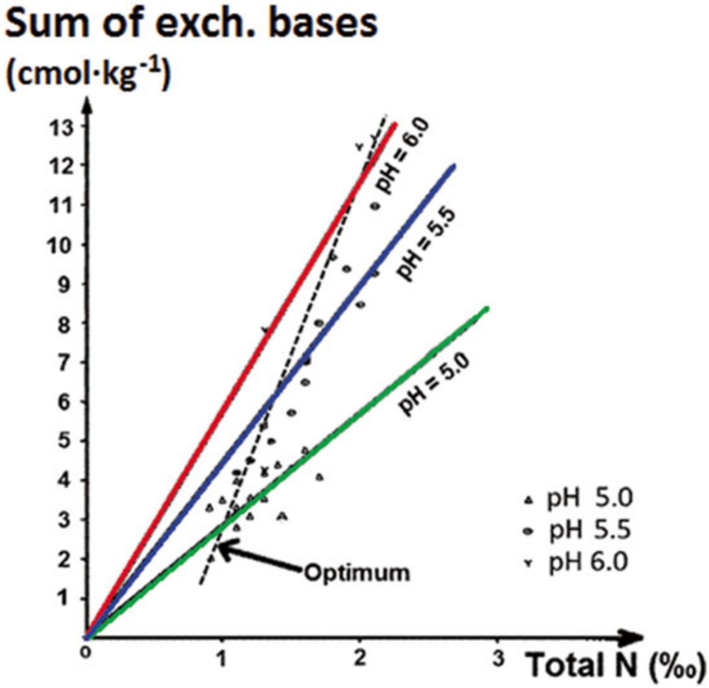

Fig. 4.1 Ratio of total exchangeable bases to N and comparison with the optimum for cocoa yield showing that the exchangeable bases are dependant of both the soil acidity and N. Soils on the right of the optimum require N fertilization (Adapted from Jadin and Snoeck 1985)

in Fig. 4.2, the dots represent the N:P_2O_5 ratio in different cocoa plots monitored during a fertilizer trial in the Central Region of Ghana (Snoeck et al. 2006).

The graph suggests the following recommendations for N and P fertilizers to be as close as possible to the optimum. If the soil is below the optimum line, P should be added to increase cocoa yields, thus moving the dot closer to the optimum. However, if the soil is above the line, adding P will move the dot away from the optimum line which is likely to have a negative rather than positive effect.

Potassium, Calcium and Magnesium The K, Ca, and Mg levels must be above threshold values which vary with the soil type. However, the %K, %Ca and %Mg are the most important ratios. These ratios correspond to the % of the three main cations relative to their sum (K + Ca + Mg = 100 %). Optimum cation levels are determined in three steps: (1) Consider the %K ratio, because best yields are obtained with a %K of 8 %; (2) Then, adjust the ratio between Mg and K, which should be Mg:K = 3; (3) The %Ca is calculated from the difference: %Ca = 100 − (8 + 24). Finally, the optimal balance between cations is 8 % K; 68 % Ca; 24 % Mg.

The ratios were confirmed through multi-local trials done in other countries (Jadin 1988; Jadin and Vaast 1990; Snoeck et al. 2006).

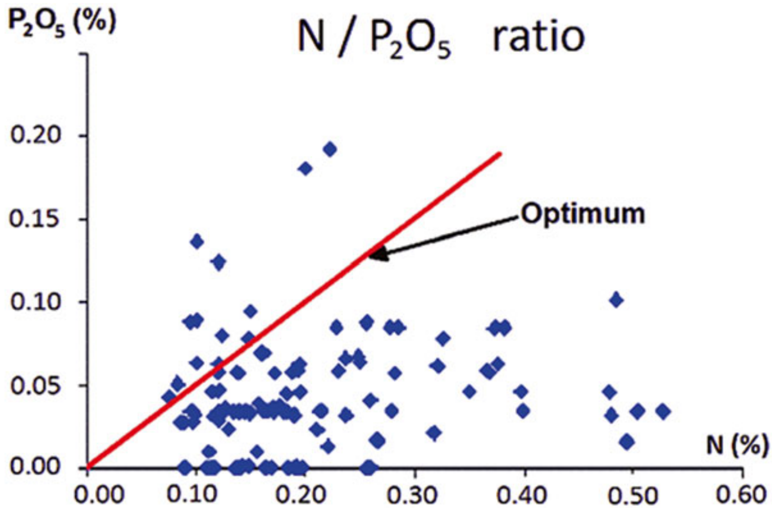

Fig. 4.2 N:P_2O_5 ratio in cocoa plantations in Ghana and comparison with the optimum for cocoa yield. *Dots* are indicating the N:P_2O_5 ratios of soil samples taken in cacao plots. *Dots* below the *red optimum line* indicate P-deficient soils that will respond to P fertilization; *dots* above the *optimum line* will respond to N fertilization (Snoeck et al. 2006)

Base Saturation: It is the sum of the basic cations (K+Ca+Mg) divided by the cation exchange capacity (CEC). The minimum threshold is 40 %; but satisfactory yields can only be obtained when the base saturation is higher than 60 %.

4.2.3 Leaf Diagnosis

The principle is based on the idea that a healthier plant can produce higher yields, and on the opinion that the number of pods produced could be linked to the level of nutrients or nutrient balances in leaf (Murray 1956).

4.2.3.1 Chemical Leaf Diagnosis

Leaf analysis is particularly recommended to detect nutrient depletion in the cacao and to follow nutrients variations and imbalances in the cacao over time (years). This means that samplings have to be repeated on the same trees at successive intervals. The diagnosis is based on variations in nutrient levels and their ratios. For example, in soils with low phosphorus contents which are poorly buffered but have a fairly high fixing power, leaf diagnosis can supplement the soil diagnosis to determine whether phosphate fertilization is required. It can also help understand if the plant will benefit from a given nutrient without causing a deficiency in another one. It gives information on the status of the cacao tree.

The use of models integrating both the levels and ratios between leaf nutrients was recently studied in Brazil (Marrocos et al. 2012). Particularly, the authors tested the Diagnosis and Recommendation Integrated System (DRIS) developed in USA (Walworth and Sumner 1987) which has already been tested on other tropical crops such as coffee. The method is based on the calculation of norms to compute an index for each nutrient. The norms consist of averages and coefficients of variation of relationships among the leaf nutrients. The data linked to lowest productivity cacao trees are used to determine the lower thresholds.

Unlike the works of Verlière (1981) who determined the thresholds and ratios in controlled medium (both green house and long term fertilizer field trials), the DRIS method is based on the thresholds and ratios that are previously determined by comparison with the contents recorded in a reference population.

4.2.3.2 Visual Leaf Diagnosis

This method provides the advantage that it can be used in the field to rapidly detect nutrient deficiency symptoms and take quick action. The deficiency symptoms normally occur when the levels are lower than the minimum thresholds as given in Table 4.1 (above).

The description of deficiency symptoms were described by Loué (1961) and Alvim (1961) and recently recalled by De Souza (2012).

For survey purpose, both macro (N, P, K, Ca, Mg) and micro (Fe, Mn, Zn, Cu, B) nutrients are analysed. For routine assessment, only macronutrients are required.

The interpretation must take into account the numerous factors able to modify the chemical composition of the leaves. Among the factors the influence of shade is fundamental (Burridge et al. 1964; Murray 1956).

The standards were determined from fertilizer trials observations. The ones most used were established in Côte d'Ivoire (Loué 1961), Brazil (Alvim 1961), and Trinidad (Murray 1967; Spector 1964). They are not very different, and served to develop other methods. The data obtained from a combination of data given by various researchers cited above were used to build the thresholds described in Table 4.3.

Particularly, De Souza (2012) showed that the visual leaf analysis interpretation is based on the comparison of actual nutrient levels with the thresholds divided into three zones as described in Fig. 4.3: a zone of deficiency where visual deficiencies are likely visible, a zone of adequate nutrition and a zone of toxicity.

The leaf nutrient contents refer to samples taken from the third leaf of the last maturing flush at the height of 1.5 m above the soil. They were 2–3 months old and were fully active.

The lower thresholds of chemical leaf analysis correspond to the apparition of leaf deficiency. Thus, both leaf diagnosis methods lead to the same interpretation (Malavolta 1997).

Table 4.3 Cacao leaf optimum nutrient thresholds

Macronutrients (%)					
N	P	K	Ca	Mg	S
1.8–2.5	0.17–0.25	1.2–2.4	0.3–1.5	0.2–0.8	0.10–0.25
Micronutrients (ppm)					
B	Cu	Fe	Mn	Mo	Zn
25–70	8–20	50–250	150–750	0.5–1.5	30–150

Actual leaf sample data below the lower limit indicate a nutrient deficiency in the cacao tree; Data above the upper limit indicate a risk of toxicity (Compilation after Loué 1961; Murray 1967; Malavolta 1997; Egbe et al. 1989)

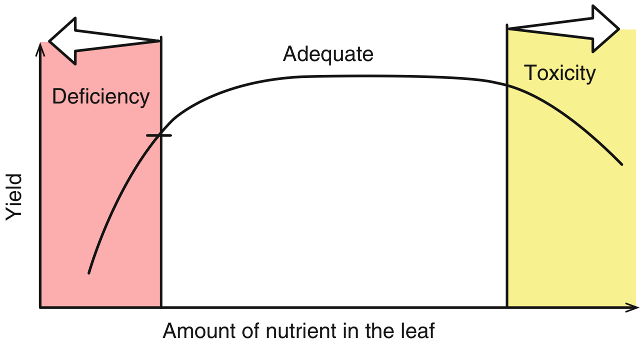

Fig. 4.3 Relation between leaf nutrient and cacao growth or yields. The three zones are used to interpret foliar analysis. Leaf nutrient data in the deficient zone indicates inadequate growth and leaf showing visual deficiency symptom (adapted from De Souza 2012)

4.2.4 Method Based on a Combination of Soil and Leaf NPK Thresholds

In Malaysia, an integrated approach is promoted (Ling 1984). It takes into consideration factors such as leaf nutrient content, trees age, cropping level, soil type, amount of shade, leaching losses and other agronomic factors, such as tree vigour and harvesting system (Table 4.4).

In Sabah (Malaysia), trials revealed that P and K were equally important, but not N (Wyrley-Birch 1987).

This last method is a first step of combination of both approaches: the soil and leaf analyses.

Table 4.4 Calculation of nutrient requirements for mature cacao in Malaysia (after Ling 1984)

Mature cacao – (kg/ha/year)			
Nutrient	Soil	Leaf (%)	Fertilizer rate
N		<2.0	100–150
		2.0–2.6	60–80
		>2.6	–
P_2O_5	<15 ppm[a]	<0.2	90–150
	<15 ppm	>0.2	30–60
	>15 ppm	>0.2	–
K_2O	<0.3 me/100 g	<2.0	120–180
	<0.3 me/100 g	>2.0	80–100
	>0.3 me/100 g	>2.0	–

The amounts of fertilizer to apply are calculated from the combination of soil N, P, K and leaf N, P, K limits

[a]Available P by Bray and Kurtz no. 2; exchangeable K in me/100 g

4.2.5 Practical Recommendations for Fertilizer Use

4.2.5.1 Prerequisite to the Use of Fertilizers

Cropping practices should be properly implemented to maximize the efficiency of nutrients to the benefit of pod production. Good cultural practices begin with the selection of an appropriate growing area, followed by an effective land preparation. Once all is done, the cocoa grower has to decide whether the cacao will be planted in agroforestry (complex or simple association with other tree crops) or in direct sunlight. This should normally influence the choice of planting material, tree planting density and cultural practices that will follow; proper pruning techniques, weed control, integrated pests and diseases control, soil management and tillage to ensure suitable water and nutrients supply. Proper installation of the root system is essential to enhance cacao tree growth and its productivity.

For example, the decision to plant in agroforestry system will influence the soil fertility and amounts of nutrients required (Jagoret et al. 2012; Snoeck et al. 2010).

The selection of appropriate planting material is very important. Indeed, in a plot planted with traditional or hybrid cacao trees, only half of them will produce pods, while the other half produces virtually very few pods or nothing (Bénac 1970). Fertilizers are applied at the foot of each cacao tree in the plot. Ideally, 100 % of the cacao trees on a plot should be productive (Bartley 1970).

Similarly, the importance of good pruning to maximize the fruit:vegetative ratio and optimize the effects of nutrients inputs can be deduced from the study of Thong and Ng (1978). The authors have shown that a 5–6 years-old cacao contains 45.5 kg (dry matter) of the vegetative parts (leaves, stem, branches and roots) but only 1.5 kg of pods (i.e. equivalent to 195 kg cocoa beans ha^{-1}). This clearly indicates that, when fertilizers are applied, nutrient consumption is used to a greater extent for growth than for fruiting. This should prompt farmers to improve their pruning practices in order to maintain shorter cacao trees, but bearing a maximum of pods. Pruning also improves air circulation and reduces humidity, which limits black pod diseases for healthier pods to thrive.

The potential fertility of a soil depends on how nutrient fluxes are managed in terms of inputs (mainly chemical fertilizers) and factors that could influence the nutrient availability (e.g. environment, type of associated trees, shade trees, farming practices, soil nutrient availability, biomass recycling, etc.) and outputs (leaching, evaporation, erosion, and harvested crop). In this context, the decision to plant in agroforestry system and how to manage them is an important aspect (Schroth et al. 2001).

In addition, fertilization of a tree crop requires long term management because mature trees have a buffer capacity that may differ responses to fertilization over several years (Viroux and Jadin 1993). The levels of nutrients in the soil are changing continuously, and once the soil is corrected regarding the nutrient levels and ratios, the fertilization programme should continue and focus on the nutrients exported through pods harvested and used for tree growth.

Selection of Suitable Area

Prior to plant a cacao field, the cocoa grower has to select suitable land. Particularly, he should consider the quality of the soil by carrying out physico-chemical analyses, supplemented by soil profiles studies.

The physical and chemical characteristics of a soil, at a given time in its history, are the result of the development of a combination of factors: environment, bedrock, rainfall, temperature, farming practices, including the level of shade and, to a certain extent, the variety (Afrifa et al. 2009; Ekanade 1987; Lotodé and Jadin 1981; Malavolta 1997; Snoeck et al. 2006).

Substratum

The potential fertility of a soil depends on the bed rock from which it was formed. For example, Verlière (1981) showed that soils in Côte d'Ivoire derived from:

- Tertiary sands that are often deficient in N and quite always very deficient in K;
- Granitic rocks poor in P;
- Schist rocks deficient in both P and K.

The influence of the soil origin on the soil fertility under cacao was also demonstrated in Brazil (Cabala-Rosand et al. 1971; Santana and Igue 1972). The authors showed that Nitosols are much richer than Latosols, particularly in N, P, and micronutrient reserves. The suitable soils for cacao growing were described by Smyth (1980).

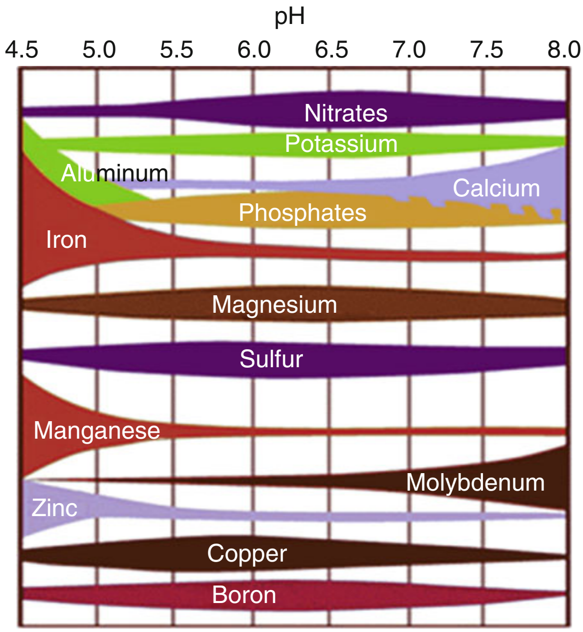

Fig. 4.4 Effects of soil pH on soil nutrient availability and toxicity (adapted from Truog 1948)

Soil Texture and Depth

The ideal soil texture contains 30 % clay, 50 % sand, and 20 % silt. However, the most important factor is the soil depth, to enable good development of cacao roots, which must be free of physical limitations (Smyth 1966).

Soil should allow root growth to at least 1 m depth (Smyth 1966). However, the presence of pebbles or stones in the soil profile, as well as the colour of the horizons are not significantly correlated to the tree yield (Souza Júnior et al. 1999a, b).

Water availability, oxygen and growth are impaired under high density planting, compaction, continuous rocks, concretions and/or deficient drainage (Silva and Carvalho Filho 1969).

Soil Acidity and Aluminium Toxicity

Soil acidity, either native or due to use of acidifying fertilizer, has detrimental effects on nutrient availability (Fig. 4.4) and leads to aluminium toxicity. Aluminium toxicity is partly responsible of poor phosphorus availability because the Al^{+++} ion tends to accumulate in the roots and inhibits uptake and translocation of both P and Ca to the aerial portion of the plant (Sanchez 1976).

Fe ions also have a detrimental effect on P fixation in the soil (de Geus 1973; Kamprath 1970).

It is worth mentioning that cacao appears to be highly sensitive to Al toxicity in acid soil. This makes cacao an important exception among native Amazonian species, which are normally highly tolerant to acid soils. Soil pH is the parameter having the most significant effect on fertilizer efficiency; thus, it can be used as a good predictor of cacao yields (Fearnside and Filho 2001; Hardy 1961).

Green house trials have confirm the reduction of root biomass and root length in acid soils. There is also a reduction of Ca, Mg, K, Cu, Fe, Mn and Zn uptake (Baligar and Fageria 2005).

Soil Water Availability

Cacao being a typical plant of the humid tropics, it requires a high quantity of water. It is sensitive to a lack of soil moisture and a water deficiency causes dire problems (Jadin and Snoeck 1981). The cocoa yields in quantity and distribution are determined more by the rain than by any other ecological factors (Alvim and Alvim 1980). Trees grown on soils with a low buffer capacity and low organic matter content are the most affected by water stress in drier years.

Soil salinity should not be higher than 0.6 dS/m; yield reduction of 10 % was noticed in soils having 1 dS/m (Smyth 1966).

Where rainfall is below 1,200 mm and poorly distributed in the year with a dry period than 30 days, cacao can only develop successfully under irrigation. This is the case in Venezuela, where the precipitation is 700–800 mm/year (Alvim 1965) and in the North of Espírito Santo, where rainfall occurs during a few months of the year, in spite of an annual precipitation of 1,200 mm/year (Malavolta 1997).

In Côte d'Ivoire, Verlière (1970) studied the influence of soil humidity regimes on the development of three different cacao varieties groups (Amelonado, Upper Amazon and Trinitario). He found very different reaction of the varieties to the ecological factors. In particular, different water regimes produced different effects regarding the trunk circumference, number of foliar shoots, and water use by the cacao. One reason could be that cacao cultivars with an efficient stomatal regulation mechanism lose less water by transpiration under water stress, which indicates an important adaptation strategy (Balasimha et al. 1988).

Fertilization trials in Côte d'Ivoire showed that with fertilization and irrigation, the number of harvested pods was 63 % higher than in non-irrigated control cacao plots (Jadin and Paulin 1988).

The scarcity of studies on how soil moisture influences production in cacao plantations might be due to the fact that cacao is mainly grown in regions where, characteristically, the total annual precipitation outstrips water losses by evapotranspiration (Moser et al. 2010).

Soil Organic Matter

Soil organic matter (SOM) plays an important role in the cacao nutrition because of its influence on the physiological, chemical and biological characteristics of the soil. It also makes the soil more porous and favours water infiltration, while

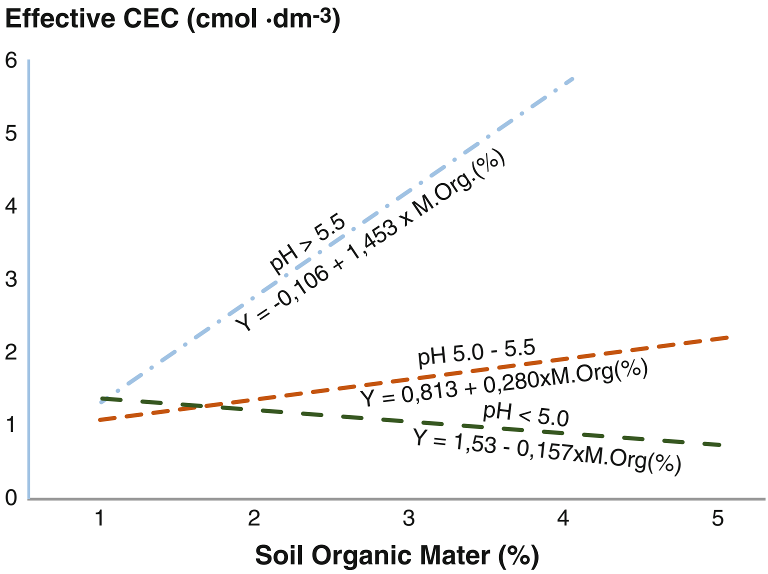

Fig. 4.5 Variation of e-CEC in relation with soil organic matter and pH showing that the CEC is dependant of both the soil acidity and the soil organic matter. *CEC* cation exchange capacity (Adapted from Malavolta 1997)

reducing erosion and activating animal life. SOM considerably improves the cation exchange capacity (CEC) of tropical soils and helps limit soil acidity (Fig. 4.5). This is important because a high level of soil acidity reduces microbial activity, as well as toxicity caused by the presence of available aluminium or manganese. SOM in the soil also encourages the activity of various microorganisms like mycorrhiza, rhizobia and other organisms. Microbiological activity plays a role in protecting crops but also in soil fertility and nutrient availability (Rousseau et al. 2012; Silva Moço et al. 2009; Snoeck et al. 2009). Consequently, it is very important to preserve the native humus level in the soil. This must be taken into consideration right from the start, particularly when preparing the land prior to planting cacao (Smyth 1966).

SOM should be preserved and, where possible, improved by good cultivation practices. At least 3 % of organic matter is required for minimum cacao growth (Smyth 1980; Somarriba et al. 2013).

The use of mulch significantly reduces the need for chemical fertilization and ensures a considerable input of SOM, which enriches the soil in nutrients, mainly potassium. However, mulching requires regular checks of the cations ratio to avoid imbalance between magnesium and potassium. Excess potassium shortens leaf life and accelerates leaf fall. It also reduces the efficiency of N fertilizers. In all cases, mulching enhances the efficiency of mineral fertilizers and the water retention capacity of the soil.

Type of Planting Material

The choice of planting material should be done considering whether the varieties or hybrids will be adapted to the cocoa farmer's decision. Particularly: local soil and climatic conditions, decision to plant in full sun, crop associations or agroforestry, and ability to practice good cultural practices and cacao pruning.

For example, in Brazil, trials have shown that clones or hybrids do not respond similarly to phosphate fertilizer, mainly because clones were planted without tap root (Pacheco et al. 2005; Rosand and Mariano 1998). Similarly, different responses to N and P by different varieties were also observed in Ghana (Afrifa et al. 2003) and Brazil (Ribeiro et al. 2008).

4.2.5.2 Role of Nutrients in Fertilizer and Recommendation for Their Application

Macronutrients

Nitrogen: N is not systematically required. For example, in a legume-cacao association, Kurppa et al. (2010) found limited net N transfer from associated legume tree species to cacao in spite of active N_2 fixation. No response to N application has generally been found in fertilizer trials, particularly in Côte d'Ivoire (Lotodé and Jadin 1981), Ghana (Ofori-Frimpong et al. 2003), or Sri-Lanka (Heenkende and Gunarantne 2000). In Cameroon, the application of N produced a depressive effect on the cocoa yields (Liabeuf and Lotode 1969). Some reasons are that N is already provided from other natural sources, such as Rainfall or litter decomposition, in amounts that are sufficient for shaded cacao trees (Ojeniyi et al. 1982). It is therefore important to apply N fertilizer only when it is a limiting factor, which is computed from the N:P and N:exchangeable bases ratios (Jadin and Snoeck 1985).

N requirements are also dependant of the cultural practices and amount of other nutrients applied. For example, in Ghana, the soil diagnosis has shown a need for N in plots that received repeated applications of P and K and in highly anthropized plots, where N was not recommended 20 years ago (Snoeck et al. 2010).

If N is needed, the agronomist selects a suitable formula (N alone or NPK) depending on the recommendation and the soil conditions. N can be brought in multiple forms as N uptake by the cacao occurs in both nitric and ammoniac forms (Santana 1982). Urea requires to be buried to avoid the lost by ammonia (NH_3) volatilization of a part of N. The rest will convert in the form of ammonium ($NH4^+$). Finally, both forms have an acidifying effect: on the one hand, the ammonium form is an active energy consumer releasing H^+ in the rhizosphere developing a very localized but strong acidifying effect; on the other hand, if the nitrification is not impaired by too acidic soil conditions, the conversion from ammonium ($NH4^+$) to nitrate ($NO3^-$) also releases H^+, thus contributing to soil acidification.

Urea is a cheap source of N, but as it acidifies the soil it might not be the best choice for acid soils.

N added as ammonium (e.g. ammonium sulphate) has a worse acidifying effect because the conversion from ammonium to nitrate releases two ions H^+ (instead of one in the conversion of urea to nitrate). The N uptake through ammonium fertilizers or urea, competes with the uptake of other cations, K, Mg, and Ca.

N added as nitrate (e.g. Calcium nitrate) is directly available but can be easily leached; thus, any application has to be avoided during heavy rains. It is the best form of N for its synergy with K, Mg, and Ca (passive uptake, concomitant uptake of cations and anions, "+" and "–", without antagonism). As a result, nitrate does not release H^+ and so, it has no acidifying effect. Or the contrary: the nitrate form ($NO3^-$) can have a favourable basifying effect in the rhizosphere, releasing OH^- ion if no concomitant cation is taken by the roots.

Phosphorus: The type of phosphate fertilizer depends on the soil pH. In acid soil, the use of soft rock phosphate (RP) or triple super-phosphate (TSP) are recommended because they have a high CaO content (20 % for TSP and up to 45 % for RP) helping the release of phosphorus in acid soil. It also helps to increase the soil pH. However, the associated CaO must be controlled because improper use could unbalance the cations ratios beyond a point where the correction becomes impossible. At pH >5.5, either triple-super, or single-super, or di-calcium phosphate can be used. The choice will depend on the amount of CaO required. The amount of P also depends on the immobilization factor of the soil towards the (P_2O_5) oxide (Jadin and Truong 1987).

Phosphorus is not very mobile in the soil, but its behaviour will depend on its solubility in the soil. The part of the quick P that is not rapidly taken by the roots will be fixed by aluminium and iron in acid soils (and by calcium in calcareous soils). Alternately, the P form that is not water soluble requires a soil reaction.

When using water soluble phosphorus (e.g. TSP), localized application is preferable. It will provoke localized saturation that will minimize the P immobilization by less reaction with Al and Fe.

When using non water soluble phosphorus, broadcasted application are required to maximize the contact with the soil to facilitate its solubility. Di-calcium Phosphate and Fuse Magnesium Phosphate are close to 100 % citric acid soluble (2 % citric acid solution method). Rock Phosphate can be hard (or very hard if it has an igneous origin) and requires strong (or very strong) acid attack to become soluble (like with phosphoric, sulphuric or nitric acids in fertilizer factories). Alternately, it can be soft if it has a sedimentary origin and can be directly used on acid soils. Reactive Rock Phosphate have a "crystal" shape that is "more like a coral than a sphere" enabling more contact surface with the soil. The best reactive phosphate rocks have a surface area of more than 20 m^2 per gram of product and about 70 % of P_2O_5 soluble in formic acid (2 % formic acid method) as demonstrated in the BET theory (Brunauer et al. 1938). To maximize the contact with the soil, the particle size of a rock phosphate must be less than 100 μ.

As phosphorus increases flowering, it must be applied at the beginning of the first heavy rainfalls.

Potassium: K is often supplied as KCl. The chloride accompanying ion can be toxic, leading to tip leave scorching, particularly in dry season. KCL releases 60 % of K_2O, but also 47 % of Cl. Cl is more rapidly leached than sulphate and will contribute to soil acidification by loss of cations in the top soil. If N is also needed and applied as NPK fertilizer, then, part of the K_2O is already added through NPK fertilizer.

The best period to apply K_2O fertilizer is the pod set and development, as they are very rich in K. As potash fertilizer is highly soluble and therefore easily leached, it is recommended that the applications be split: half the dose during flowering and the other half 2–3 months later.

Calcium: Ca is normally supplied in the form of lime; or as dolomite if CaO:MgO requirements are close to dolomite values. CaO and MgO can be applied together or separately, along with the first potassium application. If N was required and calcium nitrate was used, or if P was required and Ca-based fertilizer (e.g. TSP) was used, the amount of applied Ca along with the other fertilizers must be taken into account when calculating the amount of CaO fertilizer.

Magnesium: Mg is normally supplied in the form of dolomite (Magnesium carbonate requiring long time to be dissolved, an option for very acidic soils adequate quantity according to Soil Diagnosis) or kieserite (Epsom salt – a soluble Magnesium Sulphate to prefer in NPKMg fertilizers for quicker supply for the tree uptake, avoiding short term antagonism with Potassium coming from soluble fertilizers). If magnesium is given alone, the best time is at the end of the rainy season, because magnesium supports the leaf retention and delays their senescence.

Aluminium: Al concentration over 2 mg/kg hinders the absorption of calcium, magnesium, ammonium N, iron, boron, zinc, and manganese. Toxicity will most likely occur at low soil pH along with low cation contents. The aluminium content in the soil should be measured to calculate the required calcium fertilizer to correct soil acidity. Agricultural gypsum can contribute to CaO supply without impact on the soil pH and, thanks to the relative water solubility of this form as Calcium Sulphate, penetrate deeper in the sub-soil (sub-soil liming with aluminium detoxification as main benefit thank to the combination of the gypsum based sulphate in non-root toxic aluminium sulphate (vs. the high toxicity of Al^{+++}).

Micronutrients

Boron: B is absorbed through the roots as non-dissociated boric acid. Correction is done by applying 20–30 kg/ha borax (11.3 % B) or other B-containing substances to the soil in a ring around the tree, or by foliar spray (200–300 g/l Solubor, Polybor or boric acid) repeated 3–4 times per year. There may be a danger of toxicity after several years (Malavolta 1997).

On an industrial plantation in Côte d'Ivoire, where yields were low, Loué and Drouineau (1993) could increase the yields by 180 % after an application of borax at the rate of 4.4 g B per tree. More recently, in a trial conducted in Côte d'Ivoire, a significant positive correlation was noted between cocoa yields and soil boron levels, either already present in the soil or added through fertilization (Stemler 2012). Upper Amazon are more sensible to boron deficiency than Amelonado trees (Lachenaud 1995). This author also found that boron deficient cacao has incomplete pod filling. Thus, the application of borax to cacao grown in full sun and deficient soil, can increase the number of normal-sized beans per pod of three (deficient SCA6: 33 beans, with borax: 36 beans) and reduce the number of flat beans (from 3.5 to 1.9 %).

The positive effect of boron on cacao productivity was also observed in Nigeria (Ojeniyi et al. 1981).

Deficiencies are more common on sandy soils, with low organic matter and low pH.

Zinc: Zn is absorbed through the roots as a bivalent ion Zn^{2+} or as a chelate. Its deficiency is common in acid or exhausted soils. Correction is done by applying 10–20 kg/ha $ZnSO_4$ to the soil, or by foliar spray of 1 % zinc sulphate or zinc oxide repeated 2–3 times per year.

Main causes of zinc deficiency: highly weathered acid soils, but also in calcareous soils with high pH and poor soil aeration. Typical symptoms of zinc deficiency were in particular noticed on field borders and “light holes” in Ivory Coast (Loué and Drouineau 1993).

Copper: Cu is more common on soil with pH >7.5, or if excess N is applied.

Manganese: Mn is more common on soil with pH >7.5. Deficiencies occur with increasing soil pH and aeration, when insoluble Mn oxides are formed.

Iron: Fe deficiency is more common on alkaline soil.

4.2.5.3 Soil and Leaf Sampling

Soil Sampling

Soil sampling is an important step in soil fertility evaluation. Precise recommendations of fertilizers doses and formulae are directly proportional to the extent of good sampling. If the sample is not representative of the area, this could lead to wrong recommendations, whatever the quality of the laboratory.

Soil samples should be taken at the beginning of the rainy season when the soil organic matter is undergoing active mineralization and nitrates are being generated. This also corresponds to the period of vegetative growth and pod development.

Soil is collected in the area which normally receives fertilizer, i.e. a ring under the canopy. After removing any decayed debris on the soil surface, samples should be taken with an auger to a depth of 20 cm, i.e. where more than 80 % of the feeder roots are concentrated (de Geus 1973; Leite and Valle 1990; Wessel 2001; Moser et al. 2010). For larger farms, soil diagnosis can be performed to draw up specific recommendations at the plot level.

Soil samples are taken in the whole plantations. To reduce the amount of samples without reducing the area representativeness, it advised to mix some samples of the same area into one composite sample, which will be analysed. A composite sample consists of a mix of 30 borings collected under different trees in each homogeneous type of soil within a plot. At least 30 borings are required to reduce the variation under 20 % (Jadin 1988).

Soil analysis should be performed regularly every 4–5 years to check for possible variations in the soil fertility of the plantation and adjust the fertilizer formulae, if required.

Leaf Sampling

Sampling Number: In trials, four leaves per cacao tree are harvested on 25 cacao trees at random in each plot. In surveys, a visual evaluation is done to delimit the blocks, then 50 pairs of leaves are taken on 25 cacaos.

From 50 cacaos sampled in a same field, Acquaye (1964) noted that leaf nutrient variations between trees were very large and differences could range from one- to twofold or even threefold for phosphorus. A minimum of 40 trees must be sampled to obtain an acceptable standard deviation (below 10 %).

Sampling Position: Sampling position: Depending on its position on the tree, cacao leaf can contain very different nutrient amounts. It is therefore very important to well determine which leaves to harvest and do not modify the position from 1 year to the other (Orchard et al. 1981). The authors suggest harvesting the leaf at the fourth development stage (stage I.2: Newly produced leaves dark green with a thick cuticle and dormant apical bud). Loué (1961) recommends harvesting the second leaves of the first flush that has become mature. But he noticed that other leaves can be green and that mature leaves can be of different colours. Verlière (1970) suggested sampling leaves with the petiole still green, but becoming brownish.

Sampling Period: The hour of the day is also important as it can be a source of irregularities; the early morning is the most regular period (Acquaye 1964). The leaf age is another important parameter that can modify the dry matter content. Foliar diagnosis is sensitive to the sampling period because the nutrient levels vary with the seasons; particularly, N, P and K are higher in the dry season than in the rainy season. Calcium varies inversely of potassium and magnesium has low amplitude fluctuations following those of calcium (Alvim 1961).

Recommendation for Leaf Sampling: The most commonly used recommendation is to harvest the third or fourth leaf at breast height that is lighted (i.e. the Southern leaves in the North hemisphere and vice-versa) and after the start of rainy season when foliar activity is highest (Bastide et al. 2003).

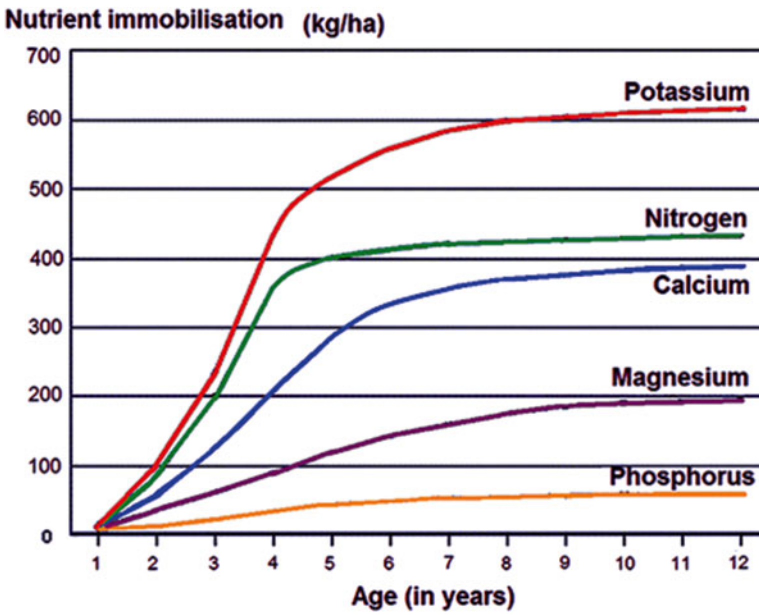

Fig. 4.6 Nutrient uptakes increase with the age of cacao from 0 to 12 years (Thong and Ng 1980)

4.2.5.4 Mode of Application of Fertilizer

Fertilizer Requirements by Age

Nutrient uptake by cacao increases with the tree age but at different speeds depending on the nutrient. For example, N uptake increases during the young stage and levels off after year 5. However, K and Mg uptake increase from year 10, i.e. when the cacao had already started producing (Fig. 4.6).

It is important to know that, regardless of environmental conditions and any effects of the soil, the nutritional requirements are growing from seedlings to mature cacao trees, with a maximum yield is attained after about 10 years (Thong and Ng 1980). Then fertilizer amounts can be reduced because the cocoa yields will drop while age increases as demonstrated by the age-yield curves (Ryan et al. 2009), either in full sun or associated (Obiri et al. 2007; Snoeck et al. 2013). This suggests that a fertilization programme should be based on actual nutrient requirements in plots containing mature cacao; therefore, for cacao above 20–25 years old the fertilizer impact will be reduced. However, it is important to be aware that nutrients applied have a residual effect that can last up to 3-year after having stopped the fertilizer application (Cabala-Rosand et al. 1971).

Practically, this shows that:

– For young cacao, the requirements can be reduced in proportion to the corresponding age.

– For mature cacao, the fertilization programme involves two steps: (i) correcting the soil nutrient levels and ratios to optimize nutrient availability; (ii) supplying nutrients to compensate for those used for physiological maintenance, lost through leaching, pruning, or those exported from the field when the pods are harvested.

Fertilizer Application Periods

Normally, fertilization is applied in four stages: in the nursery, in the planting hole, on young plants and on adult trees in production.

In the nursery, fertilizer can generally be applied every 2 months once the seedlings have two or three pairs of leaves. Fertilizer in solution or in a leaf spray is recommended.

In the planting hole, application of well-rotten cattle manure or compost (about 20 L per tree) is usually recommended. Lime should be applied prior to planting and incorporated in the soil to obtain a pH >5.5 at the minimum.

On young cacao growing in the field, three applications of fertilizer can be carried out during the rainy season. The formulae should be based on the results of the soil analysis. Fertilizer applications have to be more frequent (i.e. 3–4 times per year) to minimize losses.

Mature cacao producing fruits can be fertilized at the same time as growing trees, but the formulae and fertilizer rates should be tailored to the soil analysis results and expected yields. Fertilizer applications should be split into at least two applications per year, with the basal dressing applied at the onset of the rainy season (Chepote et al. 2013; Jadin and Snoeck 1985; Malavolta 1997).

As a general rule, 3 or 4 applications per year of N in the rainy season are advisable. The first two applications can be combined with other nutrients like potassium, phosphorus, magnesium and, where necessary, boron.

As phosphorus is less mobile, it can be supplied in one application at the beginning of the rainy season. Phosphate dislocates nitrate and the accompanying cation can dislocate potassium in the adsorption complex. As a result, large quantities of phosphorus fertilizers should not be applied at once.

As P increases flowering, it is best applied at the start of rainy season (April in the Northern Hemisphere).

As K is required for pod set and pod growth, and since it is very soluble, it is advised to split the applications in two; one after flowering and 3 months later (in the North: June and September).

Calcareous and N fertilizer doses should be separated by a period of at least 2 months to limit denitrification, or the diameter of the rings should be increased to apply both compounds in a larger ring so that the lime concentration is smaller.

Ca and Mg should be applied at the same time as the first K applications.

Fertilizer Application Localisations

To reduce the fertilization cost, it is recommended not to fertilize the entire plot, but rather to apply the fertilizers either in a ring or a crown around the base of the trunk as roots are mainly growing under the cacao tree canopy (Jadin 1975) or in strips (alleys) along the rows. On big farms, mechanization of fertilizer application can be done on alleys in a 0.8 m band in the middle of cacao rows planted at 3 m spacing. The area corrected represents about 27 % of the total surface. Application in a ring around the base of the trunk is preferred for young trees. The diameter of the ring should be similar to that of the tree canopy. Fertilizer applied in strips along rows is a method generally used for high density adult plantations. To avoid a toxic salt concentration, chemical fertilizers should not be applied to young cacao until at least 3–4 weeks after field planting.

Nitrogen fertilizers can be applied on the soil surface, but their application should be spaced out to avoid losses through rainfall or flooding and to ensure regular feeding of the cacao plants. When using urea N, which is rather volatile, it is advised to place the fertilizer under the litter.

Lime should be incorporated before planting, before rainy season. In mature plantation, applications should be split to prevent the formation of a hard crust on the soil surface.

The quantity of fertilizer to apply must also take the fertilization efficiency into account, which depends on soil pH. For example, at pH 4.5, only 30 % of N supplied in fertilizer will be available to the plants, but in the same soil at pH 6.0, 80 % of the N will be available (Jadin and Snoeck 1985).

Besides, fertilizers do not need to be applied to all cacao trees. Indeed, only a portion of the cacao trees are producing (Bartley 1970; Bénac and Dejardin 1970). The authors found that, in a cacao plot, 7.9 % of the trees are unproductive, 34.5 % produce little yields (<12 pods/tree), 27.2 % produce average yields (12–20 pods/tree), 21.7 % produce good yields (20–50 pods/tree), and the remaining 8.7 % produce high yields (>50 pods/tree).

Use of Organic Fertilizers

The recommended amounts of organic matter are normally calculated from the amounts of equivalent nutrients provided by the organic compounds.

Studies carried out in an Oxisol showed that the use of 8 $t \cdot ha^{-1} \cdot year^{-1}$ of cocoa husk compost promoted an increment of 133 % in cocoa dry seed production, as compared to the treatment without fertilizer (Chepote 2003). It was also found that the application of 4 $kg \cdot plant^{-1} \cdot year^{-1}$ of cocoa husk and cattle manure compost +50 % of mineral fertilizer (13 % N, 35 % P_2O_5 and 10 % K_2O) promoted a 188 % increase as compared to the plot without fertilizer.

Similarly, in Côte d’Ivoire, the use of compost enhances the effect of P fertilizer by increasing the soil P status (Koko et al. 2013). The authors showed that the application of 8 $t \cdot ha^{-1} \cdot year^{-1}$ of compost of cocoa +184 $kg \cdot ha^{-1} \cdot year^{-1}$ (as TSP) increased the cocoa yield of 204 %.

Similar recommendations are done in other countries, such as Brazil (Lima et al. 2012) or Nigeria (Ogunlade et al. 2012).

4.2.5.5 Fertilizer Recommendations Once the Soil Is Corrected

When fertilizing cacao, two separate but necessary aspects should be considered: (1) compensating for real deficiencies revealed by soil analyses and (2) replacing nutrients removed by harvested beans to ensure growth.

All recommendations found in the literature and described above apply to deficient or imbalanced soils with the objective to correct the nutrient levels while also correcting imbalances. Once the soil is corrected, new recommendations have to be applied. For example, in the tables given for Brazil or Malaysia, no fertilizers are necessary when available P is >15 ppm and available K is >0.3 $cmol \cdot kg^{-1}$ soil. Similarly, calculations using the soil diagnosis model will conclude on no fertilization for soil correction and only the amounts computed to compensate for nutrients exported by the harvests will be applied.

However, once the soil is corrected, fertilization must not be stopped but continued to compensate for the nutrients exported through pod harvest but also through leaching or immobilised by the cacao for its growth. Indeed, the nutrient cycling balance is negative in the cocoa production system and mineral or organic fertilizer compensation is essential (Afrifa et al. 2009; Appiah et al. 1997; Hartemink 2005). The authors highlighted the negative balance of the nutrients cycles in a cacao plantation, showing that outputs are greater than inputs. These parameters therefore have to be taken into account in the calculation of nutrients to include in the routine fertilizer formula.

– Outputs are due to immobilisation by the crops (uptake for growth and maintenance) plus harvests and soil leaching. In particular:
    - Exports through harvests of 1000 kg of cocoa dry beans = 21.1 kg N + 8.6 kg P + 11.1 kg K + 1.1 kg Ca + 4.0 kg Mg.
    - For each 1000 kg of dry beans, there is 1400 kg of pod husk produced. If not returned to the plantation field (after composting), then the following amounts of nutrients are also exported: 14.0 kg N + 4.2 kg P + 68.0 kg K + 6.6 kg Ca + 6.5 kg Mg.
    - Immobilisation: 4 $kg.ha^{-1}.year^{-1}$ N + 2 $kg.ha^{-1}.year^{-1}$ P + 6 $kg.ha^{-1}.year^{-1}$ K.
    - Leaching: 5.2 $kg.ha^{-1}.year^{-1}$ N + 0.5 $kg.ha^{-1}.year^{-1}$ P + 1.5 $kg.ha^{-1}.year^{-1}$ K.

– Inputs come from rainfall deposition (5–12 $kg \cdot ha^{-1} \cdot year^{-1}$ N + 0.2–3.0 $kg \cdot ha^{-1} \cdot year^{-1}$ P + 2.5–12 $kg \cdot ha^{-1} \cdot year^{-1}$ K), litterfalls (130 $kg \cdot ha^{-1} \cdot year^{-1}$ N + 12 $kg \cdot ha^{-1} \cdot year^{-1}$ P + 65 $kg \cdot ha^{-1} \cdot year^{-1}$ K), and fertilizers.

A big part of the output is the nutrient export with the husks. Altogether, it is quite an important exportation of K. In field, husk recycling should be promoted to decrease the net nutrients removal. In addition, the husk left in the cocoa plantation will contribute to better maintain soil carbon and organic matter.

Foliar diagnosis can be a good tool to monitor variations in a cacao field under controlled farming management over years because leaf analysis can provide a good idea of the nutritional status of a plant at a given time. Particularly, once the soil has been amended, leaf diagnosis can play a useful role in monitoring changes in the behaviour of cacao influenced by different cultivation practices. In particular, it is useful to determine continued fertilization requirements as this depends partially on the ability of the varieties to assimilate different nutrients (Chepote et al. 2013).

Both soil and foliar analyses have to be repeated at successive intervals because the nutrients levels and ratios in both soil and plant are in constant evolution. Particularly because in good soil conditions, the cocoa yields will increase and these surplus will induce new imbalances in the soil and will require new fertilizer doses (Viroux and Jadin 1993).

4.3 Effect of Nutrients on Some Cacao Physiological Characteristics

Fertilizers are required to increase yields and replace for nutrients exported by harvest or leached. However, if not properly used they can have negative effects. There is need to better know the impact of fertilizers on other characteristics of the tree and other production parameters.

4.3.1 On Cacao Growth and Yields

4.3.1.1 Macronutrients

Nitrogen

N is essential for the vegetative growth of the trees. It boosts the development of branches and leaves. It also greatly influences yields by increasing the number of flowers and pods, and by extending leaf life. It helps to fight dieback (Santana and Cabala 1982). In case of deficiency, the leaves fall and the branches gradually wither from tip to base, provoking the dieback of the tree. Tree growth slows down (Verlière 1981). Higher levels of nitrate N in the 14–110 ppm range in the nutrient medium usually produce marked increases in the cacao growth (Lockard and Burridge 1965; Loué 1961), while a level of 220 ppm tends to delay growth and produce characteristic symptoms of leaf scorch reminiscent of Ca deficiency suggesting a possible interaction between N and Ca in the cacao tree (Chepote et al. 2013). Similarly, this author noticed that leaf K was found to decrease with increasing N levels in the nutrient medium.

Phosphorus

P is necessary for the development of roots, wood and young buds, and for flowering. It is absorbed in the form of $H_2P0_4^-$ and HPO_4^{2-} ions to produce organic components (Morais 1998). P deficiency is responsible of older leaves fall. P deficiency also reduces cacao root development (Malavolta 1997).

Potassium

K is of major importance for cacao physiological development, particularly for the pod development and maturation. High K contents are found in soils that are regularly mulched. K is an antagonist of magnesium and calcium, which means that soils with a high K content commonly show Mg and Ca deficiencies and vice versa (Loué 1961). K deficient leaves fall off and are responsible of dieback at the final stage (Malavolta 1997).

Calcium

Ca is important for the development of terminal buds and flowers. Ca deficiency affects leaves but also root development (Malavolta 1997).

Higher levels of Ca in the soil increased the leaf concentrations of Ca, Fe, Zn and Mb but decreased the leaf N, Mn and Na.

Magnesium

Mg is one of the constituents of chlorophyll and is therefore important for photosynthesis. A prolonged period of Mg deficiency will cause older leaves to abscise whereas young leaves remain unaffected. Trees soon become defoliated (Chepote et al. 2013).

Sulphur

S facilitates the conversion of nitrate to ammonium in the amino-acid production process, ensuring high N use efficiency. Leaf veins are often paler than the lamina (Loué 1961).

4.3.1.2 Micronutrients

Boron

Boron is a micronutrient essential for all higher plants as a component of cell walls in shoots and roots, and for bean growth. Main causes of B deficiency are high pH and dry weather, or heavy rains in sandy soils. Boron is not a mobile element and is poorly mobilised within organic substances (Loué 1961). According to (Tollenaar 1967), foliar analysis data is less unreliable than soil data, and the author found the soil threshold to be 0.2 mg/kg (water-soluble B method). In boron deficient soils, cacao shows yield reductions of up to 40 %, deformed fruits, reduced bean size and are more prone to black pod disease (Lachenaud 1995).

Zinc

Zinc acts either as a metal component of enzymes or as a functional, structural or regulatory cofactor of a large number of enzymes. Zn deficiency is the most common micronutrient deficiency. Zinc is a component of enzymes found in the cocoa beans fermentation process (Loué 1961). Deficiencies occur first on the youngest parts of plants (Santana and Igue 1972). Zn deficiencies are more frequent where soils have high pH (overliming), high levels of P, or sandy soils with very low CEC.

Manganese

Mn is involved in chlorophyll production and photosynthesis. It helps in the proteins metabolism and synthesis. Deficiencies are more frequent where soils have high pH (overliming), organic soils, excess of Ca, Mg and K, or high levels of Fe, Cu and Zn.

Copper

Cu deficiencies occur in organic soils, or when pH is outside the range of 5.0–6.5, or where there are high levels of other metal ions such as Fe, Al and Mn. High doses of N can also be responsible of Cu deficiency.

Iron

The majority of iron is found in chloroplasts where it is essential for photosynthesis. In cases of Fe deficiency, chlorophyll synthesis is inhibited and leaf chlorosis develops. The leaves turn yellow, then white, but the veins remain green. Older leaves often remain green.

4.3.2 On Pods and Beans

The amount of nutrients provided by fertilization can increase or decrease some physiological characteristics of the pods and beans.

4.3.2.1 Number of Pods per Tree

(Lachenaud 1991; Verlière 1981)

- N has a positive effect on the number of pods per tree only when soil P and K are both present.
- P has a significant negative effect in the absence of K.
- K has a positive effect. The effect is increased (2.7-fold) when N is supplied at the same time.
- Ca and Mg deficient pods are susceptible to black pod, thus reducing the pod number per tree. This can also be observed with boron deficiency.
- Acid soils are often linked with higher black pod disease. However this might be due to the lower Ca level also observed in acid soil.
- The pod index (number of pods for 1 kg of dry beans or beans per pod) is not soil dependant, but a genetic trait.

4.3.2.2 Bean Size

(Lachenaud 1995)

- P and K have a significant effect on the bean size. The effect is negative when both P and K fertilizers are applied separately, but it is positive when they are supplied together.
- The individual effects of P and K are roughly the same (1.6 % of the control value), which explains why the main effects of either P or K are not significant.

4.3.2.3 Weight of Beans per Pod

- Fertilizers have no significant influence on the weight of fresh beans per pod or on the average weight of a bean. The number of beans per pods and their weight are influenced by water availability and the location of the pod on the cacao with the biggest pods being at the base of the trunk (Lachenaud 1995).

4.3.2.4 Mineral Composition of Beans

- In Côte d'Ivoire, no significant effect of fertilizer on the mineral composition of cocoa beans was found (Verlière 1981).

- The average mineral composition of the dry matter of a cocoa bean in Brazil was found to be: 2.34 % N; 0.41 % P; 0.97 % K; 0.08 % Ca; 0.15 % Mg (Malavolta 1997).
- Mg improves the chocolate taste by increasing the polyphenol and sugar contents in the beans.
- Zn can contribute to an improvement of the fermentation through producing enzymes that can help cocoa bean fermentation.
- The taste of chocolate was found correlated to the terroir; this includes many factors of which are the environment and varieties, and the type of soil (Araujo et al. 2014).

4.3.3 On Other Characteristics

4.3.3.1 Pest and Disease Resistance

- A positive effect of N fertilizer applied as urea was found on the population density of mealybugs *Planococcus citri* (Campbell 1984; Adomako 1972). The fact that N applications increase the swollen shoot because N makes cacao more attractive to mealybug, the main vector of the disease, was confirmed recently (Manu 2006). It could be worth to carry on further studies comparing the sap or bark soluble sugar profile and the amino acids profiles with nitrate N fed cacao versus ammonium N fed cacao.
- Boron in the soil (and applied as fertilizer) has a positive effect on pod rot reduction (Stemler 2012).
- Potassium and boron have an important role in increasing the resistance of cacao to vascular streak dieback (VSD), as demonstrated in Indonesia (Abdoellah and Nur'Aini 2012).
- Mn is the nutrient with the greatest influence on witches' broom tolerance (Nakayama 1995) because manganese is essential in the phenol compound formation process, which are important for tolerance to the disease.

4.3.3.2 Leaf Toxicity

- Application of N in the form of NO_3-N when not necessary can induce severe leaf-edge scorch. Cacao receiving NO_3-N showed leaf-scorch and deficiency symptoms for K, Ca and Mg, while those receiving urea-N showed only the P deficiency (Lockard and Asomaning 1965b; Lockard and Burridge 1965).
- High N levels (as nitrate) increase the amount of leaf-edge scorch (Lockard and Asomaning 1965a).
- Excess N increases the risk of black pod disease.

4.3.3.3 Tree Growth and Management

- Application of N promotes high vegetation growth. This will favour branch lodging, as observed in Côte d'Ivoire (Stemler 2012). Consequently, more intensive pruning will be required.

4.4 Current Challenges

Fertilization is a key practice for the sustainability of intensive cocoa production. However, there is still much to be done to better understand how to use them and the conditions to improve the recommendations. We will discuss below some particular points:

1. There are still many countries where extension services still recommend the use of a unique formula that does not take into account variations in soil and environmental conditions; this is particularly the case of the two largest world cocoa producers even though the use of several formulae has been proven (Koko et al. 2009; Snoeck et al. 2010). Fertilization must be adapted to the local soil and climate conditions; therefore, the use of more than one formula is encouraged. The model was developed and validated in West and Central Africa. It can be used for development and recommendations at different farm, regional or country level.
2. There is a need to better understand the functioning of cacao in various environments, particularly the effect of shade (agroforestry systems) or slightly shaded (often for tree-crop associations) as compared to full sun. There is a need to investigate the fluxes of the soil nutrients and how they are taken by the cacao trees.

4.4.1 Limitation of Using a Single Fertilizer Formula

Based on the observation that P and K are important and usually the only nutrients required, many countries recommend a single fertilizer formula containing P-K alone or plus a small amount of Ca-Mg; some micronutrients are also sometimes added, particularly when visual deficiencies have been noted. For example, in Ghana, the COCOBOD recommends the use of 'Asaase Wura', a concentrated fertilizer with 21 % P2O5, 18 % K2O, 9 % CaO, 6 % MgO, 7.5 % S, and 0.7 % Zn. In Côte d'Ivoire, 'Engrais cacao' is recommended, with 23 % P_2O_5, 19 % K_2O, 10 % CaO, 6 % MgO, and a small amount of S and Zn. This is the only fertilizer formula recommended throughout the country, regardless of the type of soil and environment.

Nevertheless, on the long term, the use of a single standard formula cannot fulfil the real needs of the cacao in the broad range of different situations because of the many possible interactions between the environment and farming practices, as explained above. This is why, as early as 1961, Loué had proposed using three different fertilizer formulae adapted to the three different geological origins of Côte d'Ivoire (Loué 1961). In other countries (e.g. Malaysia, Brazil, and Columbia), even more specific recommendations are given to cacao growers: fertilizer formulae are computed on the basis of critical soil N, P and K levels (Ling 1984).

The variability of responses to a single fertilizer formula was again demonstrated by Appiah et al. (2000) in 20 farmers' fields in the Eastern Region of Ghana comparing unfertilized plots with cocoa plots receiving P and K (such as triple super phosphate and potassium chloride) during. In 65 % of the farms, cocoa yields were increased thanks to fertilization; but in 33 %, the increase in yield was not significant and in 2 % there was no increase, even though the same farming practices and pest and disease controls were used. The main explanation for these differences is that the single formula with only two nutrients (P and K) cannot be suited to all farms being in so many environments and with so many cultural practices. A globally positive trend was found between cocoa yields and the use of 'Asaase Wura' fertilizer. However, statistical analysis revealed a low coefficient of correlation due to significant differences at the farm level in response to the single fertilizer used. In fact, 61 % of the cocoa plots benefited from the fertilizer application (with 6 % more than doubling the yield compared to the unfertilized control plot), while the remaining 39 % of cacao plots showed yield losses after the same fertilizer application.

In addition, regardless of the crop, soil nutrients interact with each other and when one nutrient is supplied in large quantities whereas the amounts of the others remain low, the latter may counteract the effect of the added nutrient. The balances between nutrients thus need to be taken into account to ensure optimum use of each nutrient by the crop and avoid limiting factor incident. These relationships were identified after long-term fertilizer trials on various types of soils by Jadin (1975) who concluded the need to develop localized and adapted fertilizer formulae and built up a first thematic map of cacao fertilizer requirement in Côte d'Ivoire. The formulae were given per administrative region, based on an extrapolation of the results of fertilizer trials conducted in the different regions (Fig. 4.8).

4.4.1.1 Validation of the Soil Diagnosis Tool

In Côte d'Ivoire, fertilizer trials were conducted at different locations under different types of soil and climatic conditions. At each location, unfertilized control cacao plots were compared with cacao that had been fertilized according to the soil diagnosis results, including soil correction and amounts to compensate for nutrients exported per yield of 1 $t.ha^{-1}$ of cocoa beans.

In Cameroon, Paviot (1977) used soil diagnosis to fertilize cocoa in a nursery and in young and mature plantations. He confirmed that the method is also suitable for nursery use.

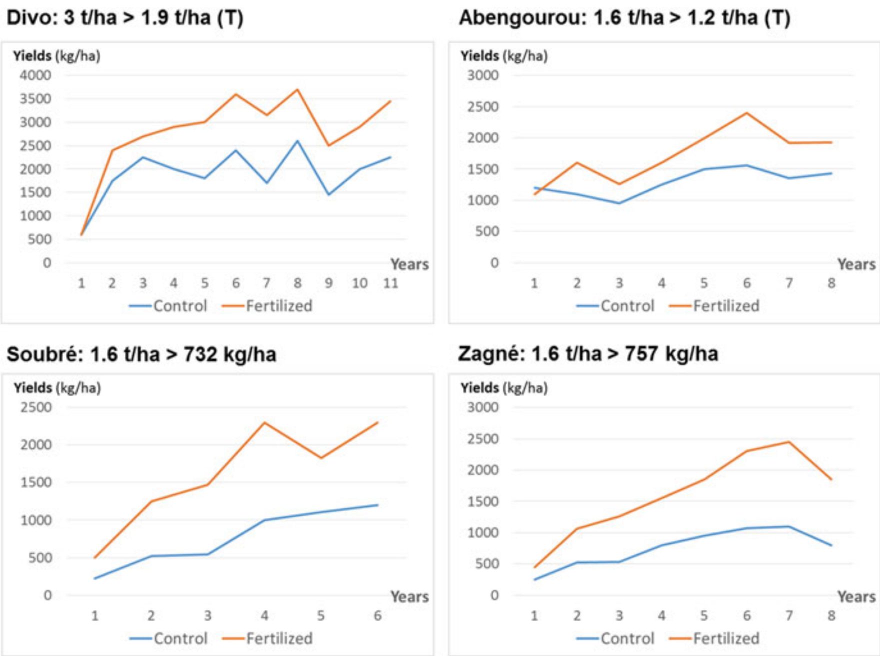

Fig. 4.7 Effect of fertilizer use per department in Côte d'Ivoire showing the significant efficiency of fertilizers in the various zones of Côte d'Ivoire. Fertilizer formulae were determined using the soil diagnosis tool (Koko et al. 2011)

In Ghana, validation of the soil diagnosis model began in 2009 on 120 young cocoa farms distributed throughout the cocoa belt. On each farm, unfertilized control cacao trees are currently being compared with trees that receive fertilizer in quantities that were computed according to the soil diagnosis method and trees receiving the traditional single fertilizer.

The advantage of using formulae calculated by the soil diagnosis model was demonstrated in a recent trial conducted in four regions of Côte d'Ivoire (Koko et al. 2011) over an 11-year period. Figure 4.7 shows that the average yields of fertilized plots were increased by at least 40 % compared to those in unfertilized plots (i.e. an increase of 580–1120 $kg \cdot ha^{-1}$). Better results were obtained in the Central (Divo) and Western (Zagné) regions, where the rainfall was higher than in the Eastern Region (Abengourou). In Divo, the average yields of fertilized plots were increased by at least 130 % compared to unfertilized plots (i.e. an increase of 1500 $kg \cdot ha^{-1}$) for 76 % of the plots.

In Togo, the soil diagnosis model was used to compare fertilized and unfertilized cacao plots. The results showed that most soils were poor in N, but also deficient in P and K (Tossah et al. 2006).

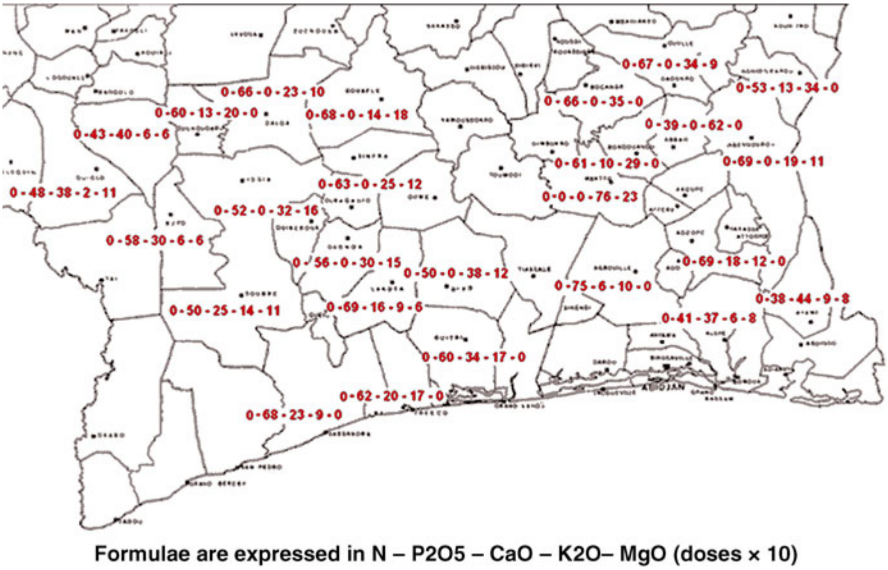

Fig. 4.8 Map of fertilizer needs per department in Côte d'Ivoire. Formulae were computed using the soil diagnosis tool (Jadin 1975)

4.4.1.2 Some Applications Using Soil Diagnosis

In Côte d'Ivoire, Jadin (1975) used the soil diagnosis model to build a map of the fertilizer formulae per department (Fig. 4.8). Twenty-six formulae were calculated from the results obtained in the regional research centres and were proposed to farmers.

In Ghana, the soil diagnosis was combined with a geographic information system (GIS) to begin a process of precision but sustainable agriculture by optimizing fertilizer application (Snoeck et al. 2010). The study was based on the analysis of soil samples collected in land units defined by combining climate data with soils from different soil associations that were defined using digital pedological (i.e. on different bed rocks) and climate maps of Ghana (Fig. 4.9).

At least, 30 different fertilizer formulae are required to fulfil the demand of the vast majority of cocoa farms. Extension services have a direct online access (www.wajae.org) to see what type of recommendation should be applied in their area.

In Togo, the soil diagnosis was used to determine the formulae required for cocoa production. It was demonstrated that all soils in the region were exhausted by overexploitation and all required N in addition to other nutrients, mainly P and K (Tossah et al. 2006). These results could be compared with those obtained in the Eastern Region of Ghana where the same types of soils are found, thus confirming the results obtained in both countries.

In Central Cameroon, the soil diagnosis model was used to monitor changes in nutritional status under young and old cacao plantations, compared with secondary

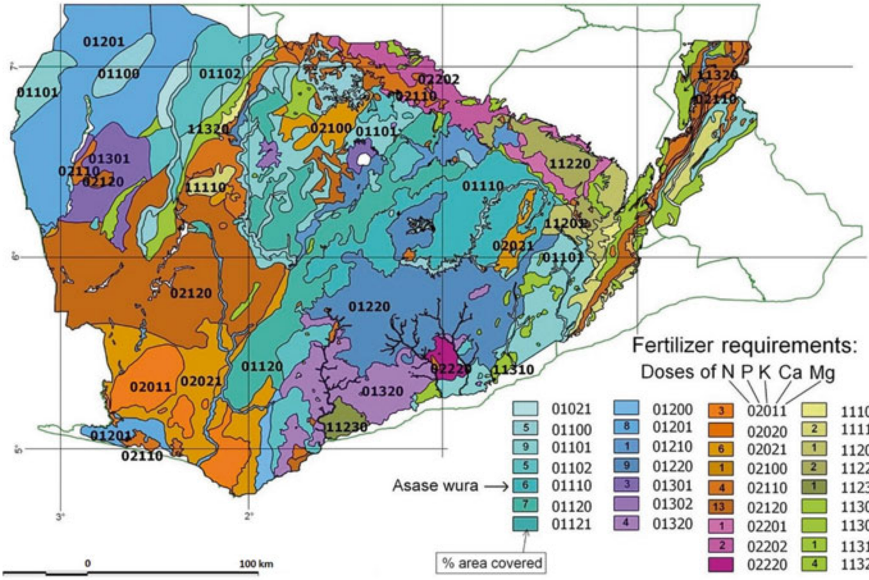

Fig. 4.9 Thematic map of cacao fertilizer requirements according to different climates and soil pedology in Ghana. Formulae were computed using the soil diagnosis tool (Snoeck et al. 2010)

forest soils (control). It was thus possible to assess the sustainability of cacao-based agroforestry in terms of soil development (Snoeck et al. 2009).

4.4.1.3 Limits to the Adoption of Fertilization by Farmers

After a century of cocoa production, after massive deforestation, after production of hundreds of thousands of tonnes of cocoa, much of the land of cocoa-producing countries is depleted (Appiah et al. 1997). Fertilization is required to sustain cocoa yields in the long-term, except in traditional cocoa agroforests where cocoa yields can be maintained for more than 70 years at level of 350 kg per hectare without noticing any yield depletion (Jagoret et al. 2011). In a cacao trial under permanent shade of Gliricidia, the cocoa productivity could even be maintained at around 700 kg cocoa beans per hectare without fertilization (Bastide et al. 2007).

However, despite its importance in maintaining cocoa yields, smallholder farmers do not use enough fertilizers. Three reasons are often given to explain this phenomenon (Ruf 2009): (1) farmers are not well informed about the correct use of fertilizers; (2) access to chemical fertilizers is difficult; and (3) chemical fertilizers are costly.

It is true that the fertilization process is somewhat complicated as productive cacao tree has specific requirements and the possibilities are endless if we consider that, for each plot, nutrients must be supplied in a balanced way to be effective. By reducing the number of formulae by grouping plots with similar needs, extension services can make fewer recommendations which hopefully will then be more easily accepted by farmers. In Ghana, for example, we were able to reduce the number of formulae to 33 (Fig. 4.9), which we felt to be an acceptable number to cover as many different situations as possible without jeopardising the quality of the recommendations. In Côte d'Ivoire, the final number of formulae proposed by Jadin (1975) was of 26 (Fig. 4.8).

However, cacao growers are aware of the importance of using fertilizers and are buying them as soon as they have access to them. The correlation between fertilizer adoption and cocoa price was clearly demonstrated by Ruf (2012). That is the reason why it is important that access to fertilizer for smallholders should be made as easy as possible. Ghana, which subsidizes 70 % of the price of fertilizer, is an example of a State that recognizes the importance of fertilizers in improving cocoa yields.

To reduce fertilizer uses, other sources of nutrients are currently being studied, for example the reuse of cocoa pod husks as a source of K, one of the most important cations (Ahenkorah et al. 1987).

4.4.2 Associated Trees

4.4.2.1 Shade Trees

Cacao being a plant native to the forest, it is particularly adapted to agroforestry systems. Particularly, such systems are known for their capability to improve soil fertility, particularly the soil organic matter (Jagoret et al. 2012; Snoeck et al. 2010). Moreover, shaded cacao plots have the advantage to provide environmental services and improved C sequestration (Gama-Rodrigues et al. 2010). However, under shade, cacao trees are not very productive and fertilization will consequently only result in a very slight increase in yield (Asomaning et al. 1971). On the opposite, because cacao can reach maximum photosynthesis with 400 µm photons.m^{-2}.s^{-1} (Balasimha et al. 1991; Bastide et al. 2003), no shade or light shade is leading to a higher overall nutrient requirement and thus a higher requirement of specific nutrients according to their physiological importance.

The impact of shading was demonstrated by Ahenkorah et al. (1987) at the Cocoa Research Station in Ghana in a trial comparing cacao crops with or without shade trees and with or without fertilization. The results showed that, over a 30 years period, cacao grown in full sun could produce twice as many cocoa beans as those under shade (Fig. 4.10).

However, the works also demonstrated the limits of full sun cultivation in the absence of fertilization (dotted lines). Indeed, in the no-shade and no-fertilizer treatment, the yields dropped after about 18 years, and thereafter, they were not better than those in the shade and no-fertilizer treatment. The decrease in yield followed the same trends as that of soil P, which was originally 24 mg.kg^{-1} in all treatments at the beginning of the trial and then dropped to less than 5 mg.kg^{-1} after 20 years in

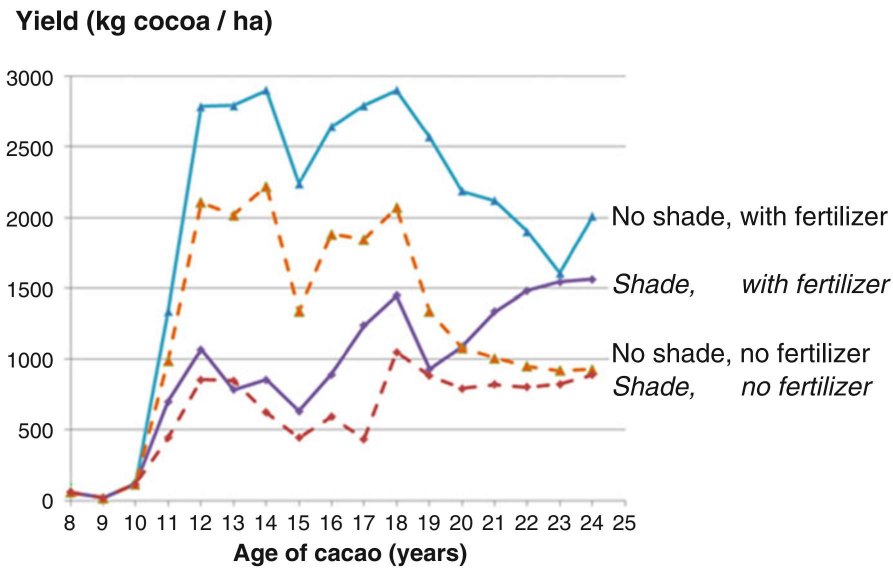

Fig. 4.10 Impact of shade and fertilizer on cocoa yield over 24 years (Adapted from Ahenkorah et al. 1974, Ghana)

both unfertilized treatments, while it remained at around 20 $mg.kg^{-1}$ in both fertilized treatments.

The trial also demonstrated the limits of using a single formula based on only two nutrients (P and K) over a very long period. Indeed, in the no-shade and with-fertilizer treatment, the yields dropped and were only slightly better than those in the shade and with-fertilizer treatment, with the former showing an upward trend and the latter a downward trend. This suggests that the addition of only two nutrients (P and K) over a 23-year period led to imbalances in relation to other nutrients (particularly Ca, Mg, N) in the no-shade and fertilized treatment; while the ratio between cations remained more balanced in the shade and fertilized treatment thanks to associated shade trees.

Under shade, N has no effect and, depending on the type of soil, phosphorus or potassium needs will predominate, whereas potassium will have a positive effect only if phosphorus nutrition is adequate. Considering the results described above, we can hypothesize that the poor response to N fertilizers is the result of the combined effects of litter and rainfall deposits which are sufficient to feed the system with N.

Without shade, N is essential. The role of potassium is related to that of N whereas high doses of phosphorus appear to be of secondary importance. With fertilization, cocoa yields increase significantly, whereas without fertilizer, yields quickly drop once the soil nutrients have been consumed.

In Ghana, Acquaye (1964) found that shade increased foliar levels of K by 14.3 % and of P by 12.9 %, but N only by 3.4 %. Shade reduced Ca by 19.5 %.

Cacao growing under shade was more balanced, but, in both cases, it is advisable to carry out soil analysis at least once every 5 years to adjust the fertilizer formulae and doses.

4.4.2.2 Tree Crop Associations

Intercropped trees can affect potential soil fertility, either by providing external nutrients, or on the contrary, by competing for nutrients.

For example, legume crops can provide N to associated cacao via their ability to fix atmospheric N thus making it available for the cacao. A 16 % increase in the litter N level was observed in cacao associated with *Erythrina* sp. compared to cacao associated with *Cordia* sp., a non-leguminous shade tree (Alpizar et al. 1986). However, legume intercropping does not systematically benefit the cacao as it depends on the levels of associated nutrients that may have limiting effects if their levels are low compared to that of N (Nygren and Leblanc 2009).

Conversely, the availability of certain nutrients for cacao may be reduced due to competition with associated trees. For example, competition for phosphorus between cacao and shade trees such as iroko (*Milicia* sp.) was observed in Ghana (Cunningham and Arnold 1962; Isaac et al. 2007).

4.5 Conclusion

This review highlights that fertilization is an important parameter for cacao cultivation sustainability. The soil should be able to provide the necessary nutrients to compensate for those lost in cocoa production. Although rainfall and the transfer of nutrients through litter can compensate for the nutrients removed by cocoa harvesting (up to 700 kg dry beans per hectare), more intense cacao cultivation induces an ecosystem imbalance, responsible of continuous nutrients depletion.

The first fertilizer trials revealed that significant yields can be achieved when cacao is fertilized and grown without shade. Mineral fertilization thus quickly emerged as a key way to increase cocoa yields. However, in light of the diversity of cropping situations, fertilizer doses and formulae should be adjusted according to the prevailing conditions, particularly regarding shade and soil.

In nature, cacao feeds from nutrients taken from the soil. Soil correction is thus the first step required to optimize cacao growth and productivity. Works carried out in various cocoa producing countries have given rise to guidelines for soil nutrient applications. The recommendations currently used can be divided into three levels: (1) a generic all-purpose formula; (2) more accurate formulae calculated on the basis of the soil fertility status. They are based on the comparison of current nutrients levels with predefined thresholds which were first defined in local fertilizer trials; (3) even more accurate formulae that take both the thresholds levels and balances between nutrients into account. The latter approach is more complex and has required the development of a decision support tool called "soil diagnosis". This tool has been validated for different soils and environments.

It is generally accepted that leaf diagnosis is not adequate to predict cocoa productivity and that it is insufficient for determining the nutritional needs (in the form of fertilizers) of existing cocoa farms whose cropping history and techniques are not known. Soil diagnosis is preferable in these circumstances. However, leaf diagnosis is useful to detect nutrient imbalances in the plant to detect incorrect use of fertilizer. Its advantages will be that it enables fine-tuning the fertilizer formula by highlighting any nutrient deficiency. Therefore, it is a good option to combine both approaches (soil and leaf) when the history of the cacao plot is known and after having corrected the soil to fit the cacao requirements and looking for intensive cacao cultivation.

Cacao responds well to fertilizer applications only if the management, cropping practices, soil and climatic conditions are favourable for optimum growth and yield and if the soils can supply the nutrients required on time. How to apply the fertilizer and the choice of ingredients used in the formula can determine the nutrient absorption efficiency, especially in marginal soil conditions. Also the fertilizers should be applied only on top of active roots to ensure optimum uptake. Poor application techniques are detrimental in view of the scorching and damage caused to the superficial root system especially in immature cocoa.

Cocoa farmers are aware of the importance of using fertilizers but fertilizers are costly and need to be used with a minimum of knowledge because nutrient excess or deficiency can affect yields and soil health as well as production costs.

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