# Plant Nutrition in Tropical Forestry

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L. Pancel, M. Köhl (eds.), *Tropical Forestry Handbook*,
DOI 10.1007/978-3-642-41554-8_105-2

## Introduction

The chapter summarizes available information on nutrition and fertilization of natural forest and tree plantations in tropical regions with emphasis on about 30 species of economic relevance in lowland wet tropical America (mainly *Eucalyptus* ssp., *Tectona grandis*, *Acacia mangium*, and *Pinus* spp.). Information on dry or seasonally dry tropical forests is scarce. Recent documents on tropical forest and plantation nutrition considered in this review include Fisher and Binkley (2000), Reddy (2002), Hartemink (2003), Rodríguez and Alvárez (2010), Paudyal (2012), and Alvarado and Raigosa (2012).

Forest fertilization in tropical countries was initiated in the middle of the twentieth century (Mustanoja and Leaf 1965) with the expansion of forest plantations around 1950 (Evans 1992). However, the gain in knowledge in forest nutrition in tropical areas is very slow (Figueroa 1986) as reflected by the fact that studies on the subject were initiated in 1970 in Cuba and in 1980 in Brazil (Herrero 2001) and in Central America (Alvarado et al. 1997). For many years forest nutrition was based on the concept that trees should grow in soils other than those devoted to planting crops. Forest operations should be carried out in poor soils leaving good fertile irrigated soils to crops, a concept accepted by foresters that never considered the nutritional or other needs of the trees (Nwoboshi 1975). This hypothesis of trees growing without inputs lasted for years and is actually accepted in many parts of the tropical world. Today we know that trees can grow in that kind of soils but also that in order to maximize productivity of plantations, adapted species to restringing conditions should be employed and soil amendments should be implemented to overcome growth impediments (i.e., drainage, subsoiling, additions of fertilizers and lime, etc.). We also know that after solving the nutritional problems of a site, other factors like water stress and weed control should be taken into account to avoid nutrient and water competence and possibly allelopathic effects from the weeds (Ladrach 1992).

During the past decades demands for forest products have drastically increased and natural forest resources mainly in the tropics have been steadily depleted. In consequence there have been increases in afforestation and replanting programs, which in the tropics have generally been on relatively infertile soils where nutritional problems have soon become apparent. Parallel to these developments, the need for increased productivity has resulted in the use of more intensive production techniques including the use of fertilizers, with increasing interest from both silviculturists and physiologists in the nutritional problems encountered in tropical conditions (Brunck 1987; Reis and Barros 1990).

The chemical analysis of plants usually reveals the following elements of vital necessity: carbon (C), hydrogen (H), and oxygen (O), which constitute the organic matter and represent about 90–95 % of the dry weight. C and O, which are supplied for photosynthesis by the air, can hardly become limiting factors, while the supply of H depends on the availability of water. The other elements constitute on the average 5–10 % of the dried plant material and are the soil's contribution to the growth of the plants: nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S), which are considered as macronutrients, and manganese (Mn), iron (Fe), zinc (Zn), copper (Cu), boron (B), chlorine (Cl), and molybdenum (Mo), which are called micronutrients due to their lower quantities in the tissue in comparison with the macronutrients. The reader is referred to specific papers while looking for information on individual elements like P (Ballard 1980), S (Johnson 1984), Zn (Boardman and McGuire 1990), or B (Stone 1990; Lehto et al. 2010). Today, several other elements are known which will be useful for some physiological processes or could replace other nutrients in some functions [cobalt (Co), silicon (Si), sodium (Na), etc.]. These elements are, however, of minor interest in tropical forest nutrition management.

The fundamental physiological relationships between mineral nutrition and growth are the same in trees as in other plants. The basic knowledge about the nutrients needed for plant growth, the nutrient uptake mechanisms, and the function of nutrients in plant physiology has been extensively examined and summarized (e.g., Bowen and Nambiar 1984; Marschner 1986; Mengel and Kirkby 1987; Wild 1988). On the other hand, there is little known, especially in the tropics, about the complex long-term relationship between soil nutrient status and nutrient availability on the one hand and tree nutrition as well as tree growth on the other.

In this chapter, information about tropical tree nutrition and nutrient cycling is summarized as it is valuable to know for nutrient management in silviculture. In the following sections recommendations for diagnosis of mineral disturbances, using visual and analytical methods, discuss the problems associated with these approaches. The last paragraphs concern practical conclusions for nutrient management and summarize experiences on fertilization.

## Nutrient Storage and Mineral Cycling in Tropical Natural Forest and Forest Plantations

### Plant Adaptation to Nutritional Constraints and Ecosystem Modification by Plants

An understanding of nutrient cycling is necessary for improving site fertility by nutrient management with or without use of fertilizers. There are several reviews and case studies on this subject (e.g., Switzer and Nelson 1972; Singh 1982; Miller 1981, 1984; Turner and Lambert 1983; Jordan 1985; Heal et al. 1997; Reddy 2002;

Alvarado and Raigosa 2012; Chapin III et al. 2012). To improve upon sustainable management of natural forest and short-rotation plantations, especially when nutrient deficiencies are common, fertilization plans based on better knowledge on tree physiology, forest nutrition, and morphological properties of trees related to their reproduction, survival, and growth characteristics are required (Gómez and Burley 1991; Grubb 1995; Medina 1995). Under natural forest conditions the majority of the nutritional problems are related to nutrient cycling, root growth habit of the species, its rotation length, and the large amount of biomass of the trees (Ballard 1980).

To overcome nutritional problems plants might have to adapt to environmental conditions or the sites should be amended to correct for such problems. Various adaptation mechanisms of trees to nutritional stress conditions had been described, but no one species manifests all of them (polygenetic inheritance), and cases where two or more mechanisms act together are considered rare. Many articles are available to explain mechanisms of adaptation to soil physical constraints (Vitousek 1984; Reis and Barros 1990), low or high soil fertility (Vitousek and Standfor 1984; Bond 2010; van Breugel et al. 2011), nutrient constraints such as soil acidity (Wright 1976; Bouldin 1979; Robson 1989; Baligar and Duncan 1990; do Vale et al. 1996; Vitorello et al. 2005; Poschenrieder et al. 2008), phosphorus deficiencies (Rao et al. 1999), salinity and waterlogging conditions (Holdridge et al. 1971; Wright 1976), and light interception (Ortín 1997; Herbert and Fownes 1999; Soethe et al. 2008). How plants modify the ecosystems is also being studied by various authors (Duchaufour 1977; Nath et al. 1988; Blazer and Camacho 1991; Márquez et al. 1993; Binckley and Giardina 1998; Widmer 1999a, b; Tobón et al. 2010; Hafich et al. 2012; Samndi and Jibrin 2012); Eviner and Chapin III (2003) recommend the use of the functional matrix concept, which builds upon the functional group and single trait approaches to account for the ecosystem effects of multiple traits that vary independently among species.

Chapin (1980) and Chapin et al. (1986) mention that the majority of species growing in infertile soils are tolerant to natural stress conditions through mechanisms like (i) synchronized low growth rates with a high photosynthetic capacity and low nutrient absorption, (ii) high biomass production of long-lasting roots commonly associated with mycorrhizae, (iii) low response to fluxes or additions of nutriments, (iv) low nutrient demands along the year to produce new tissue, and (v) low throughfall nutrient loss from old leaves. Poschenrieder et al. (2008) utilize soil and plant variables to estimate the risk of Al toxicity on trees; the author measured in the soil (i) the Al in soil solution, (ii) the percentage of base saturation, and (iii) the relationship exchangeable bases/exchangeable Al (values $<1$ indicate potential risk for toxicity and tree growth). In the tissues Poschenrieder et al. (2008) estimated (i) increases in Al/Ca ratio, (ii) inhibition of fine root development, (iii) inhibition of root elongation, (iv) callose accumulation, (v) staining of specific tissues, and (vi) reduction of species abundance in the ecosystem.

## The Nutrient Cycle

Nutrient circulation in the soil-plant interface starts with a process of absorption and ends with the return of elements to the soil after decomposition of organic residues and nutrient losses due to stemflow and throughfall (Yadav and Mishra 1982). The time required for the cycle to be completed is of nutritional and silvicultural importance since it relates to the nutritional demand distribution, the translocation capacity of the nutrient, the physiological function of the nutrient, and environmentally to the silvicultural practices which also affect the biological activity of decomposer organisms. It is accepted that nutrient cycling in tropical forest and plantations is highly variable and represents the process by which elements are absorbed and returned by living organisms from the ecosystem. It represents a process that relates biological, atmospherical, and geochemical interactions (Switzer et al. 1968; Heal et al. 1997; Hedin et al. 2003).

Originally researchers considered that nutrient cycling in humid tropical forests occurred on very rich ecosystems with high rates of net primary productivity. Later on it was discovered that the soil environment plays a very important role on the nutrient cycling (Vitousek and Standfor 1984) and that net productivity frequently was limited by the availability of soil nutrients, at the time understood as mainly dependent on soil acidity or pH (Silver 1994). Then Herbert and Fownes (1999) proved the hypothesis that a plant adapts to a nutrient availability by altering carbon and nutrient efficiency utilization (NUE) is always limited by the compensation between NUE and energy utilization efficiency.

Stone (1968) discovered that under different circumstances nutrient cycling is not enough to supply the maximum growth of trees for many consecutive years even though the species might be adapted or screened to the chemically and physically constraining properties of the environment. Considering the ecosystem as a whole, Ortín (1997) was able to recognize three groups of species: (i) those intolerant to foliar area exposure and low P and K availability, (ii) those high in lignin and fiber, and (iii) other plants not as tolerant as the ones previously mentioned. Due to changes in nutrient availability with altitude in the Ecuadorian Andes forests, Soethe et al. (2008) demonstrated that N, P, S, and K concentrations are lower at low elevations and the ratios C/N (25:1 and 34:1 at 2,400 and 3,000 masl) and C/P (605:1 and 620:1 at 2,400 and 3,000 masl) measured in the upper organic layer of the soils increase with altitude not affecting the foliar relationship N/P 11.3:1 and 8.3:1 at 2,400 and 3,000 masl, implying that N supply is more important than P supply at higher elevations.

Nutrient cycling includes additions, losses, transformations, and translocation of materials occurring simultaneously in an open system which through time affects the foliar concentration of nutrients via extraction, absorption, translocation, and utilization and finally defining tree growth and vigor (Cannon 1983a). In the case of forest ecosystems, the nutrient cycle of elements is being mainly circumscribed to the addition of nutrients from organic residues but also considering as important nutrients released by rock weathering and dry and wet additions from rain and wind. A simplified diagram of major pathways of the cycling of residues is presented in

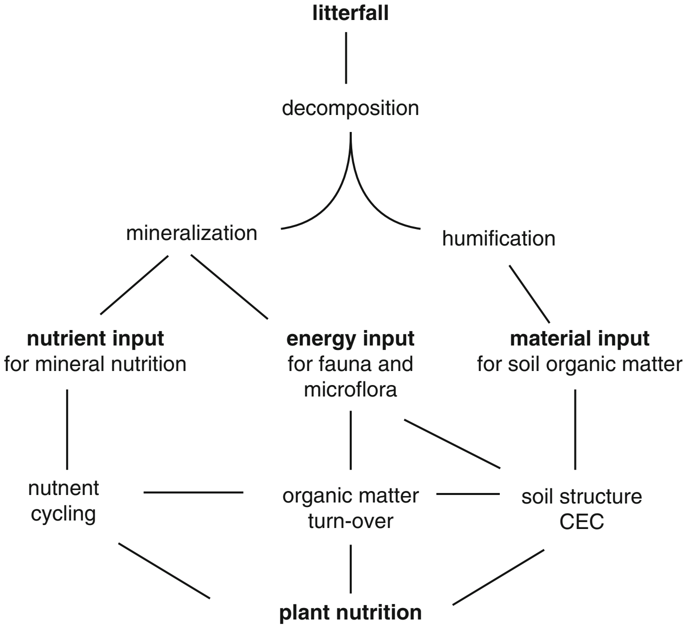

**Fig. 1** Simplified scheme of organic residue nutrient cycling in plantations and forest ecosystems (Adapted from Bernhard-Reversat and Loumeto 2002)

Fig. 1. Residues can be accumulated, burned, or decomposed on the soil surface or below ground. Burning residues release and volatilize nutrient immediately (one shoot); accumulated residues due to very low temperature, waterlogging conditions, or hardiness will not contribute to a large extent in nutrient cycling. The remaining residues can be mineralized or transformed into soil organic matter (SOM) through humus formation releasing nutrients and sources of energy for microorganisms and trees to use (Bernhard-Reversat and Loumeto 2002).

Soil organic residues represent materials accumulated above- and belowground falling from living organisms, such as leaves, twigs, reproductive parts, bark, and wood, including decomposing roots and root exudates and dead bodies and exudates from living animals that live in and around the soil (Wanek et al. 2008). How residues decompose, accumulate, and release its components (i.e., nutrients) in the system conforms to the nutrient cycle, a process which is considered to be similar in tropical natural forests and forest plantations (Bernhard-Reversat and Loumeto 2002). The analysis of residue composition and its cycling is being useful as diagnostic criteria to better estimate tree and forest growth (Heaney and Proctor 1989).

## Nutrient Storage: Quality and Quantity of Biomass Production in Tropical Forestry Ecosystems

**Effect of Soil Quality**: The major differences in soils, as related to tree growth, were identified while separating soils of the world into "pedocals" and "pedalfers" (Marbut 1927) to recognize those which accumulated mainly Ca versus those which accumulated Al and Fe. Then information related to nutrient cycling (Jordan and Herrera 1981; Sarmiento 1984) was considered as pertinent to (i) oligotrophic of low natural soil fertility (i.e., Spodosols, Psamments, and Histosols), (ii) dystrophic ecosystems of low to medium natural soil fertility (i.e., Oxisols and Ultisols), or (iii) eutrophic ecosystems of high natural soil fertility (i.e., Alfisols, Vertisols, and Rendolls). In dystrophic ecosystems (Sarmiento 1984; Bruijnzeel 1991) (i) nutrient cycling and biomass production are possible in a close system with little amount of nutrient losses, (ii) in secondary forests the quantity of available nutrients partially determines the duration of ecological succession steps, and (iii) most nutrients in natural tropical forests and plantations are tied to the aerial biomass and residues above ground. On the contrary in eutrophic ecosystems (Grimm and Fassbender 1981a, b; de Graff 1982; Bruijnzeel 1991; Szott et al. 1991), (i) nutrient cycling occurs in a more open system that allows large amounts of nutrient losses and (ii) most nutrients in the ecosystems are in the soil. However, Aerts (1996) concludes that the hypothesis of plants adapting to dystrophic ecosystems through improving nutrient recycling and translocation is not true since nutrient resorption in eutrophic conditions allows more nutrient accumulation in both foliar and total biomass.

Fassbender (1978), citing Scheffer and Ulrich (1960), mentioned the existence of dystrophic, oligotrophic, and eutrophic soils grouped on the bases of their moisture and nutritional regimes. More recently Sarmiento (1990) and Schargel (2011) using as criteria the sum of bases (cmol (+) 100 g soil) separate soils as (i) hyperdystrophic (<1), (ii) dystrophic (1–2), (iii) hypodystrophic (2.1–5), (iv) dystrophic, (v) mesotrophic (5–10), and (vi) eutrophic (>10), allowing to accommodate species previously recognized as calcicoles or calcifuges/acidophilic more appropriately. Recently tree species can be classified as foliar Al accumulators or non-accumulators (Costa et al. 2002), and according to various authors (Chenery and Sporne 1976; Pérez et al. 1993; González and Fisher 1997; Cornelius and Mesén 1997), this will allow to separate trees and shrubs as (i) non-accumulators (<100 mg Al $kg^{-1}$), i.e., *G. arborea*, *L. leucocephala*, and *T. grandis*; (ii) accumulators (100–400 mg Al $kg^{-1}$), i.e., *Graffenrieda latifolia*, *Miconia dodecandra*, *Richeria grandis*, *Coffea arabica*, and *Camelia sinensis*; and (iii) hyper-accumulators (>10,000 mg Al $kg^{-1}$), i.e., *Vochysia ferruginea* and *V. guatemalensis*.

**Effect of Tree Species**: Total biomass of a tree represents all of the above- and belowground biomass, and it is commonly measured as aboveground biomass due to the problems of economically and physically quantifying belowground biomass. Haggar and Ewell (1995) mention that total biomass is affected by the kind of tree species that dominate the ecosystem since dicot and monocot tree species in tropical wet forest possess different growth mechanisms, the latter contributing with larger amounts of wood and nutrients to recycle. Several studies on tropical conifers and broad-leaved species show that the highest concentrations of N, P, K, and Mg are found in the foliage but decline in the bark, branch wood, and stem wood (this is particularly true in teak and eucalyptus). On the other hand, the Ca concentration in the bark is at the same level or higher as in the foliage. Trees accumulate nutrients as their biomass increases. On a dry weight basis, the highest accumulation of nutrients will be in the foliage in early years and with time in the bole wood. Studies conducted in the Andes of Colombia mention the addition of residues in 9–12-year-old plantations of *P. kesiya*, *P. patula*, *P. oocarpa*, and *C. lusitanica* in the order of 3.4, 2.1, 1.9, and 1.6 Mg ha$^{-1}$, respectively, considering that *P. kesiya* is the most efficient of the species compared in absorbing and recycling nutrients; the lower values for *C. lusitanica* are attributed to the fact that this species' functions are associated with endomycorrhizae and the others to ectomycorrhizae (Cannon 1983a). For *Quercus humboldtii* (C $>$ N $>$ Ca $>$ K $>$ Mg $>$ S $>$ P), *P. patula* (C $>$ Ca $>$ N $>$ K $>$ S $>$ Mg $>$ P), and *C. lusitanica* 42-year-old plantations, Ramírez et al. (2007) and León et al. (2011) mention additions in the order of 7.5–7.9, 7.8–8.4, and 3.5–3.7 Mg ha$^{-1}$, respectively, with slow return of residues and nutrients of *C. lusitanica* due to the lower C/N ratio of its litter. León et al. (2011) measured residence time of the residues finding values of 3.3, 2.1, and 1.8 years for cypress, pines, and oaks, the last genera contributing more nutrients with time to the ecosystem biochemical cycle.

Tree species from the tropical lowland wet forest have different nutrient concentrations (Ortín 1997); some absorb large quantities such as *Croton smithianus*, while others absorb lesser amounts (*Calophyllum brasiliense*) but all of them in the order N $\gg$ K $>$ Ca $>$ Mg $>$ P (Table 1).

Normally, nutrient concentration on residues is (i) higher in Ca and N than in K, Mg, and P, (ii) higher on leaf rather than branch residues, and (iii) higher on residues from deciduous species (i.e., teak) than evergreen species (i.e., pines or eucalyptus). Sharma and Pande (1989) report that leaf residue nutrient concentration decreases as the amount of falling residues and the tree biomass increases. Under different environmental conditions and vegetation cover, Geigel (1977) found in Cuba that the concentration of nutrients under *T. grandis*, *Hibiscus* sp., *S. macrophylla*, and *P. caribaea* contained more Ca than N and Mg and much lower quantities of K, P, and Na. Ogbonna and Nzegbule (2009) also reported Ca, K, Na, and P contents to be higher in residues under *G. arborea* plantations than under *P. caribaea* plantations. While testing the nutritional value of primary tropical wet forest residues on the growth of secondary forests of the same area, Wood et al. (2009) found that tree leaf foliage biomass increased but diameter did not nor soil fertility parameters measured.

**Effect of Ecological Succession Stages, Plantation Age, and Plantation Density**: Bruijnzeel (1991) differentiates (i) primary and secondary forests in advanced stages of succession that mainly depend on nutrient cycling to sustain growth, N fixation, and other nutrient sources like dry and wet additions from (ii) forest plantations on early stages of succession with high photosynthesis rates

**Table 1** Foliar nutrient content of 11 species of the lowland tropical wet forests of Costa Rica (Adapted from Ortín 1997)

| | Samples | Median (%) | | | | | |
|---|---|---|---|---|---|---|---|
| Species | No | N | K | Ca | Mg | P | Total |
| *Croton smithianus* | 5 | **4.27** | **1.45** | **0.45** | **0.29** | **0.22** | **6.68** |
| *Apeiba membranacea* | 10 | **2.67** | **1.61** | **0.90** | **0.79** | **0.11** | **6.08** |
| *Rollinia microsepala* | 7 | **2.34** | **0.82** | **1.10** | **0.54** | **0.12** | **4.92** |
| *Simarouba amara* | 18 | **2.62** | **0.83** | **0.58** | **0.31** | **0.09** | **4.43** |
| *Virola sebifera* | 20 | **2.34** | **0.48** | **0.74** | **0.40** | **0.08** | **4.04** |
| *Laetia procera* | 10 | **2.52** | **0.47** | **0.45** | **0.30** | **0.10** | **3.84** |
| *Pentaclethra macroloba* | 20 | **2.84** | **0.42** | **0.22** | **0.17** | **0.09** | **3.74** |
| *Tapirira guianensis* | 19 | **1.88** | **0.36** | **0.92** | **0.40** | **0.08** | **3.64** |
| *Qualea paraensis* | 15 | **1.63** | **0.37** | **0.78** | **0.32** | **0.06** | **3.16** |
| *Vochysia ferruginea* | 20 | **1.86** | **0.34** | **0.63** | **0.17** | **0.06** | **3.06** |
| *Calophyllum brasiliense* | 15 | **1.45** | **0.29** | **0.36** | **0.12** | **0.05** | **2.27** |
| Range | | **1.45–4.27** | **0.29–1.61** | **0.22–1.10** | **0.12–0.79** | **0.05–0.22** | |

and high demand of nutrients in short periods of time, at least during the first 5–10 years of growth, that dominate vast riverine areas where large amounts of residues are added to the system and less soluble forms of P and K are converted to more soluble forms (Salo et al. 1986; Szott et al. 1999). Some authors assume that nutrient requirements of trees diminish with plantation age since annual growth increments also decrease with plantation rotation age (Miller 1981, 1995). Davidson et al. (1998) add that trees in early succession stages of growth have a larger foliar and wood concentration of nutrients, a fact that correlates with high growth rates, a superficial root math, and high soil coverage that minimizes soil erosion and leaching. In terms of foliar nutrient concentration, Gonçalves et al. (2005) also mention that species of medium succession stages of development like *Swietenia macrophylla* are higher when shaded, while species of late succession stage of development like *Dipteryx odorata* are not. Other authors (i.e., Segura et al. 2006b) also report that growth pattern and nutrient content of aerial biomass components vary with plantation age since wood production increases with time; similar results were found by Jiménez and Arias (2004) while studying root biomass and nutrient content for various tropical forest species. Residues returned to the environment are generally plantation density dependent. Akinnifesi et al. (2002) found that residue turnover increased in plantation density of *T. grandis* that was not affected in plantations of *Shorea robusta* and decreased in plantation density of *E. camaldulensis* and *Pinus roxburghii*.

**Effect of Understory Vegetation**: A less studied source of residue production is that related to understory vegetation in natural forest and plantations. These residues might be abundant or not depending on the main species of the ecosystem and plantation management. The nutrients associated with this biomass and residues are relevant not only for their amount and quality but also because the volume of soils they explore is different to that explored by the principal species recycling nutrients that otherwise could be leached away of the system. Frequently weeds are considered also a part of this type of vegetation even though they might play an important role in preserving nutrients in the ecosystem like absorbing N from the mineralization of residues left on the ground after harvest. As a way of weed control, some small wood producers raise cattle in the plantations “improving nutrient dynamics” but also negatively affecting the quality of the wood produced.

**Effect of Elevation and Associated Variables**: Residue production in mountain tropical forests is lower than the one found in tropical lowland forests due to a lower rate of photosynthesis and the effect of strong winds that reduce tree growth. Heaney and Proctor (1989) measured residues added to Andisols at 100, 1,000, 2,000, and 2,600 masl in Costa Rica to be in the order of 9.0, 6.6, 5.8, and 5.3 Mg $ha^{-1}$ $year^{-1}$. Soethe et al. (2008) did not find the uniform effect of altitude on similar soils of Ecuador at 1,900, 2,400, and 3,000 masl, but they found that total amounts of N, S, and Mg were higher over 3,000 masl and that contents of P, K, and Ca were not affected by altitude. Szott et al. (1999) mentions that biomass accumulation in wet tropical secondary forests is essentially linear during the first 10 years of growth and in the order of 4–15 t $ha^{-1}$ $year^{-1}$, while in dryer areas biomass accumulation accounts for 1–8 t $ha^{-1}$ $year^{-1}$ due to water availability limitations. Nambiar (1998) and Montagnini (2002) report annual increments of wood biomass production from broad-leaved plantation species in the order of 1–28 t $ha^{-1}$ $year^{-1}$, while short- and medium-term plantations might yield 1–2 to 25–30 $m^3$ $ha^{-1}$ $year^{-1}$, respectively. Fast-growing species like *Gmelina arborea* and *Eucalyptus saligna* yield 10–20 and 8–28 t $ha^{-1}$ $year^{-1}$ and other species with lower growth rates like *Swietenia* spp. and *Tectona grandis* 1–4 and 3–12 t $ha^{-1}$ $year^{-1}$, respectively. Under African conditions Australian acacias produce larger amounts of residues than *Terminalia*, teak, and eucalyptus and even more than cypress and pines.

## Soil Litter Deposition and Turnover

Tropical forests and plantations benefit from nutrient release after mineralization of residues through nutrient cycling. Some elements, remarkably K, can be washed from foliage by rainwater and large amounts of N can be retranslocated to more woody tissues before senescence of the tissues contributing less to the nutrient cycle (Aerts 1996). Nutrient cycling relevance was summarized by Nye and Greenland (1960) and later reassumed by Sánchez (1985) and Jordan (1985) who distinguished the management of residues in the "slash-and-mulch" system that mimics the effects of slow fertilizer release from the "slash-and-burn" system which causes effects similar to the starting fertilizer (lime) effects of commercial fertilizer additions. Nutrient cycling is of particular relevance for secondary forests in dystrophic environments where low nutrient availability partially defines succession step length. Apart from the nutrient effects under the slash-and-mulch pathway of nutrient cycling, it is worth to mention that residues left on the ground are focuses for disease and plagues and also fuel sources for forest fires.

**Amounts of Residues and Nutrients Deposited**: In a tropical forest plantation, the residues added to the system range from 5 to 20 Mg $ha^{-1}$ $year^{-1}$, and nutrients associated with the residues represent 50 % of total nutriments associated with aerial biomass contributing with 40–45 % of the N, 54 % of the K, 56 % of the Mg, and 28 % of the P (Montagnini 2002). Geigel (1977) and Akinnifesi et al. (2002) indicate that the amount of residues and associated nutrients increases linearly with plantation age mainly due to woody tissue production until they reach 8–10 years of age and attain its maximum growth. The effect of sites and species on residue addition is demonstrated by Akinnifesi et al. (2002) at Ibadan, Nigeria, in 10-year-old plantations of *C. alliodora*, *G. arborea*, *Irvingia gabonensis*, *Leucaena leucocephala*, and *Pterocarpus soyauxii* that deposited residues in the range of 4.6–9.7 Mg $ha^{-1}$ and those of 7–10-year-old plantations of *P. caribaea* that ranged 5.9 Mg $ha^{-1}$. Samra and Raizada (2002) found that the amounts of residues deposited by five eucalyptus plantations in Nilgiris, India, ranged between 2.1 and 6.8 Mg $ha^{-1}$ $year^1$ with nutrient quantities of Ca $>$ N $>$ K $>$ Mg $>$ P, indifferently of the species compared (*E. acmenoides*, *E. eugenioides*, *E. paniculata*, *E. pilularis*, and *E. propinqua*). Deposition of residues on fast-growing plantations of *E. terricormis*, *E. globulus*, and *P. patula* is normally more than 2 Mg $ha^{-1}$ $year^{-1}$, mainly during the early stages of growth. Exceptionally high residue additions are mentioned for *Casuarina equisetifolia* (8.7–29.6 Mg ha$^{-1}$ year$^{-1}$) growing on good soils and more than 2,000 mm of rain per year in different regions of India.

**Amounts of Residues Deposited Along the Year**: Residue deposition is not constant throughout the year. In tropical deciduous forests or plantations, the major addition of foliage and root residues occurs at the beginning of the dry season, like what happens after pruning or thinning of the plantations. Most of the litter deposited starts to mineralize at the beginning of the wet season creating a nutrient boom that enhances new root growth and the formation of new roots (fertilizer if needed should be added later considering this as natural addition of nutrients). The dilution effect of nutrients in the canopy created after regrowth can reduce growth rates of trees unless foliar deficiencies are corrected through fertilizer additions at the pick of the rainy season. Apart from residues added after selective extraction of wood from the forest or pruning, thinning, and harvest of the trees in plantations, other natural additions of residues are the result of falling leaves and twigs that depends mainly on drastic climatic changes and also on natural soil fertility, age of the trees, season of the year, species composition, and occurrence of catastrophic events (i.e., hurricanes, acid rains, earthquakes, etc.). While comparing tree phenology in the wet and the seasonally dry tropical forests of Costa Rica, Frankie et al. (1974) found that in the wetter environments species diversity is higher (185 species) than in the dryer environments (113 species) and that a larger amount of deposited leaves occurred at different times of the year (17 % of trees defoliate in the less humid months of the wet areas, while 75 % of the trees defoliated during the clear dry season in the seasonally dry forest).

## Nutrients in the Biomass

Nutrients in the biomass depend among others on age and floristic composition of the forest (Nye and Greenland 1960; Cuevas and Medina 1986), the bioclimatic characteristics or the sites (Bruijnzeel 1991; Soethe et al. 2008; Arias et al. 2011), and the natural fertility of the ecosystems (Schlesinger 1997; Szott et al. 1999; Hartemink 2003). Nutrient content of *E. globules*, *G. arborea*, and *T. grandis* is considered larger than nutrient concentration found in many other tree species (Totey 1992), particularly for N, Ca, and K concentrations that tend to accumulate in woody tissues (Grimm and Fassbender 1981a, b; Totey 1992; Stanley and Montagnini 1999).

**Nutrient Use Efficiency**: To explain the relationship of nutriments and forest ecological processes, various indices had been developed, among them the nutrient use efficiency (NUE), the nutrient use efficiency of residues (NUER),and the plantation stability index (PSI). The ability of a species to produce biomass with small amounts of nutrients is a property used to screen genetic material for recuperation of degraded lands (Montagnini 2002). In mature forests NUE values are high maybe limiting net primary productivity, but in less efficient ecosystems the nutrient availability is adequate and NUE values are low (Vitousek 1982); however, Vitousek (1984) found that tropical forest ecosystems yield systematically more dry biomass residues per N unit than other ecosystems such as temperate, conifer, Mediterranean, and fertilized plantations with less N circulation in aerial biomass. To improve the NUE of a species, different mechanisms can be applied including (i) genetic improvement to obtain plants that are photosynthetically more active and (ii) through plantation arrangement that maximizes nutrient absorption and biomass production (Ewell and Hiremath 1998). While comparing species planted alone or combined, Hiremath et al. (2002) and Hiremath and Ewell (2001) found that NUE is not constant and relevant deviations from the mean depend on variable environmental conditions that determine among all nutrient availability. The NUE decreases in the following order *Hieronyma* > *Cedrela* > *Cordia* while planted as monocrops, but when helicoids and palms are included, NUE values follow the order *Cedrela* > *Cordia* > *Hieronyma*.

In the majority of forestry ecosystems, NUE values for N, K, Ca, and Mg are alike. High values of NUE are common when tropical forests with naturally available P are low with species adapted to mycorrhizae associated with their root math. However, species like *Bombax macrophyllum* and *Plathymenia foliolosa* show extremely high NUE values for most elements and are considered as ideal for restoring degraded ecosystems (Montagnini and Jordan 2002). In teak plantations nutrients are bound to the biomass very efficiently returning little amounts to the ecosystem: in evergreen species such as pines and eucalypts, nutrients (particularly N and P) are recycled in large quantities. In the case of eucalyptus, the fast recycling of nutrients and the large amounts of nutrients exported in the wood harvest tend to mine soil fertility, particularly of sandy soils (Samra and Raizada 2002).

**Nutrient Translocation (Resorption)**: Some authors (Karmacharya and Singh 1992; Konsaeng et al. 2005; Tully et al. 2013) agree that nutrients move via xylem to growing tips where they move via phloem (translocate) to other tissues like roots, branches, and leaf cells; however, mobility of nutrients varies notably in the phloem. Nutrients kept in tissues and organs can later be translocated to new growing tips or reproductive organs. Nambiar (1984) mentions that this mechanism is highly developed in trees where they are active as long as they live; trees have large amounts of nutrients in the leaves and the stem, and they possess the ability to mobilize them to maintain their short- and long-term growth.

Translocation of nutrients is a mechanism used by trees from temperate zones before senescence at autumn to translocate nutrients to wood tissues and similarly by senescent species in tropical regions responding to changes in photoperiodism, small changes in air temperature, or lag of humidity in regions with seasonal rainfall distribution (Reich and Borchert 1984; Borchert 1994; Borchert and Rivera 2001). Nutrients like N are translocated to woody tissues before senescing in deciduous species, but not in less efficient evergreen species; in deciduous species nutrients need to be translocated to the foliage to form new leaves every year and to replace nutrients removed by rain as leaching, avoiding the costly energy requirement of absorbing them from the ground (Samra and Raizada 2002). Monthly leaf variations of nutrients like N, P, and K are larger than those of Ca and Mg due to the rainwashing effect and the translocation of the first elements mentioned.

The amount of nutrients translocated in wild species is considered to vary between 0 % and 83 % (Chapin 1980). Gordon and Jackson (2000) describe the translocation of nutrients in the root math of conifers and broad-leaved species as dependent on the C/N and C/N/P ratios, and Aerts (1996) found differences in resorption of N in deciduous species (54 %) against evergreen species (47 %); P resorption in the two groups of species did not vary significantly (50–51 %). Inagaki et al. (2011) found larger amounts of litter N in residues of *Acacia mangium* than in residues of *Swietenia macrophylla* and *Araucaria cunninghamii*, but values of P are 12–22 % lower than those found in the latter two species: these results indicate the lower translocation efficiency of P by *A. mangium* in contrast to its high N cycling mechanism under field conditions.

## Nutrient Additions Through Rainfall and Tissue Leaching

In spite of the difficulties encountered while measuring nutrient addition from rain (Bruijnzeel 1991), some values from various tropical forest environments are available (Vitousek and Standfor 1984; Fölster and Khanna 1997; Hendry et al. 1984; Eklund et al. 1997; Montagnini and Jordan 2002). The following values represent ranges of most likely amounts added to the ecosystems in kg $ha^{-1}$ $year^{-1}$: 5.0–21.0 N, 0.2–1.1 P, 2.5–24.0 K, 1.4–34.0 Ca, and 1.1–26.0 Mg. The quantities might seem not too large, but through the 20–25 years of length to harvest, the nutrients added this way might have some impact on growth. Park and Cameron's (2008) summary on water interception by trees concludes that major pathways for rainfall water to reach the ground includes throughfall (and leaf drip) and stemflow. Through the second pathway, nutrients can be washed away from the canopy by rain, particularly P, K, Ca, and Mg, whose foliar concentration diminishes with precipitation augments (Santiago et al. 2005) and is related to the form of the canopy of species (Hiremath et al. 1997). Quality of rainfall water is also affected by the properties of tissues of the trees of the wet tropical regions (McColl 1970; Grimm and Fassbender 1981a, b; Hiremath et al. 1997; Wilcke et al. 2001; Cavalier and Vargas 2002; Cleveland et al. 2004; Jiménez et al. 2006). In areas near the ocean, small amounts of nutrients like Na, B, Mg, Cl, and $SO_4$ can be dissolved and suspended in rainfall water affecting vegetation growth in land (Forti et al. 2000). In areas around deserts rainfall water can be enriched with Ca and near industrial centers or active volcanoes with $SO_4$ and $NO_3$ (Hendry et al. 1984; Rodríguez et al. 1995; Eklund et al. 1997; Schlesinger 1997; Montagnini and Jordan 2002; Fabian et al. 2010). The effect of burning the Amazonian forest on the acidification of rainfall water that affects vegetation growth in the Ecuadorian Andes is being described by Boy et al. (2008).

## Effect of Microorganisms on the Nutrient Cycle of Tropical Forest and Forest Plantations

Dommergues (1997) mentions that N fixation of species like *Casuarina* sp. and *Alnus* sp. is high, but real amounts of fixed N are low since the potential for fixing the element is limited by unfavorable environmental conditions, wrong silvicultural practices (which can be improved), and the low fixation capacity of actinomycetes (which can also be optimized). In greenhouse conditions the growth of *Frankia* on the root math of *Alnus glutinosa* is severely diminished at pH values lower than 5.5 (Griffiths and McCormick 1984) as also happens with the one on *Alnus incana* due to B deficiencies (Lehto et al. 2010). In a natural humid tropical forest, Moreira and Arnáez (2009) and Eaton et al. (2012) found large amounts of *Frankia* spores and a large amount of nodules attached to the fine roots of *H. alchorneoides*, a mechanism proposed as a strategy of trees to survive in soils of low fertility.

The need to apply mycorrhizae in native species plantations is minimal since the amount of spores in the soil is large even after long periods of time (Rojas 1992; Fisher et al. 1994; Johnson and Wedin 1997). However, it is imperative in highly deteriorated soils (Alvarado et al. 2004) and when exotic species are introduced like what happens with the introduction of *P. caribaea* in Costa Rica (Vega 1964). The response to the application of mycorrhizae is common under low-fertility soil conditions, particularly low P availability (Davey 1995), where it is attributed to the fungus capacity to absorb nutrients directly from decomposing residue surfaces and absorbing the ones released after mineralization and making them available after death, reducing chances of P retention in acid soils (Jordan 1985).

Inoculation with microorganisms is a common practice in forest nurseries for species like *Acacia mangium* (Pérez et al. 1998; Martin-Laurent et al. 1999; Schiavo and Martins 2003), *Alnus acuminata* (Echandi 1994; Gardner et al. 1984; Michelsen and Rosendahl 1990; Rondón and Hernández 1995; Russo 1995; Budowski and Russo 1997), pines (Costa et al. 2002; Carlson and Dawson 1985), eucalyptus (Trappe 1977; Xianheng et al. 1998; Adjoud and Halli 2000), and teak (Verma and Jamaluddin 1995; Raman et al. 1997; Kelly et al. 2004; Durga and Gupta 1995; Ramírez et al. 2011; Aditya et al. 2009; Zhou et al. 2012). However, results are commonly found to be erratic or negative since the introduced microorganisms do not efficiently compete with native and more adapted microorganisms that end feeding on them and inoculating seedlings (Marx et al. 2002).

Soil microorganisms and root distribution in plantation ecosystems are closely associated (except for the free-living organisms) topics recently reviewed by Vogt et al. (2011). In general root distribution in the soil profiles decreases with soil depth and the distance from the tree trunk and so does population of soil organisms like nematodes, bacteria, and fungus (Srivastava et al. 1986; Behling 2009). Root biomass is also affected by vegetation species composition as reported by Jiménez and Arias (2004) who found 441 g $m^{-2}$ root biomass under a 24-year-old secondary forest of the humid tropical area of Costa Rica but only 75 g $m^{-2}$ under the nearby grassland.

Freiberg (1998) mentions that free-living organisms (*Scytonema*, *Cyanobacteria*) can fix up to 2–5 kg N $ha^{-1}$ $year^{-1}$ on the phyllosphere of the premontane forest trees of Costa Rica. This N fixation mechanism might explain why many forest ecosystems do not show N deficiencies (Hedin et al. 2009) as well as the high foliar concentration of N described in other species like teak (Nwoboshi 1984) and *Gmelina* (Rodríguez 2006).

## Contribution of Nutrients by Soil Weathering

Nutrients supplied by the soil to forest growth by weathering can be small or large depending on factors of soil formation, mainly the composition of the rocks where they form. In Suriname where soils develop from highly siliceous materials, they show sandy texture, and during the rainy season nutrient contribution to the trees is meaningless (de Graff 1982). In the tropical humid forest soils of Costa Rica developed from basaltic to andesitic rocks, nutrients are more abundant, and lateral underground nutrient additions occur due to the presence of lavas that impede deep leaching (Pringle et al. 1986; Pringle et al. 1990; Pringle et al. 1993; Generoux and Pringle 1997; Generoux et al. 2002; Jordan 2003).

### Aboveground Residue (Litter) Accumulation

Accumulation of large quantities of residues in forest plantations is not frequent. According to Reddy (2002) in broad-leaved plantations like teak, residue accumulation is not common, since undergrowth vegetation is limited and falling leaves decompose rapidly. In the case of *Eucalyptus*, the open crown and the small size of the leaves allow weeds to grow and a rapid decomposition of residues. In the case of leguminous species that fix N and produce large quantities of residues, microorganisms mineralize them rapidly due to their favorable C/N ratio. In the tropical humid lowlands, recycling is fast and happens in very short periods of time (Montagnini 2002). In the dry tropical lowlands, residue accumulation depends on the length of the dry season and their fast mineralization at the beginning of the rainy season (Bernhard-Reversat and Loumeto 2002). In fast-growing plantations the amount of residues produced is larger than the one added under natural forest conditions. In the same type of plantations, residues accumulate more under middle altitude conditions where productivity is large and mineralization rate is moderate. Under natural conditions the rate of mineralization is larger than in exotic species plantations since decomposer organisms are more adapted to the climatic conditions.

### Residue Mineralization

**Effect of Residue Quality on Mineralization**: Concentration of minerals in the tissues, their organic chemical composition, and soil physical properties associated define its quality in leaves or in the total of the residues. Some properties of residues are little known (i.e., leaf thickness), while others like N content are abundant, and to a lesser degree the presence of soluble organic substances, secondary metabolites like phenols and tannins, fiber, cellulose, and lignin contents is relatively unknown. In very rare cases the content of tannins is mentioned due to its allelopathic effects (Bernhard-Reversat and Loumeto 2002). Verhoef and Gunadi (2002) attribute the pine needles' relatively slow decomposition rate (50 % after 7 years) to its high tannin content, the low pH, and nutrient contents of the organic layers of the soil, common in mountainous tropical regions. Hard-to-decompose residues are considered as a good attribute for trees to have when coverage is needed in site restoration. Montagnini (2002) mentions the case of large amounts of hard residues added by *V. ferruginea* against lower amounts of soft residues added by *H. alchorneoides* in relation to reduce soil erosion.

**Rate of Mineralization**: Fresh forest residue mineralization rate lasts approximately 15–20 months (Fassbender 1987; Babbar and Ewell 1989; Byard et al. 1996; Horn and Montagnini 1999), except for woody residues which might last up to

10 years to decompose under tropical humid forest conditions and even more in drier and cooler ecosystems (Poels 1994). Nutrients associated with the residues are rapidly released at first, changing to a moderate rate and to a very slow rate at the end in a synchronized mechanism similar to the one trees use to absorb nutrients after planting. During the first 4 months, more than 50 % of the residues decompose, and after 14 months 80 % of the residues are gone (Horn and Montagnini 1999; Boniche et al. 2008). Potassium is released during the first 3 months (Waterloo 1994), while Mg, P, N, and Ca are released more slowly leaving a small amount of materials that accumulate in the soils associated with the organic matter fraction. In mountain tropical forests 15–70 % of residues decompose per year, while in tropical humid lowland forests, more than 80 % are mineralized per year (Fassbender 1987) and usually all residues mineralize in less than 15 months (Montagnini and Jordan 2002). The slow residue mineralization rates in mountain ecosystems is attributed to (i) the low soil temperature, (ii) the low relative humidity related to relief conditions, (iii) the low N concentration of the residues (Heaney and Proctor 1989) that also induces N limitations for vegetation growth (Tanner et al. 1998), (iv) the increase of phenols of residues with elevation (Montagnini and Jordan 2002), (v) the low population densities of arthropods at high elevation (Bruhl et al. 1999), and (vi) the large amounts of soil organic matter that form humic-allophanic complexes resistant to decomposition at middle elevation Andisols.

**Coefficient of Decomposition** ($K$): Some authors use the ratio "deposited residues/remnant residues" ($K$) to measure the rate of residence of residues in the ecosystem. The ($K$) values do not relate to the age of a tree or plantation, but it relates to species genera, origin of the plant material, and climatic conditions. Results show that lower values are found in pine and eucalyptus residues, while species like *Terminalia* rank in the high range. If addition of residues is continuous, then the decomposition rate follows a linear model with time and ($K$) values in plantation 12–24 months old in India that vary in the order of 0.69–0.91 for *A. nepalensis*, 0.39–0.93 for *C. equisetifolia*, and 0.46–0.78 for *P. kesiya* (Akinnifesi et al. 2002); for various *Eucalyptus* spp., they varied in the range of 0.30–0.94 (Lima 1996) and in tropical natural forests and plantations in a range of 0.2–5.0 (Bernhard-Reversat and Loumeto 2002). Decomposition rates of fine roots vary among tropical humid forest species being very slow ($K = 0.29 \pm 0.15$ year$^{-1}$) for *V. koschnyi* and seven times faster for *V. guatemalensis* ($K = 2.00 \pm 0.13$ year$^{1}$), while for *H. alchorneoides* and *P. macroloba,* they were 1.36 and 1.28 year$^{-1}$, values related to the lignin/N ratio of the roots (Raich et al. 2009).

**Effect of Decomposer Population**: Decomposers are very abundant in forests under natural conditions where they are a key factor in biochemical degradation but also in comminuting residues and then augmenting the surface area exposed to mineralization. Wilde (1958) considered that the smaller the organisms, the more abundant they are and the more specific is their function in the residue cycling. The complexity and specificity of microorganisms in the soil are considered important to assure ecosystem sustainability and soil health (Kibblewhite et al. 2008). According to Garretson et al. (1998) leaf-cutter ants (*Atta cephalotes*) affect the diversity of plants in tropical humid lowland ecosystems. Heneghan et al. (1998) estimate the effect of micro-arthropods on residue decomposition from various tropical forest ecosystems using decomposition bags treated and untreated with naphthalene finding that decomposition rates varied with N residue content and the N released through decomposition was significantly larger when micro-arthropods were more abundant.

Microbial activity is moisture dependent and varies with rainfall distribution. During the rainy season residue decomposition is enhanced due to a larger population of micro- and macroorganisms (particularly that of earthworms, ants, and termites) and the proliferation of fine roots. Microorganisms like fungus and bacteria play an important role in decomposing residues along the year but are more relevant during the dry season when macro-arthropod activity reaches it minimum (Costa et al. 2002).

Mesofauna of arthropods is normally larger (at least 1.5 times larger) on residues of exotic plantation of eucalyptus where they favor from the microclimate created by the shade of trees rather than the harsh climatic condition of the adjacent open savanna (Reddy 2002). However, this effect is temporal since with time the quality of residues under the plantations changes negatively affecting their populations (Folgarait 1998; Bernhard-Reversat and Loumeto 2002). Other studies conducted to better understand diversity and abundance of collembolans (Guillén et al. 2006a, b) and scarabide (Hall 2003) under primary and secondary forests and coffee-cocoa plantations in Costa Rica document reductions in diversity and abundance while changing land use and the effects of soil compaction, organic matter (litter) content, and low fertility and pH on the variables. Studies carried on in Java on *P. merkusii* plantations (Reddy 2002) and India's eucalyptus plantations (Verhoef and Gunadi 2002) show that among arthropods collembolans and acari are the most abundant dominating populations in the upper soil layers of plantations and adjacent savannas. Samra and Raizada (2002) also report that collembolans and acari dominate the population of arthropods over earthworms that do not tolerate high amounts of needle litter under conifer species. The effects of lignin and phenols on the wood of various species on population dynamics and residue decomposition of termites and ants are being documented by Samra and Raizada (2002) and Bernhard-Reversat and Loumeto (2002).

## Nutrient Fate After Residue Mineralization

The quantity of nutrients in residues returned annually to the soil varies with forest/plantation ecosystem differences and is species-age dependent. Under many different circumstances, various authors have demonstrated that nutrient concentration in aerial biomass of species varies little with age but nutrient absorption increases exponentially with tree growth (Nwoboshi 1984; Waterloo 1994; Samra and Raizada 2002; Segura et al. 2005). Nutrients released from *P. patula* plantations 6–14 years old and various eucalyptus species 7 years old (kg ha$^{-1}$ year$^{1}$) are 16–89 N, 1–4 P, 3–20 K, 17–120 Ca, and 2–15 Mg (Samra and Raizada 2002). Wood et al. (2009) estimated additions of P as residues in the secondary humid tropical forest of more than 15 years of age to be 5.2–10.6 kg ha$^{-1}$ year$^{-1}$.

When residues mineralize their C/N ratio decreases rapidly in the residues and the tissue decomposer bacteria and fungus. It is in order to reach a new nutrient balance that some of the elements get lost (leached) but others are used to synthesize proteins and microorganism's biomass, a process known as "nutrient immobilization." Later on, organic residues limit energy for decompositions and microorganisms die releasing the nutrients immobilized in the biomass; the term then is "partial immobilization." Nutrients can also be tied very strongly to clay and oxyhydroxide surfaces, almost permanently, a process also known as immobilization, retention, or fixation. Rodin and Bazilevich (1967) cited by Gosz (1984) use the term immobilization of nutrients referring to the fact that conifers and deciduous species of temperate zones keep ("immobilize") nutrients in their residues in the order $N > K > Ca = P = S = Al = Si > Mg > Fe = Mn = Na$.

## Burning Vegetation and Residues in Tropical Forest Ecosystems

Burning the land is the most common mechanism to clear areas for cropping or raising cattle in tropical regions. Fires also are used to cheaply (not sustainable) convert residues into nutrients and lime (slash and burn and slash and mulch), remove weeds and pests in grasslands, reduce expansion of diseases and pests, and pasture regeneration. From the forestry point of view, it is worth to mention that planting pyrophilic species such as pines, eucalyptus, and bamboos might increase the quantity of flammable material in tropical environments. More ecological implications of fires in tropical regions can be looked in papers written by various authors (Nye and Greenland 1960; Ewell et al. 1981; Otsamo et al. 1995; Richter et al. 1982; Lal et al. 1986; Balagopalan 1987; Cochrane 2009; Rodríguez et al. 2011).

Naturally forest fires might start under climatologically predetermined conditions (i.e., long dry periods) and of management (residue accumulation after pruning during the dry season) releasing instantly all nutrients associated. Their effects as related to the additions and losses of nutrients are observed in all altitudinal belts, in any soil depth, and far away from the fire occurrence (Forti et al. 2000; Titiz and Sandford 2007; Boy et al. 2008). Fires can be divided considering their intensity, duration, and effect on the soil properties as "partial fires" when they occur naturally or are provoked by humans by chance and "total fires" when the forest is clear and burned intentionally. Most fires in the world concentrate in tropical regions (Cochrane 2009) particularly in monzonic areas where they concentrate during long dry seasons associated with ENSO fluctuations as it happens in Nicaragua, Honduras, and Guatemala in Central America (Observatorio del Desarrollo 2002; Asociación Conservación de la Naturaleza 2005).

Fire effect on soil properties starts by diminishing organic matter content and Al saturation at the soil surface with an increase of soil base saturation (this last effect not as clear under pine litter burning). Waterloo (1994) reported that the decomposition and burning of residues of *P. caribaea* in Fiji reduced their amount from 37 to 6 t $ha^{-1}$, increasing some nutrient availability and losing large amounts of P, N, and K. Forest fires also might accelerate erosion of bare soils at the beginning of the rainy season and the volatilization of nutrients like C (31 %), N (22 %), and S (49 %) (Ewell et al. 1981). In terms of homogeneity soil fertility properties are highly deteriorated since ash deposited on the ground concentrates around large pieces of wood or where residues are accumulated before burning.

Frequently soil sterilization is mentioned as the major damage due to the high temperature developed by the fire over the soil, the situation being enhanced when soils are compacted (Costa 1990); however, the soil humidity, the length of time required to burn large amounts of residues, and the high porosity and low thermal conductivity of the soils impede soil temperature to increase but only in the atmosphere-soil interface. Ewell et al. (1981) report burning temperatures on the soil surface over 200 °C that decrease to 100 °C at 1 cm and lower than 38 °C at 3 cm depth and conclude that soil sterilization should not be a problem ever. A similar conclusion was found by Ramsay and Oxley (1996) after finding temperature oscillation between 400 and more than 500 °C on the burning herbaceous vegetation of the Ecuadorian Paramus but lower than 65 °C at 2 cm soil depth.

Forestry-wise it is relevant to mention that clearing the land by burning increases the germination of the Gramineae family making it more difficult (at least more expensive) to establish plantations (Horn and Sandford 1992). Grasses compete with trees for light, water, and nutrients and might produce allelopathic substances and increase chances for soil compaction and fire development (Otsamo et al. 1995). Hartemink (2003) and Costa (1990) also mention that after fires soil water infiltration capacity is reduced due to superficial pore sealing and also by increasing soil hydrophobicity. Fires also provoke a reduction of fine roots attached to organic particles, and in some cases enhancing shoot production also correlated with a process of blocking water and nutrient absorption; high occurrence of nutrient deficiencies in the shoots is also associated with dystrophic environmental conditions. The loss of soil coverage and nutrients by erosion retarded the initial growth of teak plantations (Ramnarine 2001).

The amount of ashes deposited after prescribed fires is relatively small (0.58–1.14 t ha$^{-1}$), but the burning of residues that might be considered as fuel reduces the possibilities for natural fires to occur and also helps in preparing the land for establishing new plantations (Richter et al. 1982; Zelaya and Guillén 2002; Shlisky et al. 2009). Larger quantities of ash are deposited after clearing and (total) burning of the land (1.2–12.1 t ha$^{-1}$) depending on the type and age of the forest cut and the natural fertility status of the soils where the forest grew (Nye and Greenland 1960; Ewell et al. 1981; Richter et al. 1982; Lal et al. 1986; Balagopalan 1987). In general elements like N, Ca, Mg, and K are the most deposited followed by those of Fe, S, P, and Mn and very much less by those of Zn, Cu, and B. Drechsel and Zech (1994) consider that the N added this way plus the one that forms rainfall might supply over 70 % of the N required for a turn of teak.

Szott et al. (1991) and Fölster and Khanna (1997) established that large quantities of the nutrients deposited as ash will not be available for trees to grow but will be lost through leaching, erosion, seepage, and volatilization. Nutrients like P and in some cases K can also be retained on clay-sized particles (Sánchez 1985). Cravo and Smyth (1997) proved that nutrient losses after burning the residues vary within elements; just after burning Ca, Mg, K, and Zn, pH increases, but exchangeable Al is reduced; however, Ca, Mg, and K contents decreased by 50 % after 23, 15, and 5 months later, respectively. Costa (1990) adds that in hilly lands nutrient losses are high due to erosion and wind removal. Ewell et al. (1981) report volatilization losses after burning a humid tropical secondary forest in the order of 1.600 g C $m^{-2}$, 49 g N $m^{-2}$, and 13 g S $m^{-2}$, associated with aeolian erosion and leaching losses of g N $m^{-2}$, 20 g K $m^{-2}$, 1 g P $m^{-2}$, 39 g Ca $m^{-2}$, and 7 g Mg $m^{-2}$. Sarmiento (1984) considers that S losses via volatilization are not limiting the establishment or growth of new plantations in the same ecosystem since aerial biomass might have 5 kg $ha^{-1}$ (assuming nutrient concentration to be 0.1 % and a biomass of 500 g $m^{-2}$), quantity being similar to deposition of S through rainfall and aerosols in suspension. Even though volatilization losses of N are large, its soil concentration increases after burning the land (in the same manner N content is increased in drinking water in areas with high volcanism activity) suggesting that this practice favors symbiotic and nonsymbiotic N fixation.

## Silvicultural Implications

According to Miller (1984), there are two or three distinct phases of plantation development and nutrient requirements, showing that nutrient deficiencies are essentially problems of youth and old age:

1. In the early stages of stand development prior to canopy closure, the annual rate of nutrient accumulation increases rapidly and tree growth is very dependent on current nutrient uptake. Mineral deficiencies are common during this stage. Turner (1986) shows that *Eucalyptus grandis* on poorer quality sites reaches its peak of biomass accumulation some years earlier than on the better quality sites. On the other hand, Herbert and Schönau (1991) found that fertilization will increase CAI in *Pinus taeda* but not the time where CAI peaked.
2. Once the canopy has closed, the reduction in the rate of nutrient accumulation is associated with attaining maximum foliage biomass, high internal retranslocation of mobile nutrients, as well as increasing amounts of nutrients in litterfall and by capture from the atmosphere. This will decrease the nutrient contribution by soil reserves to the amount incorporated in the wood or less. Therefore, fertilizer response will be unlikely during this second stage (Miller 1984), unless thinning will not return the stand to the first stage (prior to canopy closure). The magnitude of nutrient requirement met by retranslocation may be the dominant influence on the longevity of response to early fertilization (Switzer and Nelson 1972). On the other hand, it is supposed that on marginal sites, early fertilization (enhancing root growth) may become eroded later in the rotation as internal competition within the stand sets in.

   With decreasing stand density by thinning, the nutrient demand and content of the stand decrease but of the single tree increase due to enhanced biomass production, especially for renewed crown development. The magnitude of crown diameter increase depends on species and age. In this stage fertilization may accelerate recovery, but also weed growth and water depletion. Studies on teak and *Pinus caribaea* in Nigeria showed that after recovery, the amount of litter has reached the same or higher levels in comparison with unthinned control (Egunjobi and Onweluzo 1979; Nwoboshi 1980). Since on the other hand the nutrient demand of the thinned teak stand was reduced, the nitrogen balance of this plantation became more harmonized by thinning (Nwoboshi 1980).

A major role of nutrient management is to find the best compromise between ecological and silvicultural rotation in view of perpetuity. Due to increased nutrient use efficiency in the stand with time, lengthening the rotation age of fast-growing species will reduce net nutrient uptake (from soil reserves) (Switzer and Nelson 1972). "Nutritional costs" decrease especially after heartwood commences to form due to P and K withdrawal. In many eucalypts this will be at about age 5–7 years, but in *P. radiata* about 10 years later. Therefore, early thinnings or short rotations (5 years) will cause high nutrient removal due to the high nutrient contents in the sapwood and increasingly greater removals by pine than eucalyptus harvesting in rotation periods longer than about 7 years. For *Eucalyptus delegatensis*, the P export by harvesting wood and bark increased from 51 g P per ton of wood (57-year rotation) to 87 g P per ton of wood (18-year rotation). For *Pinus radiata*, the comparable increase was from 169 g per ton of wood (40-year pulpwood and log rotation) to 258 g P per ton of wood (18-year pulpwood rotation). Therefore, eucalypts on longer rotations seem to be more efficient (mainly in their phosphorus requirements) than the pines under study (Crane et al. 1981; Baker and Attiwill 1985).

3. There may be a third phase (Miller 1984) in older stands or in successive rotations of short-rotation forestry, where growth rate decreases due to disturbed nutrient cycling and soil nutrient depletion. The reasons may be, e.g., N or P deficiency due to nutrient "lockup" in undecomposed litter or continuous N loss by fire (see section "The Nutrient Cycle"). In the example of Fig. 1 (Drechsel and Zech 1993), stem and branch harvesting at the age of 25 years will result in a loss of 872 kg N ha$^{-1}$. The input by precipitation (and $N_2$ fixation) over 25 years will be in the same order. This agrees with Stewart and Kellman (1982), Hase and Foelster (1983), Chijioke (1980), and Baker and Attiwill (1981) that undisturbed older forest plantations are nearly in N balance. On the other hand, the demands of K and P usually exceed atmospheric inputs. Mean pantropical inputs (kg per hectare and year) of water-soluble nutrients present in bulk precipitation are 32.5 ± 25.3 kg N, 0.41 ± 0.31 kg P, 7.6 ± 6.2 kg K, 12.2 ± 9.9 kg Ca, and 6.4 ± 3.5 kg Mg (Stewart and Kellman 1982). Besides precipitation, inputs due to stemflow and throughfall are of significance, e.g., for Ca (Yadav and Mishra 1982).

   In view of successive rotations, it is strongly recommended for, e.g., teak and smooth-barked eucalyptus that bark and foliage be left in the plantation during harvest (Turner and Lambert 1983; Hase and Foelster 1983; Ferreira et al. 1984). Large amounts of Ca (and P) are stored in the bark of these species and only smaller amounts in the bark-free bole.

Although fertilizing may correct intermediate-age deficiencies, research is also necessary into the management of organic matter, species rotation, and the use of cover crops and other practices which improve soil fertility. The correct management of $N_2$-fixing species either as groundcover or understory (e.g., *Lupinus* spp.) or accompanying species (e.g., *Leucaena* spp.) may be a critical factor in tropical forestry. Once the perennial tree legume *Lupinus arboreus* had become established in New Zealand pine plantations, natural seeding ensures a lupin understory between rotations and whenever thinnings reduced tree canopy (Nambiar et al. 1984). Maggs (1985) pointed out that a second P addition could also have a positive effect on the N economy of (pine) plantations by increasing nonsymbiotic $N_2$ fixation in the upper forest floor (and litter breakdown) due to higher P concentrations in the litter. The nutrient dynamics over several rotations are under discussion, since there are only few long-term projects (Sanchez et al. 1985). An attempt to predict the expected reduction of total nutrient stores during transformation by Drechsel and W. Zech of exploited rain forest and during successive generations of forest plantations is given by, e.g., Fölster and Ruhiiyat (1991).

## Visual Diagnoses of Mineral Disturbances

A tree or stand may suffer a “nutritional disturbance” if the supply of one or more nutrients is either too low or too high for optimum growth. The lack or excess of one or more nutriments produces visible symptoms that, when observed, have already negatively affected growth. Major symptoms include chlorosis, death of tissues, and growth reduction and are specific for each nutriment. Nutritional disturbances which are caused by excess of nutrients are rare in natural forests or plantations with some exceptions mentioned below. The common case is insufficient nutrient supply per se or induced by other environmental factors.

### Causes and Occurrence of Mineral Deficiency and Toxicity

**Causes**: Major soil constraints associated with nutrient deficiencies or sufficiencies include the following (after Evans 1992 and Webb et al. 2001):

- Sandy and eroded soils or soils derived from large deposits of garbage, mine deposits, etc.
- Low-fertility soils where residue decomposition allows litter accumulation and then nutrient immobilization in the topsoil.
- Nutritional deficiencies induced by factors like:
  1. Nutrient leaching in very rainy areas
  2. Rain shortages inducing nutrient deficiencies during the dry season
  3. Overliming inducing Fe and Mn deficiencies

4. Low pH effects like P precipitation under alkaline conditions or retention as P-Al and/or P-Fe in acid soils or P retention on short-range crystallization order clays
5. Soil physical properties that affect root growth like shallowness, water pounding, compaction, etc.
    - Interactions with other nutrients. Concentration of nutrients in the soils can affect requirements of others, notably the relations N-P and P-K. The addition of fertilizer P might induce K deficiency in soils without the deficiency under natural conditions.
    - Low or inexistent mycorrhizal associations or poor population of N-fixing microorganisms.
    - Strong weed competence.
    - Planting the trees in wrong sites, i.e., *Leucaena leucocephala* in soils with pH below 5.

**Occurrence**: Nutrient deficiencies might be the result of (i) the stage of growth of the trees or (ii) interactions between soil, site, and species. In the first case it should be remembered how nutrient dynamics in a plantation changes as trees grow and pass from one stage of growth to the next. However, it is worth to mention that nutrient deficiencies, or the lag of, are more common during the first stage of growth and few weeks after establishing the plantation as follows:

- After planting seedlings, do not show deficiencies until the residual effect of fertilizer applied in the nursery disappears.
- Once established, for a period that lasts a few weeks up to a few months, seedling growth in height, branching, surface area, and root system growth are accelerated augmenting nutrient needs.
- Nutrient cycling in soils is almost nil until the crown fully develops.
- Root math development might not be capable to compete with weeds, especially when mycorrhizae are not present like what happens in acid soils or other adverse soil physical properties in teak plantations.

In the second case, many factors interact affecting tree growth and nutrient availability making it difficult to predict when problems are to be encountered. It is more the personal experience on the sites that will help in “expecting” problems like water deficits that will induce the deficiencies of N or the lower absorption of P by the tree. Waterlogging conditions affect nutrient availability and absorption as demonstrated by Hernández et al. (1993) in teak plantations where foliar concentrations of Mg, Fe, and Mn were higher in well-drained soils but K and P concentrations were lower. Natural geographical distribution of forest species (Table 2) helps planting commercial plantations in Cuba avoiding nutrient deficiencies (Herrero 2001).

**Table 2** Nutrient deficiencies commonly found in Cuba by species, soil type, and region (Adapted from de Herrero 2001)

| Especies | Soil type | Limiting elements | **Region** |
|---|---|---|---|
| ***Pinus tropicalis*** | Ferralítico cuarcítico amarillo | P > Ca > B > K | Viñales |
| | Rojizo lixiviado | | Viñales |
| ***Pinus maestrensis*** | Ferralítico rojo lixiviado | P > N > Mg | Los Números, Sierra Maestra |
| ***Pinus cubensis*** | Ferrítico púrpura hidratado | N > P > K | Pinares de Mayarí |
| ***Eucalyptus saligna*** | Arenoso cuarcítico | P > B > N > K | Las Taironas |
| ***Eucalyptus citriodora*** | Ferralítico cuarcítico amarillo | P > B | Galindo |
| ***Tectona grandis*** | Gley oscuro plástico | N > Mg > P | Itabo, Villa Clara |
| ***Swietenia macrophylla*** | Ferralítico rojo típico | P > B | Artemisa |

## Symptoms of Mineral Deficiency and Toxicity

There are two intensities of deficiency: (i) latent deficiency without any visual foliar symptoms but with lower nutrient levels and some lower growth than under optimal conditions (the observation of foliar deficiency symptoms is a simple method to detect mineral disturbances) and (ii) visual deficiency with reduced or stunted growth and/or foliar discoloration and in severe cases shoot dieback and mortality. Latent as well as visual mineral deficiency could be best seen and verified by a positive response after some months to controlled fertilization experiments (diagnostic fertilization). Due to high requirements in time and costs, this method will only be practiced in commercial plantations.

Great efforts have been made been made to find other diagnostic methods such as (i) visual symptoms in the trees, (ii) greenhouse missing element technique, (iii) field experiments to determine fertilizer and lime requirements, (iv) searches for indicator plants to identify nutrient deficiencies, (v) chemical and physical soil analysis, and (vi) soil mapping that helps in selecting best sites to plant. Symptom description is differently made for conifers and broad-leaved species (Zöttl and Tschinkel 1971; Cannon 1983b) as well as for their rotation length (short, medium, long). Short-term rotation length species are *Eucalyptus*, *Acacia*, *Gmelina*, and *Pinus*; medium-term rotation species are *Cedrela*, *Terminalia*, *Aucoumea*, samba (*Triplochiton scleroxylon*), *Araucaria*, and *Agathis*; and long-term rotation species are teak, caoba (*Khaya* and *Entandrophragma* spp.), and *Chlorophora excelsa* (Brunck 1987).

Two major characteristics of the intensity of foliar symptoms can be differentiated: (i) chlorosis (reversible yellowing or loss of green color) and (ii) necrosis (irreversible brown discoloration, dead tissue). Mobile elements in the tree (N, K, Mg, P) show symptoms in older tissues, while less mobile elements (Ca, B, Zn, Fe, Mn) show symptoms first in younger leaves and shots. The detailed description of the kind and location of these phenomena on the leaflets is important for identification and differentiation of the symptoms: there could be chlorosis or necrosis at the leaf margins, as spots on the leaf and as patches between the veins (intercostal or intervenal), at the tip of needles or leaves, etc. In several cases the margins are scorched or look “burnt,” the leaf surface could be wrinkled, the tips could be curled, etc. (Fig. 2).

The age of the affected foliage gives hints as to the mobility of the deficient nutrient: for example, intercostal chlorosis on older leaves may be caused by retranslocation of the “mobile” Mg from older foliage toward younger shoots; the same symptom on young leaves could be caused by deficiency of the usually less mobile Mn.

Although there are for some elements typical symptoms which do not greatly vary between the species, several nutrient deficiencies do not induce a specific symptom or the same symptom on different species, like deficiency. Therefore, the given keys for the identification of mineral deficiencies should be used with care. In addition, the more common case in nature is multiple deficiency of more than one nutrient due to marginal soils (e.g., low organic matter: N, P, S deficiency) or physiological interactions (N-P, N-Cu, P-Zn, etc.) resulting in more or less complex deficiency symptoms (Lambert 1984; Zech and Drechsel 1992; Webb et al. 2001).

Symptoms caused by plagues, diseases, and agrochemicals can be confused with nutritional deficiencies, and some criteria are being developed to properly identify each of them. Problems of identification also arise from abnormalities or discolorations caused by water stress, leaf aging before leaf shed, and virus and similar diseases or combinations of nutrient deficiency followed by virus attack. In addition, deficiency symptoms may vary over the vegetation period due to changing nutrient availability in the soil or requirement in the plant.

**Toxicity Symptoms**: These are usually less specific than most deficiency symptoms. Common toxicity problems are due to excess of Al or Mn in the humid tropics or excess of B, e.g., in the arid tropics. While Mn and B are essential for all plants, Al is essential for only a few plants like teak, but toxic to a wide range of crops and trees.

In most cases Mn toxicity may be visible by dark brown spots on older leaves and veins, starting at the margins. Al toxicity may reduce growth by root damage, inhibition of mycorrhiza, and uptake of several nutrients including Al itself. Therefore, there is no clearly identifiable symptom. On the other hand, several tropical trees like *Pinus taeda* and *P. elliottii* are well adapted to moderately acid soils. Their foliage could show Al concentrations of more than 1,000 ppm without physiological problems (Reissmann 1981; Zöttl 1978). The same has been reported for well-growing *Eucalyptus viminalis* and *E. grandis* on acid soils in South Brazil (e.g., Bellote 1990; Neufeldt, personal communication) which passively take up high amounts of Al. According to these circumstances, the tissue which is best suited for determination of deficiency may not be the best for toxicities. For Al (Cu, Na) often fine root analysis (e.g., Ca/Al ratio) is recommended. Similar to Al, Mn

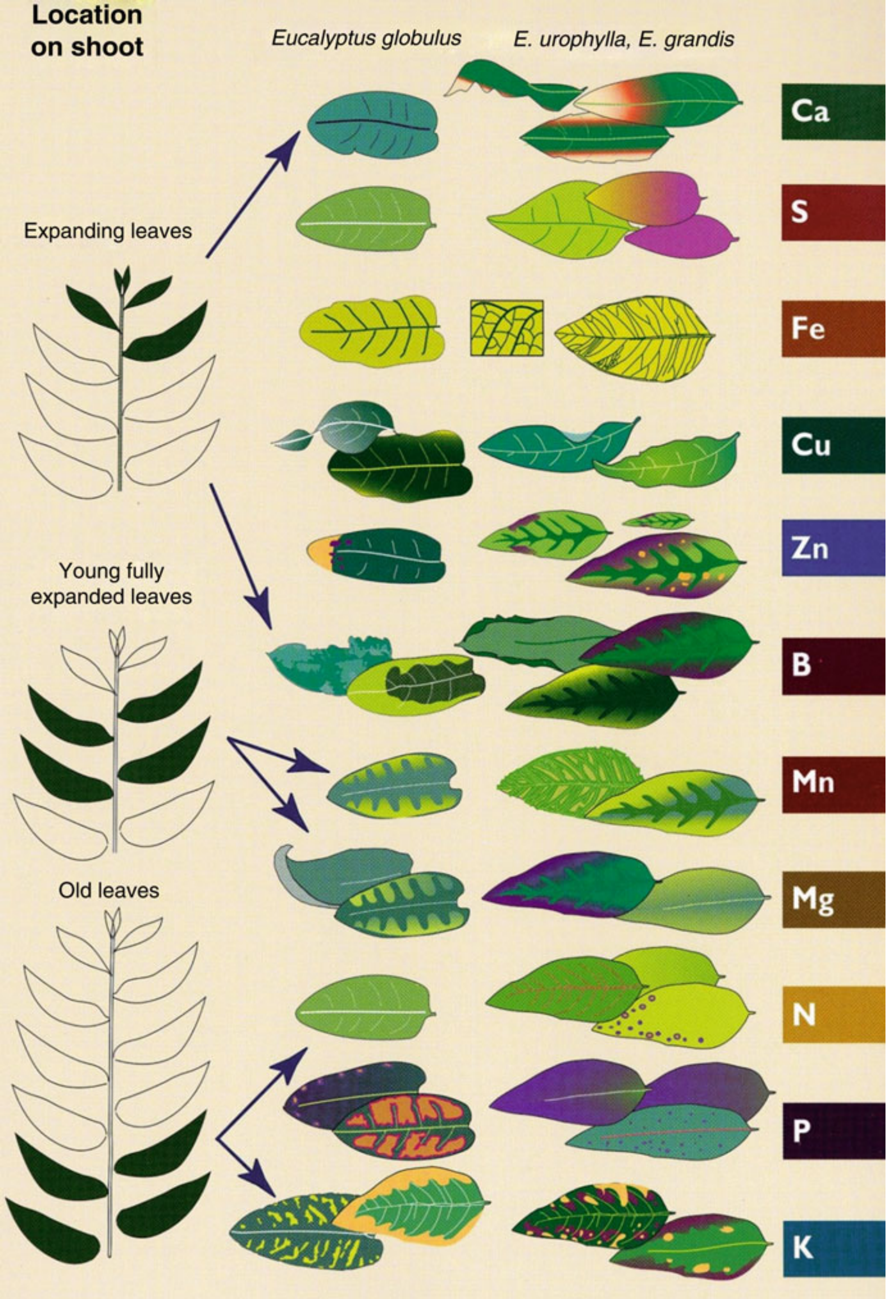

**Fig. 2** Diagram showing position of new shots and nutritional deficiency symptoms in eucalyptus (Taken from Dell et al. 2001)

tolerance varies greatly between the species. Manganophobic trees like cypress may suffer from Mn toxicity even at low Mn levels (<200 ppm) while, e.g., *Eucalyptus grandis* has no problems at much higher foliar levels up to 2,000 ppm (Chamberlain and Searle 1963; Bellote 1990). Since the nutrient concentration range of starting deficiency is much smaller than that of starting toxicity, foliar analysis will not reveal toxicity in such cases. That means that poor tree growth on acid soils could be due to Al or Mn toxicity, but even with high foliar levels of these elements, there could be other reasons (e.g., Al-P interactions). B toxicity is recorded for, e.g., *Cassia siamea* with chlorosis and necrosis on leaf margins as well as loss of foliage (Zech et al. 1990).

We could state:

Foliar symptoms only allow detection of severe and single nutrient deficiency with corresponding clear symptoms well known for the affected tree species. The common cases of an intermediate nutrient supply, multiple overlapping symptoms, or symptoms on trees without references cannot clearly be detected without the help from foliar analysis and, even with foliar analysis, not in all cases of temporary sampling. Deficiency and toxicity phenomena should be observed over longer periods, since, e.g., nutrient availability may change with time. In the case of Al toxicity, fine root analysis may give more information than foliar analysis.

## Deficiency Symptom Identification Guides

Alvarado and Raigosa (2012) summarized available literature on nutrient deficiencies from seedlings of tropical tree species under controlled mono-deficiency nutrition in greenhouse/hydroponic conditions and the few papers on the subject under field conditions. Works exist for species like ***Acacia mangium*** (Boardmann et al. 1997; Australian Center for International Agricultural Research 2000; Clavero et al. 2001; Lehto et al. 2010), ***Alnus acuminata*** (Dawson et al. 1980; Rodríguez et al. 1984; Sharma 1993; Mills and Jones 1996; Segura et al. 2006b), ***Bombacopsis quinata*** (Rodríguez 2010), *Cedrela odorata* (Zech and Drechsel 1992; Webb et al. 2000,2001), ***Cordia alliodora*** (Cadena 1989; Drechsel and Zech 1991; Zech and Drechsel 1992; Bergmann et al. 1994; Herrera and Finegan 1997), ***Cupressus lusitanica*** (Tschinkel 1972), **eucalyptus** (Evans 1982; IPI 1962; Schönau and Herbert 1989; Boardmann et al. 1997; Dell et al. 2001; Silveira et al. 2001; Millner and Kemp 2012), ***Gmelina arborea*** (Drechsel and Zech 1991; Stuhrman et al. 1994; Boardmann et al. 1997; Azofeifa et al. 2003), ***Hieronyma alchorneoides*** (Azofeifa et al. 2003), **pines and conifers** (van den Driessche 1974; Vidal et al. 1983; Hernández and Lombardo 1987; Bergmann 1988; Weetman and Wells 1990; Chaves and Corrêa 2003), ***Shorea robusta*** (Kaul et al. 1966), ***Swietenia macrophylla*** (Drechsel and Zech 1991; Webb et al. 2001; González et al. 2005), ***Tectona grandis*** (Kaul et al. 1972; Nwoboshi 1975; Kairiala et al. 1986; Zech and Kaupenjohann 1990; Drechsel and Zech 1991, 1994; Boardmann et al. 1997; Bebarta 1999; Jayamadhavan et al. 2000; Webb et al. 2001; Sujatha 2005, 2008; Murillo et al. 2014), ***Terminalia amazonia*** (Montagnini 2000; Montenegro 2005),

***Vochysia ferruginea*** (Alvarado et al. 1997; Horn and Montagnini 2002; Arias and Calvo 2011), and ***Vochysia guatemalensis*** (Montagnini et al. 1991, 1993; Pérez et al. 1993; Cornelius and Mesén 1997; González and Fisher 1997; Di Stéfano and Fournier 1998; Montagnini 2000; Arias and Calvo; Badilla 2012). As examples, guidelines for the identification of mineral deficiencies of eucalyptus, pines, and teak will be described:

***Eucalyptus spp***.: The following key for the identification of mineral deficiency symptoms in *Eucalyptus* spp. is according to the Wattle Research Institute (Evans 1982) and the IPI (1962). For supplementary information, see Schönau and Herbert (1989). The deficiency symptoms described for, e.g., Ca or K are not identical in all reports. In the field the symptoms may overlap in the case of multiple deficiencies.

### Symptoms First Localized in Older Leaves

**Yellowing First, Spotting Later** Slight yellowing of older leaves at first and then younger leaves. As the deficiency becomes more acute, the leaf blades show a lemon-yellow color, after which small reddish spots develop and cover the entire leaf. In seedlings, stems and leaf stalks are redder than normal; branching is restricted resulting in tall spindly seedlings with few or no side branches.
— > Nitrogen

**Spotting First, Yellowing Later**

(a) Numerous dark spots appear on the green leaf. These subsequently increase in size and the background develops an orange-yellow tint. Leaves of seedlings have bluish-purple blotches, and the surrounding green is darker than normal. Branching is restricted as in nitrogen deficiency.
— > Phosphorus

(b) Reddish spots appear on a pale green background. As the deficiency becomes more acute, the tissues in the reddish areas die (necrosis), and the leaves wither and fall.
— > Calcium

**Yellowing Between the Main Lateral Veins** Older leaves yellow along the midrib. Green color gradually changes to brown with dying of tissues. The affected regions are separated from the main lateral veins by areas of green tissue. The lower leaves of seedlings become pale green and are often shed prematurely, leaving a bare stem with a tuft of leaves at the top. The seedlings of *E. grandis*, *E. saligna*, and *E. botryoides*, in particular, produce larger than normal leaves at which have developed in the shade.
— > Magnesium

## Symptoms First Localized in Younger Leaves

**Uniform Yellowing** Younger leaves show a uniform yellowing, later changing to a bronze-like color. Branches show a purplish tinge.
— > Sulfur

**Mottling**

(a) Yellow mottling appears on the leaf blades, with the areas along the veins retaining their green color. Occurrence is mainly on calcareous soils unless foliar leaves >140 ppm Fe.
— > Iron

(b) Yellowing appears between the veins, but tissues near the veins remain green in color. As the deficiency becomes more acute, the tips and margins of the leaves begin to wither and show a sandy color, which spreads throughout the blade.
— > Manganese

**Yellowing Between the Veins** Leaves are normal in size and shape.

(a) Yellowing of younger leaves occurs between the lateral veins, starting at the leaf margins and proceeding toward the midrib. Alongside the lateral veins the tissue remains green but later takes on a purplish tinge. The lower surfaces of the leaves become light green. This occurs mostly on acid granite-derived soils, on volcanic soils, and especially in dry climates unless foliar levels >46 ppm B.
— > Boron

(b) Yellowish spots occur between the lateral veins of mature leaves. Narrow bands along the veins remain green, with a purplish color along the leaf margin.
— > Molybdenum

Leaves are normal in size and abnormal in shape.

(a) Younger leaves become yellow between the lateral veins, accompanied by deformation of the blade, with leaf margins irregular. This occurs often on sandy soils (Spodosols) unless foliar levels >6 ppm Cu; symptoms will be enhanced by N(P) application.
— > Copper

(b) Leaves are abnormally small in size and narrower in shape. In the beginning, the upper surfaces of the leaves show purplish areas between numerous discolored patches or spots. Small circular areas of lighter discolored tissue with brownish edges occur near the leaf margins far from the midrib. The whole leaf becomes pale green, the veins being darker in color, and later shortening of stem length forms a rosette of small, narrow, yellowish leaves. This occurs often on sandy soils (Spodosols) unless foliar levels >10 ppm Zn.
— > Zinc

Leaves are not abnormally discolored, but margins and veins are dying off.

Leaves of seedlings are smaller than normal, often with crinkled surfaces and margins. Branching is pronounced, giving a bushy, round-topped appearance.

— > Potassium***Pinus***: For *Pinus* foliar symptoms for micronutrient deficiencies are described by Hill and Lambert (1981). Macronutrient deficiency symptoms typical for pines are given by Bergmann (1988) and for conifers summarized by Weetman and Wells (1990). Hernández and Lombardo (1987) show photos of induced deficiency symptoms in seedlings under greenhouse conditions.

| | |
|---|---|
| N | Markedly reduced shoot growth and uniformly light-green to yellow needles, occurring first in the older foliage. Partly stunted needles. |
| S | In general similar to those of the N deficiencies, but more on younger foliage. |
| P | Untypical symptoms on older foliage: yellow (later dead) needle tips or purple-brown-tinged needles or thin and small needles. |
| Mg | Yellow (“golden”) needle tips on older foliage with distinct borderlines to the rest of the needle. |
| K | Variable symptoms (after tip yellowing) brown-reddish needle tips on older needles and no distinct borderlines to the rest of the needle or, e.g., bluish-green needles. |

With the exception of Mo, micronutrient deficiency appears first on the youngest parts of the trees:

| | |
|---|---|
| B | Terminal and leader dieback often with orange-red discoloration. Resinous bud often fails to flush; main stem forks (multiple leadering) and becomes deformed. Black or dark brown pith and shortened needles. Deficiency (mature needles) between 5 and 12 ppm dependent on rainfall [the higher the moisture stress, the higher the foliar levels at which the tree develops deficiency symptoms; Lambert (1984)]. |
| Cu | Often dark blue-green foliage, distorted (snake-tailed) shoots and branches, and bushiness. Some needle tips burnt. Prostrate growth in extreme cases. Deficiency range: less than 2–4 ppm. In Australia, in most cases (acid Spodosols) trees less than 5 years old are affected. Application of N (PK) fertilizer accentuates the deficiency. |
| Fe | Older needles green. Increasing chlorosis toward younger foliage. White colors in extreme cases (only common on calcareous soils). |
| Mn | Yellow-tipped needles, sparse, light green foliage, stunt. Deficiency range: $<10$ ppm (especially on dry, alkaline soils). |
| Zn | Terminal needles very short. Premature needle fall and rosetting, tip dieback, and yellowing. Partly multiple leadering (Rance et al. 1982). Deficiency range: 5–12 ppm. |
| Mo | Blue-green needles, partly purple-brown tips with distinct borderlines to the rest of the needle, may occur on older or younger foliage. |

***Tectona grandis***: Symptom descriptions are based on pot experiments with seedlings by Kaul et al. (1972) and Kairiala et al. (1986). Other important references to consider include Nwoboshi (1975), Zech and Kaupenjohann (1990), Drechsel and Zech (1991, 1994), Boardmann et al. (1997), Bebarta (1999), Jayamadhavan et al. (2000), Webb et al. (2001), Sujatha (2005, 2008), and Murillo et al. (2013).

- *Nitrogen* deficiency caused typical symptoms of stunted growth, smaller leaves, and chlorosis. Older leaves were in the beginning yellowish green, uniformly chlorotic, and then completely yellow and started falling prematurely. These leaves were very thin and translucent. Younger leaves were light green with well-marked intervenal chlorosis which started from margins and progresses toward the midrib. Shoot growth was very much restricted with thin and yellowish green stem, short internodes, and no branching. Lateral buds were visible.
- *Phosphorus* deficiency was exhibited by scorched margins and intervenal chlorosis followed by necrotic patches on older leaves. Younger leaves were light green, showing well-marked marginal chlorosis and wrinkled surface. The stem was green and thick, but its growth was restricted. There was no branching.
- Deficiency of *potassium* caused well-marked intervenal chlorosis and scorched margins of leaves. Younger leaves showed a wrinkled surface and curling of margins inward. In the beginning, shoot growth was better than in all other deficiencies, but later shoot dieback occurs. Several lateral branches appeared at the base of the stem. The stem was green and thick in contrast to other deficiencies. The root system was well developed.
- The deficiency of *calcium* caused pale-green foliage with severe intervenal chlorosis. Younger leaves developed reddish-brown spots and became distorted with their tips curled. Older leaves had scorched margins and curled and there was premature defoliation. Shoot growth was better than control during the first 3 months but it was restricted thereafter. Branching was restricted to one basal branch. Symptoms of magnesium deficiency appeared comparatively at a later stage. The seedlings showed dark green foliage with well-marked intervenal chlorosis and necrosis first in the older leaves and then in the younger ones. Shoot growth was restricted with short internodes and there was some branching.
- *Sulfur* deficiency was manifested relatively late by greenish-yellow foliage with well-marked chlorosis, curling of margins, and premature defoliation. Shoot growth was normal in the beginning but was restricted later. It was, however, better than nitrogen-, phosphorus-, calcium-, and magnesium-deficient seedlings. Branching was restricted to only the basal branch.
- *Copper*. Stunted growth of seedlings and shortening of leaves are seen; younger leaves that formed after the first set of leaves do not grow. Yellow patches appear on the leaves and expand as the leaves age. In 10 % of the seedlings, loosely transparent white patches also appear at leaf margin. Tips and edges of the leaves turn whitish yellow.

- *Zinc*. Stunted growth of the seedlings and shortening and curling of leaves occur, with unequal leaf margins and blades. The stems become tender and, in about 30 % of the seedlings, assume the appearance of a creeper.
- *Manganese*. Development of chlorotic spots at leaf tip and yellowing of younger leaves occur. The younger leaves remain stunted in growth and show curling at the tip that gradually spreads to the entire leaf; curling is followed by blackening of the leaves.
- *Boron*. Blacking of leaf tip, subsequently spreading to half of the leaf. Yellow and white patches on the leaf, increasing in number as the leaf grows, result in the death of the leaf. In about 10 % of the seedlings, the stem becomes elongated.
- *Molybdenum*. Stunted growth of the seedlings and shortening and curling of the leaves occur. In about 90 % of the seedlings, the stem becomes tender and elongated assuming the appearance of a creeper. Development of lateral branches occurs.

## Analytical Diagnoses by Soil and Foliar Analysis

### Possibilities and Limitations

**Soil Analysis**: It is an important tool in forest nutrition research. Nutritional problems are in many cases only symptoms of unfavorable soil conditions like acidity, salinity, shallowness, stagnating water, low organic matter, low nutrient adsorption or high nutrient fixation, low available water capacity, etc. In addition, the advantage of soil over tissue analysis is that nutrient supply of a soil as well as site quality can be determined before establishing a plantation. However, the value of soil analysis in predicting nutritional disturbances of forest stands is limited due to the discrepancy between the physiological and temporal complex system of nutrient uptake processes (e.g., over mycorrhiza) and the laboratory soil extraction methods. In addition fertilizer recommendations based on soil analysis results are limited since it cannot certainly define a positive response to its addition neither predict the magnitude of the response. Soil analysis has generally been developed and verified in agriculture, where it is easier to analyze the nutrient uptake by whole-plant analysis. It will be impossible to analyze the really available fraction of a specific nutrient in the soil for a relevant lifetime of a tree beyond the seedling stage.

**Foliar Analysis**: Foliar analysis refers to the determination of the total concentration of elements in plant tissues (mainly leaves and needles). The methodology is in use since 1920 (Richards and Bevege 1972) but of little use in forestry until recently, adducing that concentrations in the leaves are very low and variable. Foliar analysis allows defining deficiency, critical, optimal, luxury consumption, and toxicity levels by species (Richards and Bevege 1972; van den Driessche 1974). It can be used and also helps (i) as a tool to diagnose which nutrient(s) is deficient in low-yielding plantations (requires low precision) and (ii) as a predictive tool to quantify the effects of fertilizer needs to maximize plantation productivity (requires high precision). The agricultural method of plant tissue analysis has been used with advantage in forestry. The nutrient status of a tree seems to be reflected best by the chemical composition of its foliage. Other parts, such as roots, inner bark, fruits, etc., may also be reliable for certain species or elements but are not generally preferred. The analytical data are usually expressed as element concentrations in percent, mg $g^{-1}$, or mg $kg^{-1}$ (ppm) of leaf dry matter.

Foliar analysis makes most sense if the data are as comparable as possible in view of a distinct species and regions. To obtain best and representative information on soil fertility and the state of nutrition of the trees, sampling procedure and time of sampling should be standardized. Although there are available several guidelines in temperate forest science, the procedures vary from institute to institute. For tropical trees the situation is more confusing, but various authors (Zöttl and Tschinkel 1971; van den Driessche 1974; Cannon 1983a; Lambert 1984; Mead 1984; Brunck 1987; Bonneau 1978; Evans 1992; Weetman and Wells 1990; Fisher and Binkley 2000) coincide in mentioning that variables like season of the year, yearly climatic differences, time of sampling during the day, age of the tree (stand), canopy position sampled, leaf age, tree DBH, genetic variability of the stand population, slope aspect in the area of sampling, nutrient balance, and competence and health of the stand help to explain foliar concentration variability. The important factors which influence foliar nutrient levels are discussed by, e.g., Drechsel and Zech (1993). In summary, these are the most important factors in practice:

– Time of sampling during the vegetation period
– Age of the foliage
– Crown position

The effect of the seasons of the year on foliar concentration helps define the best moment to sample tissues, considered to be the one when larger concentrations with lower coefficients of variation occur (Vidal et al. 1984). In the lower montane belt of Costa Rica, Birkelbach et al. (1996) found significant correlations between foliar concentration of nutrients of five tree species and their soil availability only during the rainy season, attributing the effect to the ability of the trees to explore deeper soil layer and nutrients associated than those the trees could absorb during the dry season. Under natural conditions in dystrophic seasonally dry tropical ecosystems, the foliar concentration of N, K, P, and S might be reduced to the half or to the third, while Ca foliar concentration increases from the beginning of leaf formation until the half of the dry season, but Mg foliar concentration first increases and then decreases in the same period. The increase of foliar concentration of some elements is being attributed to the increase in their soil availability due to the mineralization of organic residues at the beginning of the rainy season. As a result lower foliar concentrations are found during the dry season and the higher values during the wet season coinciding with maximum tree growth, in spite of nutrients being rainwashed during the wet season (Sarmiento 1984).

The variability in nutrient concentration between components (tissues) of the tree biomass is large and it is attributed to differences induced by tree growth and physiological functions of biomass components (van den Driessche 1974). Several studies show that over the vegetation period in most species, foliar concentrations of highly mobile nutrients, like N, P, and K, decrease, partly due to increasing dry weight of the foliage (dilution effect), while elements which are less mobile in the phloem, like Ca, Si, Mn, or Fe, are accumulated in the leaves. These changes may occur continuously and/or in steps, e.g., before leaf shed. Differences of nutrient levels over the season may be over 100–1,000 % in several nutrients. Tree species that retain their foliage more than 2 years show peak levels of N, P, and K in the first or second year, followed by decreases of as much as 50 % for (2)3–6-year-old foliage (for literature, see Weetman and Wells 1990).

With increasing shading from upper to lower and outer to inner crown, the concentrations of such nutrients as N and P decrease, while those of Ca and Al increase. Intensity and variability of concentration changes, as well as the behavior of the elements, depend on the species (Waterloo 1994). Such studies were carried out on several tropical species, like the evergreen *Eucalyptus deglupta* (Lamb 1976), the deciduous *Gmelina arborea*, or medium-altitude *Alnus acuminata* (Segura et al. 2005, 2006b). A summary of observations is listed by Weetman and Wells (1990). Besides these factors there could be quite different foliar levels on the same soil by analyzing trees of different ages (Lambert 1984) or provenances or the same trees from year to year (van den Driessche 1974; Cornelius and Mesén 1997). Regular controlled fires could reduce foliar N and increase foliar P (Bevege et al., in O'Connell et al. 1981). Additionally, flowering and fructification need nutrients, which will be transferred from other organs, e.g., foliage. Therefore, we must state that there are many limitations to the use of tissue analysis, which must be considered by sampling and interpretation. In spite of these problems, its use in forestry is expanding, since the only alternative is expensive diagnostic fertilization.

## Plot Selection, Size, and Description

**Number of Plots**: For statistical tests the minimum number of observation units (stands, plots, treatments, trees) and/or of replications should be carefully taken into account (Cellier and Oorrell 1984). For statistical background the comprehensive documentation of Steel and Torrie (1980) is recommended. In summary, some rough guidelines are given below (see in addition Appendix i of Anderson and Ingram 1989):

1. If between sites or seasons, differences in foliar or soil nutrient levels should be tested for significance by analysis of variance; at least three replications of each treatment, litter bag, etc., are recommended; five replications are desirable in most cases, especially where the area is variable.
2. In studying different treatments (fertilization, weed control thinnings, etc.) or plantings (species), the experiments should be carried out with all treatments (species) in the same stand (area), better with all treatments (species) and

replications under different site conditions. The site uniformity of each stand or area should be ensured. Allocate treatments if possible randomly. Usually factorial treatment structures are recommended (e.g., randomized complete block design, Latin square design). The number of replications (see, e.g., Cellier and Oorrell 1984) depends on the number of treatments and size of the total area.

3. If the purpose is to obtain information on relationship between growth I and, i.e., foliar N or soil N, as many trees as possible per stand (see below) and/or as many stands as possible per region (study area) should be sampled. For correlation analysis minimum numbers of necessary observations have not been published. But correlations with $n = 6$ or less observations (treatments, plots or stands) are only recommended if these data are means of several soil or tree or subplot samplings. If the data are not means, a correlation analysis should be based in more observations (>10). For multiple regression or discriminant analysis, the number of observations should be at least twice the number of parameters in the equation.

**Plot Size**: For the study of mineral disturbances in tree plantations, e.g., by correlation analysis, a common plot size of 20 × 20 m (0.04 ha) to max. 30 × 30 m (0.09 ha) will be representative for the stands in view of growth, density, as well as topography and soils. For foliar sampling (see below) there must be several (co) dominant trees on the plot. In natural forests a plot size of 50 × 50 m will be more representative in view of botanical variability. In plantations with obvious variations in tree height, a larger representative plot size or several subplots representing the diversity are necessary.

For experimental studies on mineral nutrition (e.g., fertilization), no rigid rules can be laid down for plot size. It depends on the number of trees necessary (see below), tree spacing, and on the number of buffer rows required. The latter may depend on tree age (Cellier and Oorrell 1984). In cases where there is a range in soil or plant properties within a treatment block, the plots should each contain the full range of the gradient conditions The following recommendations mainly concern tree plantations.

**Plot Description**: The value of interpretation of soil and foliar data often depends on a careful plot description. The following data may be necessary and/or valuable in nutritional studies in established stands:

- Location and plot number
- Growth parameters (if available $m^3\ ha^{-1}$, site index or mean top height, DBH root collar diameter, etc., of the sampled dominant or codominant trees)
- Planting year (or if coppiced, age of the stand)
- Trees per hectare (former and recent spacing)
- Provenance of the trees
- Previous land use (farmland, natural forest, fallow, etc.)
- Thinnings, possibly best stems removed
- Weeding (how long, how frequent)
- Occurrence and frequency of controlled fire or bushfire

- Degree of crown closure, understory, weeds (species, ground covering)
- Pests, diseases, termite, or fungal attack
- Deficiency or water stress symptoms of the foliage or shoot
- Fertilization
- Flowering/fructification at present

## Site and Soil Description

Nutrient availability depends on several parameters other than those detected by soil nutrient analyses, like limited water availability or excess of water. However, in the following paragraphs we generally deal with questions regarding sampling for chemical analyses. Soil analysis usually refers to topsoil samples (0–20 cm depth) collected at random with the help of a spade or an auger from at least ten points to conform a composite sample of half a kilo. Occasionally subsoil samples (20–40 cm) are taken since the subsoil might contain not enough water and nutrients for the deepest roots to absorb (i.e., Al accumulation that might reach toxic levels).

**Soil Pit Location and Description**: The soil morphology should be studied on at least one lead profile (pit) in the middle of the plot. The representability of the lead profile(s) should be controlled during soil sampling with a soil auger (see below). If these samplings give information about a change of main soil properties, a second pit will be necessary.

The depths of the pit should be about 120 cm. In the arid tropics deeper soil pits are necessary for trees with taproots; in the humid tropics over 90 % of the roots of most species are situated in the upper 100 cm. Limitations below a depth of 120 cm usually have no great influence on tree growth, until tree growth does not depend on taproot development (in arid areas for water supply). The pit should be situated in front of a dominant tree to study possible inoculation as well as the rooting behavior and rooting intensity as indicator for the most important depth for nutrition as well as root- and growth-limiting soil properties. In semiarid regions, legumes (such as *Prosopis* sp.) with taproots may have nodules only in greater depth near the groundwater table. Activity of nodules usually can be controlled by their reddish inside color.

Soil and site characteristics which are routinely noted are described (e.g., by Hodgson 1978). From the nutritional point of view, some parameters are of special interest, depending on site and species:

- Rooting depth and/or the physiological usable soil depth (down to a hardpan, a saline horizon, a pumice, or a clay layer)
- Main rooting depths with the bulk of fine roots
- Depths with, for example, 20 % or 50 % mottles by stagnic properties (important with respect to, e.g., teak or *Pinus radiata*)
- Bulk density and stoniness for nutrient storage calculations
- Soil texture, drainage, and parent material
- Darkness of the topsoil as indicator of organic matter content

If there are no possibilities for laboratory analyses, at least the pH [and salinity ($EC_e$ or $EC_{1:2}$) in semiarid areas] should be determined on the plots, using a field.

## Soil Sampling and Analysis

The difficulty of obtaining representative samples results from variability in soil properties in the vertical, horizontal, and time dimension, which may be greater than between-tree variations in foliar nutrient concentrations on the same area (Mead 1984). Samples should be located within plots according to a systematic sampling regime with a random start scheme rather than completely at random (Anderson and Ingram 1989).

**The number of soil samples** to be taken depends on the parameter variability, the aim of the study, and the time consumption of sampling and analyses. Usually 20 samplings (soil auger) per ha are called the minimum for visual homogeneous areas; 5–6 sample points on 20 × 20 (3O)m plots are common. The samples are bulked to reduce analytical efforts, if on-plot variations are not of interest. Although it is very common to sample three sides of a "lead profile," this is not recommended. Some data may explain this: in forest plantations in Togo, Benin, and the Ivory Coast, six soil samples per plot (ca. 0.05 ha) have been taken in two depths on visual homogeneous sites (Fig. 3).

The mean standard deviation on 50 plots of organic carbon was ±0.25 % $C_{org}$ per plot and on 10 % of all plots ±0.5 % $C_{org}$ that means on a distance of 10 cm, $C_{org}$ may increase from 0.8 % to 1.8 % in the topsoil (Table 3). One reason for these variations is frequent fires. The ash will be unequally distributed by surface flow. Generally, the mean coefficient of variation (std. dev./mean in %) was greatest in more or less sandy soils, where a small increase in clay content causes high variability in depending parameters (CEC, exchangeable cations, etc.), while variance of pH or C/N ratio usually was small (care should be taken to avoid samples with charcoal rests or ash accumulations).

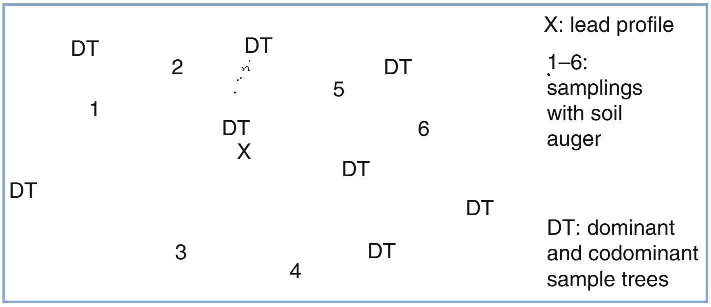

**Fig. 3** Schematic map of a 20 × 25 m sample plot in a teak plantation

**Table 3** Mean coefficients of variation (±std. dev.) on 50 "homogeneous" teak plantation plots in West Africa (six samplings per plot) (Fig. 2, Drechsel and Zech 1993)

| | | | | | |
|---|---|---|---|---|---|
| **Topsoil** | | | | | |
| **Corg** | 19 ± 13 | N | 19 ± 12 | C/N | 6 ± 4 |
| **Caex** | 24 ± 14 | Mgex | 22 ± 11 | Kex | 31 ± 20 |
| **CECeff** | 21 ± 13 | CECpot | 18 ± 11 | | |
| $\mathbf{P^H}$ $\mathbf{(H_2O)}$ | 4 ± 3 | BSeff | 5 ± 5 | Bspot | 14 ± 10 |
| **Subsoil** | | | | | |
| **Caex** | 30 ± 20 | Mgex | 27 ± 19 | Kex | 32 ± 18 |
| **CECeff** | 24 ± 17 | CECpot | 22 ± 15 | | |
| $\mathbf{P^H}$ $\mathbf{(H_2O)}$ | 4 ± 3 | BSeff | 6 ± 8 | Bspot | 17 ± 14 |

Aweto (1982) found on plots of the same pedotopographic series in Nigeria mean coefficients of variation for P-Bray of 67 %. According to Oriola and Adesina (1988), a coefficient of variation over 33 % indicates heterogeneous conditions.

The soil depths which should be sampled for chemical analyses depend on the main rooting zone of the species. In the humid tropics this is usually 0–10 cm, 10–20 cm, and 20–30 cm, where about 70 % of the fine roots of several common forest species are situated, as well as most (available) nutrient reserves. However, sampling up to 60 cm will give more reliable information and is recommended especially for subsoil acidity and storage calculations. In arid zones subsoil horizons of greater depths should be tested for alkalinity, salinity, or hard gypsum or limestone accumulations.

**Sample Preparation and Analysis**: In total not more than 500 g of fine earth (<2 mm) is needed (exception: salinity test in a saturated soil sample). The soil should be transported in PE bags, inside a piece of paper with the sample number. All samples must be air-dried for analyses (30–40 °C) for several days, until no soil solution analyses are required. Results should be corrected by the amount of materials >2 mm (stones, iron concretions, nodules). Litter layer samples are collected with, for example, 20 × 20 × 5 cm squares. For all methods the reader is referred to the following literature: useful handbooks of soil nutrient analysis methods are published by CSTPA (1980), Anderson and Ingram (1989), and PAGE et al. (1982). Selected methods are described by, e.g., IITA (1979) and Cottenie (1980). However, before a method for "available" nutrients is used for soil evaluation, it must be checked if there are interpretation guidelines for tree species, if possible for nearly the same soil and species (see also section "Evaluation of Soil and Foliar Data by Correlation Analysis"). Guidelines for agricultural crops are given in the Tropical Soil Manual (Landon 1984) and by Walsh and Beaton (1973) or Westerman (1990).

**Table 4** Mean coefficient of variation (std. dev./mean in %) per plot of 50 West African teak plantations of different age and minimum number of (co)dominant trees which have to be sampled to detect differences (D) of 5 %, 10 %, and 20 % between means

| Element | Coefficient of variation | 5 % | D 10 % | 20 % |
|---|---|---|---|---|
| N | 13 | 41 | 10 | 3 |
| S | 14 | 48 | 12 | 3 |
| P | 14 | 48 | 12 | 3 |
| Si | 16 | 63 | 16 | 4 |
| K | 15 | 55 | 14 | 3 |
| Ca | 17 | 71 | 18 | 4 |
| Mg | 14 | 48 | 12 | 3 |
| Al | 20 | 98 | 25 | 6 |
| Fe | 18 | 79 | 20 | 5 |
| Mn | 21 | 108 | 27 | 7 |
| Zn | 17 | 71 | 18 | 4 |
| Cu | 16 | 63 | 16 | 4 |

**Table 5** Number of trees of different species to be sampled to allow a detection of 10 % difference of nutrient means. *Eucalyptus deglupta* (Lamb 1976), *Pinus radiata* (Mead 1984), teak (see Table 4), and *Pinus elliottii* (Mead and Pritchett 1974). With the exception of teak, the values are based on trees of a single site or plot. Both pine stands had been fertilized. Sample numbers calculated for *Eucalyptus* (Lamb 1976) concern the two crown positions (out of 12) with lowest coefficient of variation for nutrients

| | *Eucalyptus deglupta* | *Tectona grandis* | *Pinus radiata* | *Pinus elliottii* |
|---|---|---|---|---|
| N | 4 | 10 | 7 | 2 |
| P | 2–8 | 12 | 12 | 7 |
| K | 23–28 | 14 | 16 | 26 |
| Mg | 11–12 | 12 | 30 | 18 |
| Ca | 22–25 | 18 | 36 | 32 |
| Al | | 25 | | 27 |
| Fe | 13–24 | 20 | | |
| Mn | 31–44 | 27 | 69 | 27 |
| Zn | 29–33 | 18 | 48 | 3 |
| Cu | 25–31 | 16 | 11 | |
| B | 20–25 | | 52 | |

## Number of Trees to Sample

Generally, it has been shown to be more representative for a plot to sample only a few leaves from several trees than many leaves from a few trees. Measurements of between-tree variation have enabled estimates to be made of the number of trees that need to be sampled in order to detect differences of, for example, 10 % between element means of two populations ($p < 0.05$). Table 4 shows the mean coefficient of variation (std. dev./mean in %) per plot of 50 West African teak plantations of different ages. In addition, the minimum number of (co)dominant trees is listed which has to be sampled in this region to detect differences (D) of 5 %, 10 %, and

20 % between means. Foliar sampling was strictly the same on all plots (Drechsel 1992).

With increasing plantation age the coefficient of variation decreases slowly in view of Cu and increases some percent in view of Zn. Table 5 compares the number of trees of different species which must be sampled to allow a detection of 10 % difference between nutrient means.

The data show that foliar N shows the smallest variations. For differences in the N and P nutrition between two stands, about ten trees should be sampled. For other nutrients, sampling of five to ten trees allows only interpretation of differences of 20 % or more.

According to Ellis (1975), Brunck (1987), van den Driessche (1974), Weetman and Wells (1990), and Mead (1984), a rough guideline will be to sample not less than ten dominant or codominant trees per plot to detect differences between means of at least 20 %. Differences of 10–15 % need about 20 trees per plot for most nutrients; therefore, 20 trees are recommended to be adequate in nearly all cases. Differences of 5 % or less are for practical reasons not detectable.

## Foliar Sampling and Analysis

Guidelines for sampling of litter as well as of roots and aboveground biomass are given by Anderson and Ingram (1989). In fertilizer trials, for example, often all trees per plot except on edges and margins are sampled. For nutrient inventory studies, trees representative of growth classes of the stand must be selected (Cochran 1977). For the study of possible nutrient disturbances, usually dominant or codominant trees are sampled in tree plantations to obtain site representative data and to avoid large tree-to-tree variations due to shading. Unfortunately, foliage sampling has not been standardized until now. Proposals on the part of the crown, age of foliage, sampling time, etc., depend on the species and in several cases on the research institute (van den Driessche 1974; Ellis 1975; Lamb 1976; Mead 1984; Brunck 1987; Zech 1991). However, there seem to be some agreements over a broad range of species.

**Age and Position of the Foliage**: On pines, needles from the youngest fully developed shoot of the third (first to seventh) whorl below the terminal bud should be sampled. On broad-leaved species, the most recent fully formed (mature) non-shaded leaves of at least two branch ends of the upper third of the crown are taken. These leaves will have nearly the same color as the older leaves, often a somewhat paler green, but they are not as reddish green and small as immature foliage. To reduce in broad-leaved species within-crown variations of specific nutrient levels, other sample positions are possible (Ellis 1975; Lamb 1976). For several species, the differentiation between branches, twig, leaf, and leaflet is difficult (*Casuarina* spp., *Grevillea* spp., *Cupressus* spp.). In these cases, the exact sampled tissue should be sketched for comparison. The aspect will not influence nutrient concentrations near the equator (e.g., West Africa), but farther away (e.g., in South Brazil or North Thailand); foliage from the equator- or sun-exposed side of the trees should be sampled.

**Sampling Older Trees**: It is easy to sample foliage of young trees. Since older dominant trees are normally not harvested for some leaves, they must be climbed to retrieve samples. The sampler has to cut one or two exposed branches of the distal upper crown, from which the leaves could be taken on the ground with care as to leaf position, age, and possible contamination (dust).

**Deficiency Symptoms**: If there are leaves with visual symptoms outside the standard sample position, they should be sampled in addition separately and their foliar data compared with green leaves of the same position and age in healthy stands. In all cases, only to sample foliage with the most pronounced symptoms should be avoided, as due to interactions usually several nutrients are reduced. Samples of different symptom intensities can give more information on the initial limiting nutrient. All foliar samples should be described in detail (smaller than usual, uniformly chlorotic, intercostal/intervenal chlorosis, marginal necrosis, spot necrosis, etc., as well as the age/position of the affected foliage as indicator whether a phloem-mobile (older leaves) or phloem-immobile nutrient (young foliage) is limited).

**Sampling Time**: The effect of the seasons of the year on foliar concentration of trees is important in defining the best moment to sampling; this is considered to be the one when larger concentrations with lower coefficients of variation occur (Vidal et al. 1984). Evergreen species, e.g., pines, often are sampled in the period of most stable nutrient concentrations that means at the beginning dry or dormant season, deciduous trees about 3–4 weeks before the onset of mobile nutrient translocation and coloration. Other authors suggest analyzing nutrient disturbances when nutrients are most in demand. Therefore, sampling for eucalypts in South Africa is carried out at the height of the growing season (Herbert and Schönau 1991). Foliar samples should not be taken in the first 4 weeks of the rainy season and not within 12–36 h after a single rainfall. In the lower montane belt of Costa Rica, Birkelbach et al.'s (1996) sampling is done during the rainy season since significant correlations between foliar concentration of nutrients of five tree species and their soil availability exist during the rainy season, attributing the effect to the ability of the trees to explore deeper soil layer and nutrients associated than those the trees could absorb during the dry season. The rainy season is the most appropriated to sample leaves under natural conditions; in dystrophic seasonally dry tropical ecosystems, the foliar concentration of N, K, P, and S might be reduced to the half or to the third than the one of the rainy season, while Ca foliar concentration increases from the beginning of leaf formation until the half of the dry season, but Mg foliar concentration first increases and then decreases in the same period. The increase of foliar concentration of some elements is being attributed to the increase in their soil availability due to the mineralization of organic residues at the beginning of the rainy season. As a result lower foliar concentrations are found during the dry season and the higher values during the wet season coinciding with maximum tree growth, in spite of nutrients being rainwashed during the wet season (Sarmiento 1984). According to Schönau and Herbert (1983), it seems that 12 months after planting is the optimum age for foliar sampling in order to detect meaningful responses to fertilization.

**Exceptions**: Flowering trees or those with heavy cone or fruit production or trees which suffer from an insect or fungal attack should not be sampled. Trees near to laterite pists are usually contaminated with dust. If such avoidance is impractical, these factors should be taken into account in sample preparation, laboratory analysis, and data interpretation. Analysis of individual trees (rather than composite samples of the stand) is recommended by Weetman and Wells (1990) if sample trees vary with regard to these factors.

**Number of Leaves**: Depending on the species and on leaf size, the number of leaves taken varies between 5 and about 30. On teak trees with a mean 10-leaf dry weight of up to 160 g in young trees, instead of four leaves, eight semi-leaves may be more representative, while on eucalypts about 20 leaves per tree may be representative. On legumes several leaflets consisting of 10–20 pairs of sub-leaflets will be sufficient for all analyses; on *Pinus* sp. often all needles from the sampled young shoot are taken. The analyses need only about 10 g dry weights for all common nutrients. If the on-plot variations between the trees are to be compared with differences between the plots, the foliar sample of each tree should be done in separate labeled paper bags (plastic bags can support fungal growth), which have to be marked with plot number, tree number, sample position, and possible symptoms. In other cases, the sampled leaves of all trees could be mixed per plot and a part of the bulk sample used for analyses.

**Sample Preparation**: Usually the samples (especially those taken in the dry season) are gently washed twice with distilled water to remove dust (e.g., Al, Fe); for micronutrient analyses chloroform has partly been used with more success. However, even brief washing can remove significant amounts of soluble elements like potassium. In such situations the only answer is to divide the sample – one part washed and the other unwashed. Thereafter the samples have to be dried as soon as possible at 65–70 °C for about 2 days. If no oven-drying facilities are available, thorough air-drying should be done (with protection from dust). If the analytical data are to be used for comparing foliar data between fertilizer treatments, for example, or if the foliage appears stunted, the mass (dry weight) of a constant number (e.g., 100) of needles or leaves has to be determined to calculate, for example, the N content per leaf. The leaf stalk has to be cut; on teak leaves the basal third part of the finger-thick midrib could also be removed. The samples have to be finely ground (at least 40-mesh screen).

**Foliar Analysis**: Samples of the humid tropics (ca. >1,000 mm precipitation) should be analyzed at least for N, P, Ca, Mg, K, Mg, Al, Zn, Cu, and if possible S or $SO_4$-S. Concerning N-fixing species, MO will be of interest as well. Foliar samples from arid regions (ca. <80 mm) should be analyzed at least for N, P, Mg, K, Na, Mn, Zn, and B (Cl). Principles of foliar analysis and of different methods are discussed by van den Driessche (1974) and Walsh and Beaton (1973). Reference methods for plant analysis are described by Martin-Prével et al. (1987) and selected methods by Cottenie (1980) and IITA (1979), among others. A useful recent publication is edited by Westerman (1990). For all methods the reader is referred to the literature cited. All samples must be digested and analyzed twice. Results are usually expressed as concentrations on the dry weight. Analyses must be checked routinely for accuracy after every 50 samples by an internal laboratory standard sample. Acceptable variation should be $<5$ % for, e.g., N and P and $<10$ % for other elements. However, a low standard deviation within the laboratory may mean only that the errors are consistent. At least for publication, the results must be checked by analyzing international standard samples (e.g., from the Comité Inter-Instituts d'Etude des Techniques Analytiques du Diagnostic Foliarire, CIIAF). The range of values for between-laboratory differences in foliar analytical results proved to be unexpectedly large and alarming in an IUFRO test of 1985 (Weetman and Wells 1990). Information on CIIAF, the reference samples, and their analyses are available on request from ORSTOM, 70–74 Route d'Aulnay, 93140 Bondy, France. It is also possible to write to International Plant-Analytical Exchange (IPE), P.O. Box 8005, 6700EC Wageningen, the Netherlands.

## Interpretation of Soil and Foliar Data

Works calibrating soil and foliar analysis result against agricultural crop yield are common but an exception in forestry. Some general principles of plant nutrition are valid to interpret soil analysis for forest species as well as agricultural crops. After new information develops critical values might help in improving interpretation of soil analysis results for different elements and forestry species. The interpretation of the results will be also dependent on other site characteristics and silvicultural practices. Due to differences in root math development between forest plantations and agricultural crops, results found in agriculture are hardly applicable in forest plantation management. In the case of trees, especially conifers, it is being found that its nutrient extraction capacity possessing a deeper root system that will explore the soil for longer periods of time is much superior to the assimilation mechanisms of major crops (Zöttl and Tschinkel 1971).

Commonly, soil analysis interpretation is done to take decisions from the fertility point of view. In addition, in the following paragraphs the same information will be discussed in terms of site quality to plant the different tropical forestry species. Several approaches have been used to interpret foliar analysis data from forest stands (Weetman and Wells 1990; Mead 1984), from which the most common are described in the following paragraphs.

### Interpretation Without Reference Data

The first step will usually be to compare the analyzed soil or foliar data in well- and less well-growing stands between themselves with growth as quality guideline. This does not require prior knowledge of critical values. Differences between means of stands or treatments could be tested for significance by variance analysis. In addition, correlation analysis between soil or foliar data and growth may point to limiting nutrients.

## Evaluation of Soil and Foliar Data by Correlation Analysis

As mentioned above, most methods of soil nutrient analysis have been developed and verified under agricultural as well as nontropical conditions. Therefore, only a few guidelines from case studies for the interpretation of soil nutrient levels exist in the tropics. Studying a large number of trees or plantations, it will be possible to establish such guidelines for oneself by linear correlation analysis as well as multivariate analysis, like multiple regression or discriminant analysis. These procedures could help:

1) To identify tree growth-related nutrients (analyzed in soil or foliage)
2) To test soil analysis data (of different methods) by comparison of soil nutrient contents or concentrations and corresponding foliar nutrient levels or growth

In both cases it will be favorable if data of a wide range of soil fertility (or fertilizations) and corresponding different growth or foliar levels are available. An example of how critical soil test levels will be determined in comparison with tree yield (e.g., by Cate-Nelson graphics) is described by Dahnke and Olson (1990). In several cases, it will be useful to consider, besides absolute values, nutrient coefficients, such as K/CEC, and soil pH or soil texture classes.

The identification of tree growth-related nutrients (soil and foliar data) by correlation analyses has been widely used in the tropics and subtropics (e.g., Lambert 1984; Srivastava and Mim 1978; Bellote 1990; Drechsel 1992; De Hoogh 1981; Lamb 1977) as well as in fertilization research for assessment of optimum foliar levels (Schönau and Herbert, 1983). Foliar levels of *Eucalyptus grandis* had been considered too high when their relationship with growth was inverse and vice versa. Multiple regression analysis has also been used for determination of critical foliar levels (see next paragraph) of, for example, phosphorus in *Pinus elliottii* and *P. taeda* (Bevege and Richards 1971).

In contrast, the few studies on interpretation guidelines of soil nutrient analyses only concern some nutrients and a few of the most common tropical plantation species, like pines, eucalyptus, and teak (e.g., Sankar et al. 1988; Reissmann and Ziittl 1984; Glaser and Drechsel 1992). In South Brazil, topsoil limit values for deficiency of *Pinus taeda* are reported by Reissmann and Ziittl (1984): K, 10 ppm; Ca, 30 ppm; and Mg, 10 ppm (all extracted with 1 % citric acid). Critical soil P, K, and Mg ranges using two different methods according to Mehlich are reported by Lea et al. (1980) for the same species (e.g., double-acid extractable phosphorus, 3–5 ppm; new Mehlich phosphorus, 5–6 ppm). In West Africa, a sufficient phosphorus supply of teak occurred at soil levels of more than 150–160 ppm P in the topsoil (extracted with in $H_2SO_4$ after dry ashing at 550 °C) (Glaser and Drechsel 1992). According to Khanna (1981), the development of soil tests and interpretation

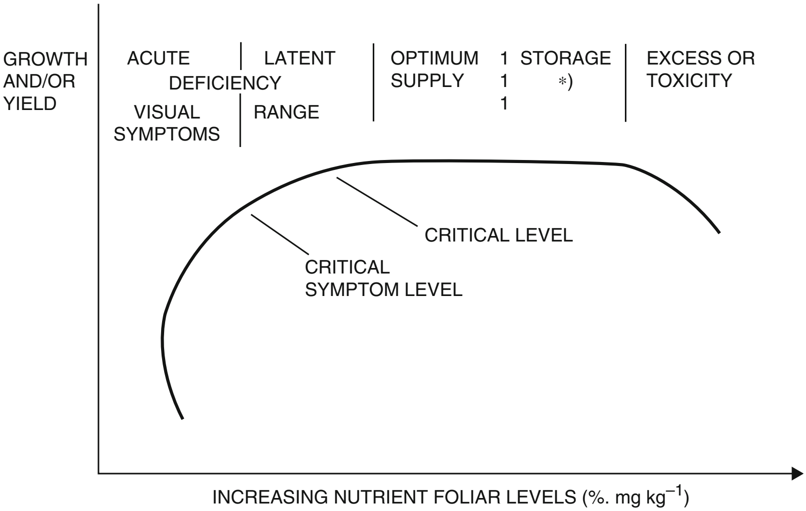

**Fig. 4** Relationship between foliar nutrient concentration and growth (schematic). Both "critical levels" do not represent a sharp, well-defined point but a narrow range of concentrations. *): store of nutrients (e.g., P) in time of excess (e.g., fertilization) for retranslocation in times of short supply or "waste basket" of, e.g., Al in Al-accumulating trees, such as some pines

guidelines for tropical forestry needs more investigation, taking into consideration the dynamics of tree growth, nutrient requirements, and nutrient mobilization from "capacity factors," like organic matter. This will be true especially in view of P or N (see, e.g., Humphreys and Pritchett 1972).

## The "Critical Level" Approach

The interpretation of foliar data will be easier if frequently studied species of commercial forestry are of interest, where reference data exist. Among these interpretation guidelines for foliar data, "critical levels" are the most common. Especially in forestry we must distinguish between two critical levels (Fig. 4):

1. The critical level between latent deficiency and optimum supply, which is considered as the foliar nutrient concentration at which yield attains 90 % of the possible maximum
2. The critical level between acute deficiency and latent deficiency at which deficiency symptoms appear

The first critical level is the more common (van den Driessche 1974), although it is only well established in interpretation of foliar analysis in temperate and (sub) tropical agriculture, for pasture crops, fruit trees, coffee, etc. (Reuter and Robinson 1986). Exact critical levels could only be established if the amounts of all other

**Table 6** Optimum foliar nutrient concentrations for mostly 1-year-old *Eucalyptus grandis* in Natal and Zululand. Levels have been used for DRIS (Herbert and Schönau 1991)

| **Macronutrient** | N | P | K | Ca | Mg | S | Na |
|---|---|---|---|---|---|---|---|
| % | 2.9 | 0.14 | 0.75 | 1.6 | 0.35 | 0.2 | 0.32 |
| **Micronutrient** | Mn | Fe | Al | Zn | Cu | B | |
| **mg kg$^{-1}$** | 600[a] | 110 | 160 | 18 | 12 | 32 | |

[a] Typical range in this region, 151–2,875 ppm Mn (Schönau 1981)

nutrients are non-limiting, since the levels of a specific nutrient depend on the supply of the others. This means that under tropical conditions optimum and 90 % critical levels could be established only in fertilized pot cultures or industrial plantations, where optimum yield is known (Table 6), since the typical case of tropical plantations is suboptimal growth. Due to anatomical and physiological characteristics, there can be large differences in optimal and critical values for different species or biotypes even under the same site conditions. Until now such data have been published only for some (subtropical) species (e.g., Richards and Bevege 1969; Bevege and Richards 1971). Besides nutrient concentrations, optimal or critical nutrient ratios (e.g., N/P) could also give valuable information (Schönau 1984).

Published critical levels often refer to seedling experiments and lack the required field verification (Weetman and Wells 1990). If fertilization is not possible, more practicable guidelines than the “90 % critical levels” will be regional “optimum” levels, which could be referred to those stands with a class I site index. The occurrence of “luxury” supply should be taken into account.

The “critical level” of deficiency symptom appearance is of interest in suboptimal growing plantations if there are only limited possibilities for fertilization. This level is well established in temperate forestry (e.g., Ballard and Carter 1986), will be easier to analyze, and could be used as a guideline to diagnose considerable (acute) deficiency (Table 7). Foliar discoloration is accompanied by a pronounced decrease of photosynthesis and assimilation for wood production.

Such ranges in concentration (Table 7) indicating low (visual deficiency), marginal, and intermediate (not optimum) nutrient levels have been reported for some other tropical and subtropical species as well (Leaf 1968; Stone 1968; Drechsel and Zech 1991). The data indicate that the nutrient concentrations at which visible deficiency symptoms appear are more comparable between conifers or broad-leaved trees than the “critical levels” of 90 % optimum supply.

As mentioned above, the comparison of foliar symptoms and foliar nutrient levels is complicated by several reasons like seasonal changes of nutrient levels. Another important factor is nutrient interactions as a result of deficiency or fertilization (Lambert 1984; Schönau 1981). Nutrient interactions complicate the identification even of mono-nutrient deficiency. Kaul et al. (1972) analyzed the following secondary effects on foliar levels in *T. grandis* seedlings under controlled mono-nutrient deficiency (+, tendency to higher concentrations; −, tendency to lower concentrations; ++ and − −, clear effect):

**Table 7** Preliminary guidelines for foliar nutrient level interpretation for teak in West Africa according to Drechsel and Zech (1991) and Drechsel (1992). "Reference" foliar levels refer to unfertilized class I stands. Samples were taken 1 month after the beginning of the main rainy season, as recommended in section "Foliar Sampling and Analysis." According to DRIS, the levels of probable deficiency of N and Ca seem to be too low and the level of Mn possible too high (Drechsel 1992)

| | | Deficiency symptoms probable | Deficiency probable | Reference foliar levels (class I trees or stands) |
|---|---|---|---|---|
| N | Age < 4 | ≤1.75 % | ≤2.25 % | 3.20 |
| | Age > 9 | ≤1.30 % | ≤1.50 % | 2.60 |
| P | Age < 4 | ≤0.15 % | ≤0.19 % | 0.27 |
| | Age > 9 | ≤0.12 % | ≤0.17 % | 0.23 |
| S | | ≤0.11 % | (0.13) | 0.18 |
| K | | ≤0.45 % | ≤0.90 % | 1.90 |
| Ca | | ≤0.40 % | ≤0.60 % | 1.00 |
| Mg | | ≤0.13 % | ≤0.20 % | 0.33 |
| Fe | | | ≤50 ppm | 100 |
| Mn | | ≤25 ppm | ≤33 ppm | 49 |
| Zn | | ≤11 ppm | ≤14 ppm | 23 |
| Cu | | | ≤7 ppm | 17 |

N—deficiency P (++), K (+), Ca (++), Mg (− −,. S (+)
P—deficiency N (+). K ("−L Ms (−), 5 (r)
K—deficiency N (−), Ca(++), S (−)
Ca—deficiency P (+), K (+), S(−)
Mg—deficiency N (+), P (−), S (−)
S—deficiency N (++), P (++), K (++), Mg (−)

N and P deficiencies reduce the leaf dry weight markedly, while Ca, Mg, and S deficiency to about 40–50 %. Results like these show that it is undoubtedly necessary to consider the nutrient interactions to obtain a clear and distinct understanding of fertilizer requirements, and the best way would be to consider all nutrient ratios simultaneously. This is possible using the DRIS system.

## The DRIS

The foundation of the diagnosis and recommendation integrated system (DRIS) is the concept of nutrient balance. The interrelationships between all nutrients are considered simultaneously. DRIS was developed due to problems associated with the critical level approach (see above), especially for common cases of multiple deficiencies. In contrast to critical levels, DRIS is able to consider, for example, dilution effects and nutrient interactions and to reveal the order of requirements (e.g., P > N > K). This will be a valuable tool in the choice of an adequate fertilizer. Although DRIS has been developed for agricultural purposes, the system was used with success in forestry (Truman and Lambert 1980; Schutz and de Villiers 1987; Herbert and Schönau 1991).

The application of DRIS requires four steps (for details, see Walworth and Sumner 1987).

**The Creation of a Data Bank**: For a specific tree species, the data bank includes plant analyses with corresponding yield data under the widest range of conditions possible. The greater the number of observations, the higher the precision of the DRIS norms. The lowest recorded data number cited by Schutz and de Villiers (1987) was 30 trees (*Populus* sp.), but much higher observations (>100) will be better. The population of samples is then divided into usually two subpopulations on the basis of yield (e.g., mean top height) or site index. If there are plantations of different age, it will be possible to establish for different age classes a high- and low (er)-yielding subpopulation.

**The Development of DRIS Norms**: For the high-yielding population, each analyzed element is expressed in as many combinations as possible with other elements (N/Pf N/K, N/Ca, and so on). The mean and coefficient of variation (CV) of all ratios (testing for variance homogeneity) have to be calculated as DRIS norms. Another possibility is to use known optimum foliar data for norm calculation, if these are valid for the species, season, age, etc.

**The Calculation of DRIS Indices**: For all trees or stands of interest not belonging to the norm population, the same calculations have to be carried out. The coefficients and means of these trees or stands will be compared with the norms by calculating DRIS indices for each element (see Walworth and Sumner 1987). These represent relative insufficiency (negative values) or relative excess (positive values). The most negative index is the most limiting. The sum of all absolute index values (N index, P index, etc.) reflects the nutrient imbalance of the whole tree or stand under study. An example is given in Table 8.

**The Testing of the Norms**: The results should be compared with interpretation guidelines – if available – for foliar nutrient concentrations and tested by fertilization response (see Walworth and Sumner 1987).

From Table 8 the main conclusions are that there seems to be no severe nutrient deficiency, although supply of especially N and Mn is insufficient. The order of requirements is N > Mn > S > Mg > Cu, Zn > Fe, etc. At first sight, these results are astonishing in view of high soil Mn and N levels, but studies show reduced N availability due to waterlogging and a highly significant correlation between foliar N and growth, while supply is limited due to lime and high pH (7.0–7.6) (Drechsel 1992). All this accentuates the sensibility of DRIS.

If fertilization trials are not possible, DRIS could also be used for the interpretation of specific unknown deficiency symptoms. Table 9 shows the DRIS indices for teak trees with green leaves (1) and for only those trees with, as example, symptom 9: streaked, pronounced intercostal chlorosis (partly with first necrotic

**Table 8** Comparison of foliar nutrient concentrations and DRIS indices for a 23-year-old *Tectona grandis* on a Vertisol in southern Benin [S.I. (50) = 28 m; class II]. DRIS norms have been established for two age classes (1–6, 11–45 years; n = 90) (Drechsel 1992)

| Element | Foliar nutrient concentration | DRIS indices |
|---|---|---|
| N | 2.11 % ± 0.49 | −18 |
| P | 0.27 % ± 0.05 | 8 |
| S | 0.15 % ± 0.03 | −9 |
| Si | 11.6 % ± 2.50 | 13 |
| K | 2.14 % ± 0.37 | 2 |
| Ca | 1.30 % ± 0.14 | 11 |
| Mg | 0.30 % ± 0.04 | −7 |
| Al | 119 ppm ± 31 | 14 |
| Fe | 96 ppm ± 15 | −2 |
| Mn | 30 ppm ± 4 | −14 |
| Zn | 18 ppm ± 4 | −6 |
| Cu | 14 ppm ± 3 | −6 |
| Sum of absolute index values | | 110 |

**Table 9** Comparison of foliar nutrient DRIS indices for green teak leaves (1) and leaves with a specific nutrient deficiency symptom (9); sampling position, age, etc., were similar (Drechsel 1992). The most negative index value indicates the most limiting nutrient

| Sympt. | Si | N | Cu | Al | K | Mg | Ca | Fe | Zn | Mn | P | S |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | −6 | −9 | 0 | 8 | −1 | −1 | −4 | 2 | −2 | 1 | −4 | −3 |
| 9 | −15 | 4 | 19 | 18 | 8 | −6 | −56 | 6 | 2 | 26 | −6 | −8 |

patches), wrinkled leaf surface, and partly burned margins. From Table 9 the following conclusions could be made:

1. Even in green leaves we find some nutrient imbalances with, for example, relatively low N levels and relatively high Al levels.
2. The most limiting nutrient for the development of symptom 9 is Ca, followed by Si. On the other hand, there is a relative excess of Mn, Cu, and Al.

Until today, several possibilities of the DRIS are not used in forestry, since as many as yield-determining factors capable of quantitative or qualitative expression could be considered in the system. Besides foliar data, this will be soil or rainfall data as well (Walworth and Sumner 1987).

## Interpretation of Soil Analysis to Choose Lands for Planting Forest Species

***Acacia mangium***: This is a rustic fast-growing pioneer species of the humid and very humid flat tropical lowlands up to 300 m elevation. The species grows better under short dry period conditions due to its large daily water consumption (Sánchez 1994). Under dry periods longer than 3 months, trees tend to die after the second or third year of age due to the fact that trees do not shed foliage (Ocaña 1994; Ilstedt et al. 2004). Water excess and low-fertility conditions are not recommended since many diseases are favored causing growth problems to the trees (Ilstedt et al. 2004). Soil fertility-wise, *A. mangium* does not tolerate soil salinity (Martínez 1987; Sánchez 1994) but takes acid with pH between 3.4 and 5.0 (Otsamo et al. 1995), low organic matter content (Nirsatmanto et al. 2004; Kim et al. 2008), and low available P with a minimum of 100 μmol P to maximize nodulation (Ribet and Drevon 1996). Acacia growth is severely reduced at bulk density values between 1.35 and 1. 52 Mg $m^{-3}$ in clayey shallow Ultisol of Panama and Malaysia but drives well in sandy soils and mine spoil residues (Majid et al. 1998).

***Alnus acuminata***: This species possesses an extended lateral root system that favors chances for colonizing hilly lands where it is used to protect and restore eroded sites and road cuts, particularly in well-drained soils of alluvial or volcanic origin and unfertile and rocky soils (Tarrant and Trappe 1971; Cervantes and Rodríguez 1992; Budowski and Russo 1997; Muñoz 1998). It grows well between 1,500 and 2,600 masl with reported limits of 610 in Costa Rica (Horn and Rodgers 1997) and 3,050 masl in Ecuador (Nieto et al. 1998). *Alnus* species are considered as pioneers that grow well under extreme climatic and soil conditions. Soil fertility-wise it grows well in a wide range of soil conditions like pH water 4.7–6.4, cation exchange capacity 0.4–18.7 cmol (+) 100 $g^{-1}$ soil, organic matter content 0.6–28.1 %, exchangeable Mg 0.1–6.5 cmol (+) 100 g-1 soil, exchangeable Na 0.2–8.8 cmol (+) 100 $g^{-1}$ soil, N 0.01–1.5 %, and a C/N ratio 1.4–38.9 (Camacho 1983; Sánchez 1985; Muñoz 1998; Grime 1992). The species overcome N deficiencies by fixing the element in symbiosis with *Frankia* (Álvarez 1956; Carlson and Dawson 1985; Muñoz 1998; Ritter 1989; Rondón and Hernández 1995) if available P is sufficient (Gardner et al. 1984; Michelsen and Rosendahl 1990; Russo 1995; Añazco 1996; Budowski and Russo 1997; Segura et al. 2006a).

***Cedrela odorata***: This species grows abundantly as individual trees in lowlands and piedmonts of mixed deciduous tropical and subtropical (wet and very wet) forests (Guevara 1988). Its root math development is affected by soil depth being superficial and extended if soils are shallow, but deep soils are fertile and well drained (Ponce 2010). Good soils like Cambisol and Acrisol with pH 5–7, 2–6 % organic matter, over 4 ppm P (Olsen mod.), less than 1 ppm Al (KCl), and Ca $>$ 5, Mg $>$ 2, K 0.12–0.65, Na $<$ 0.2, and CIC $>$ 15 cmol 100 $g^{-1}$ soil favor high productivity of the species (Galván 1996). Castillo (2008) and Méndez (2012) consider that the species performance might be improved inoculating with mycorrhizae and fertilizing at planting in degraded soils. When the species is planted in leaving fences (Viera and Pineda 2004) or in plantation, the trees grow better when mixed with other trees since insect damage is reduced (Piotto et al. 2004; da Cunha and Finger 2013). High values of bulk density in Andisols (critical value 1.20 Mg $m^{-3}$) reduce the growth of *C. odorata* (Castaing 1982), but in soils derived from calcareous materials of México, values of 1.38–1.88 Mg $m^{-3}$ did not (Murillo 2008).

***Pinus caribaea***: This species adapts to varied ecological conditions (Isolán 1972; Tobar 1976; Camacho 1983; Ortega 1986; Vásquez 1987; Vásquez and

Ugalde 1995; Fornaris et al. 2004; Corrêa and Bellote 2011). However, when planted in highly degraded or marginal areas, yields do not correspond with the potential of the species (Herrero 2001) and tend to decrease as total precipitation increases from 850 to 3,500 mm year$^{-1}$ or temperature increases from 20 °C to 27 °C (Camacho 1983; Vásquez 1987; Vásquez and Ugalde 1994). According to Ladrach (1992) the species can take long dry periods on sandy dystrophic soils, but under these very conditions the author reports the dieback of trees negatively affecting site quality (Márquez et al. 1993; Fornaris et al. 2004; Corrêa and Bellote 2011). Nutritionally *P. caribaea* yields are positively affected by the adequate supply of Ca, K, Mg, and Na (Camacho 1983; Zamora 1986), Cu (Ortega 1986; Vásquez 1987), organic matter (Herrero et al. 1983), pH values 6–7 (Vásquez 1987), and medium to high base saturation (Corrêa and Bellote 2011). At establishment Mg salts might negatively affect the initial growth of the species in Cuba so that when Ca/Mg values vary between 1 and 5, the Mg excess causes brown-yellowing color in the needles and trees to die when soil pH is over 6.7 (Acosta et al. 1975). Some authors have found good correlations between soil properties and site index for the species (Tobar 1976; Watanabe et al. 2009; Arias and Calvo 2011). Low yields can be obtained in shallow soils (less than 25 cm total), poorly drained soils, high bulk density, and effective soil depth of less than 80 cm (Isolán 1972; Ortega 1986; Vásquez 1987; Zamora 1986; Corrêa and Bellote 2011). To improve shallow or compacted soils, deep planting holes or subsoiling is being demonstrated to help to increase productivity (Hernández et al. 1976).

***Cordia alliodora***: This species grows in clusters after clearing the forest, as individual trees or in small groups in secondary forests and grasslands in dry or humid tropical and subtropical lowlands or intercropped in cacao and coffee plantations. It is naturally found from sea level to 2,000 masl, with optimal growth below 500 msnm, and in regions with 1,300–2,000 mm of annual precipitation, short dry periods, and average mean annual temperature near 24 °C (Boshier and Lamb 1997). Herrera and Finegan (1997) mention that the tree is more abundant in undulated landscapes than in stepped lands where soils have higher amounts of exchangeable acidity. According to several authors (Johnson and Morales 1972; Giraldo et al. 1980; Graves and McCarter 1990; Bergmann et al. 1994; Reyes 1997; Hummel 2000), *C. alliodora* grows better in soils with the following characteristics: (i) of high natural fertility (the acidity saturation should be lower than 80 % and pH greater than 5.5); (ii) medium to high contents of N, P, and K; (iii) a cation exchange capacity higher than 40 cmol (+) 100 g$^{-1}$; (iv) a content of Mg that should be sufficiently low not to cause K/Mg imbalances; (v) free of seasonal floods; (vi) humid but well drained; (vii) sandy loam texture; and (viii) deep of alluvial origin (although it also grow in lateritic, clayey, moderately drained, relatively fertile, red forest lowland soil). The best stands are found in high dissected alluvial terraces of fertile soils or in deep rich soils, high in organic matter content, like Andisols. Other authors (Peck 1976; Poel 1988; Bergmann et al. 1994) do not recommend planting *C. alliodora* in (i) poorly or excessively drained alluvial valleys, (ii) degraded grasslands of low fertility, (iii) deep and infertile sandy soils with little organic matter, (iv) saline-sodic soils, and (v) hard, shallow lateritic soils;

poor drainage badly affects the growth and quality of the wood of *C. alliodora* (Pérez 1954).

***Gmelina arborea***: This species adapts to an ample range of climates and soils (Arce 1997; Herasme 1997), especially to soils of high fertility, in flat to undulating landscapes, in slopes between 0 and 600 elevation, with a mean total annual precipitation of 2,500 mm, and with 2–4 months' dry spell (Murillo 1996). Several authors have developed good correlation models between physiographic and climatic characteristics associated with the quality of the sites and the growth of *Gmelina* in several countries (Salazar and Palmer 1985; Hughell 1991; Stuhrman et al. 1994; Vallejos 1996; Agus 2001; Agus et al. 2001). To attain the best rates of growth of the species (Camacho 1983; Zeaser and Murillo 1992; Vásquez and Ugalde 1994; Stuhrman et al. 1994; Zech 1994; Vallejos 1996; Moya 2004; Arias and Calvo 2011; Muñoz et al. 2009), it should be planted in soils with the following characteristics: (i) loam to clay loam texture; (ii) pH between 6.0 and 7.0; (iii) acidity saturation lower than 7 %; (iv) more than 80 cm depth (at least 30 cm A horizon); (iv) well drained; (v) more than 8 g $L^{-1}$ available P; (v) Ca 18–23, Mg 6–7, and K 0.3–0.7 cmol (+) $L^{-1}$; (vi) minor elements in the ranges of Fe 29–66, Cu 5–250, and Zn 0.9–2.2 g $L^{-1}$; (vi) effective exchange capacity over 20 cmol (+) 100 $ml^{-1}$; (vii) high organic matter content; and (viii) irrigation in dry areas. *G. arborea* yields less if soils are (i) compacted ($Bd > 0.9\ Mg\ m^{-3}$), (ii) trees are planted above 500 elevation, (iii) lands are exposed to strong winds, (iv) soil acidity saturation is over 25 %, and (v) the available Ca is over 10 and Mg less than 6 cmol (+) $L^{-1}$ (Obando 1989; Zeaser and Murillo 1992; Stuhrman et al. 1994; Vásquez and Ugalde 1995; Vallejos 1996; Osman et al. 2002; Alfaro 2000). Because the radical system of *G. arborea* is superficial, the species should not be planted in overgrazed acid soils (Ruhigwa et al. 1992) unless compaction and addition of K leached are corrected (Stuhrman et al. 1994).

***Swietenia macrophylla***: This species grows in humid and subhumid seasonally dry tropical lowlands at elevations between 50 and 1,400 masl. It grows best in seasonally dry (up to 4 months dry) tropical areas with rainfall ranging 1,000–4,000 mm $year^{-1}$ (Grogan and Schulze 2012) and an annual mean temperature range of 15–35 °C (Mayhew and Newton 1998). Grogan and Landis (2009) found in old natural forests of Brazil that major factors constraining caoba growth are lianas covering the crown, the illumination of the crown, and the production of fruits, although the main limiting factor for its development is its susceptibility to the attack of the borer of the stem *Hypsipyla* spp. (Hauxwell 2001). Several authors (Verwer 2006; Negreros and Mize 2013) consider that the species prefers flat sites and red-brown to very dark brown soils, instead of the brown-reddish deep and often P-depleted soils; the species drive well in clayey to sandy soils with pH values 6.5–7.5, well drained and with good water holding capacity; caoba grows poorly in areas flooded for long periods of time. Under natural conditions, the best growths have been observed in grounds of volcanic origin, and although it tolerates better than other species, nutritional deficiencies do not prosper either in argillaceous black soils (Vertisols) or in shallow compacted, degraded soils, low in organic matter.

***Tectona grandis***: Teak is associated with the deciduous dry and humid forests of India (Briscoe 1995). Thiele (2008) mentions that growth is more affected by physiographic, climatic, and plantation management variables than by the chemical and physical properties of the soil; therefore, it is common to find poor quality sites on good soils due to late planting or poor weed control. Bebarta (1999) mentions that among the physical-chemical properties of the soils, nothing is more important for teak growth than the pH, which is also related to other soil variables like base saturation, Ca saturation, and acidity saturation. In acid soils the teak mycorrhizal association is also negatively affected (Raman et al. 1997; Alvarado et al. 2004), and inoculation is recommended to increase the number of leaves and the height and diameter of seedlings (Gadea et al. 2004). Sites considered as good to plant teak (Camacho 1983; Gangopadhyay et al. 1987; Drechsel and Zech 1994; Vásquez and Ugalde 1994; Vallejos 1996; Jha 1999; Kumar 2005; Favare et al. 2012; Alvarado and Mata 2013; Segura et al. 2013) should have soils with the following characteristics: (i) preferably fertile and of alluvial and calcareous origin, (ii) pH neutral, (iii) average N and K availability and average exchangeable Ca and Na, (iv) high saturation of bases (over 70 %) and low acidity saturation (below 5 %), (v) loamy textures, (vi) bulk density in the A horizon lower than 1.16 g $cm^{-3}$, (vii) moderately deep (>90 cm), (viii) granular to subangular blocky structure, (ix) well drained, and (x) with low electrical conductivity. While planting teak, soils with the following properties should be avoided: (i) poorly drained depressional Vertisols with flooding problems, although according to Muñoz et al. (2009) teak grows well in these sites if irrigated during the dry season, (ii) shallow soils like rocky and stony Entisols, (iii) shallow soils on the top of windy slopes, (iv) sandy soils in rustic or drier environments, and (vi) regions where the levels of acidity of the soil and the subsoil are very high. Several authors have developed correlation models between the growth variables of teak and the environmental variables that determine tree growth in Mexico and Central America (Vallejos 1996; Mollinedo 2003; Vaides 2004; Bermejo et al. 2004; Sima 2010) environments where teak grows better as rainfall increases and also exchangeable Ca content increases in the soil (Rugmini et al. 2007), but is retarded when the hydric deficit increases, the annual mean air temperature increases, and the acidity saturation increases (Oliveira 2003; Alvarado and Fallas 2004; Mollinedo et al. 2005).

## Amelioration of Site and Tree Nutrient Status Without Mineral Fertilizer

If soil analysis indicates before planting that soil fertility will limit tree growth, the forester can reduce nutrient disturbances by:

- Accumulating organic residues and conserving soil organic matter after clear-cutting and during site preparation, since organic matter is a keystone of sustained productivity.

- Planting site-adapted and/or less demanding (local) species or provenances. On less suitable sites foresters should support natural regeneration. Often the quality and biomass production of native (pioneer) species is underestimated. These secondary forests should be protected in early years from livestock and could be managed by weeding and thinning as well. They may be more suited for smaller projects, e.g., on village level. Additionally, degraded soils could be ameliorated using tree legumes or other pioneer trees, like *Musanga* sp. in West Africa, *Macaranga* sp. in SE Asia, or *Cedrela odorata* in Central America (Piotto et al. 2004), for restoring soil fertility on "planted fallows" (Sánchez et al. 1985; Drechsel et al. 1991), before highly productive (tree) crops are introduced to the area. However, more research is needed for the establishment of site-adapted mixed plantations or natural forest management.
- Improving soil and silvicultural practices by mechanically rather than chemically weeding or adding organic residues.

In established stands, soil and foliar analyses will give qualitative information on the occurrence and kind of nutrient deficiencies. It is usually also possible to analyze the reasons for mineral disturbances, such as low-nutrient reserves, low or high pH, waterlogging, water stress, weed competition, etc. (see Webb et al. 2001), by the description of foliar nutrient deficiencies in conifers and broad-leaved species (Zöttl and Tschinkel 1971; Cannon 1983b; Drechsel and Zech 1991). In addition, it will be possible to distinguish between weak and severe deficiency and to say which nutrient supply is more and less limited.

What kinds of conclusions are possible after deficiency diagnosis?

First of all, it may be possible that the magnitude of nutrient deficiency, in a few cases the deficiency itself, is man-made and avoidable (e.g., frequent controlled fires or bushfires, waterlogging due to soil compaction during site preparation, insufficient inoculation, regular litter harvesting). Secondly, it may be possible to reduce nutrient deficiency by, for example:

- The promotion of $N_2$-fixing undergrowth
- Low-intensity fire to support the decomposition of long-term accumulated litter
- Soil tillage to avoid inundation or to increase effective soil air volume on compacted soils

Since nutrient uptake depends largely on water supply, it will be necessary:

- In relatively dry environments, to control weeds longer and more frequently than usual
- To keep the canopy closed or the soil covered to avoid evaporation
- In semiarid regions, to establish site-adapted rainwater harvesting systems if irrigation is not possible (Drechsel et al. 1989)

Generally, early thinning will increase nutrients and water available to the remaining trees. During thinning and harvesting, foliage, twigs, and bark should be left and crushed in situ. Slash will also be of value as mulch if there is no other understory or soil cover against erosion. Slash burning between rotations is the main reason for the second-rotation decline in South Australian pine plantations (Woods 1990). The knowledge of the restricted productivity of the site is often used to reduce the rotation period, since maximum CAI will be reached earlier. In view of later rotations, this practice will strongly deplete nutrient reserves: as discussed above, the nutrient removal per unit of biomass will be very high in short rotations in comparison with longer rotations. One possibility will be to plant soil-ameliorating species and/or indigenous trees or shrubs after clear felling. In plantations of smaller size (e.g., village forestry, farm forestry), non-mineral fertilizer may be available [decomposed (not fresh) farm manure, rice straw, or other compost]. Weeds or grasses used for compost may bear a lot of seeds! In established stands livestock will find shade and could browse undergrowth by “fertilizing” the plantation.

## Fertilization of Forest Plantations and Natural Tropical Forests

Diagnostic foliar analysis without fertilization trials is not able to provide quantitative estimates of nutrient requirements and fertilizer application. Therefore, the next step should be to establish fertilization trials using the deficient nutrients in different amounts and mixtures to establish site-adapted recommendations. How fertilizer response data could be interpreted for recommendations is described by Dahnke and Olson (1990). The alternative is to use the experiences of comparable projects (species and sites) for application of a deficiency-corresponding fertilizer. This may be suitable as a practice, since the start of fertilization at planting should first of all support the development of the root system and not of soil fertility. The most popular experiences will be dealt with in this paragraph.

Fertilization trials are widespread in tropical forest plantations, since most of the soils for plantation forestry are low to moderate in fertility. Therefore, fertilization only makes sense where the soil is able to hold the nutrient in the rooting zone, especially in view of water-soluble fertilizer. This will be possible in less weathered soils or in soils with adequate amounts of organic matter (humus). Nutrient management in the tropics is for that reason also humus management. Although fertilizer trials are widespread, systematic research and reevaluation and verification of experiments and results are limited to a few countries and commercial forestry, usually for financial reasons.

Conclusions from fertilization research, which may be useful in this book, should:

- Result from long-term studies
- Encompass a wide range of soils and climates
- Encompass the major trees of commercial interest (eucalypts, pines)

According to these basic conditions, the following experiences and recommendations summarize to a great extent results from South Africa surveyed by Herbert and Schönau (1991) and May et al. (2009) and commercial and native species plantations in Latin America by Alvarado and Raigosa (2012). For regional or country-specific information and literature on fertilization of teak and *Acacia mangium*, see Paudyal (2012), and for *Eucalyptus* spp. and *Pinus* spp., Crane (1984), Schutz (1976), Schönau and Herbert (1989), Barros and Novais (1990), Dell et al. (2001), and Rodríguez and Alvárez (2010) should be used; for other (multipurpose) species, see Waring (1984).

No reference is made to laboratory experiments with seedlings or nursery trials. Nevertheless, nutrient deficiencies are often found even in the nursery, often due to nonoptimal inoculation with mycorrhiza, a high acid or alkaline soil pH, or inadequate irrigation. For nitrogen a careful fertilizer application to seedlings is necessary to avoid overfertilization and tree mortality or susceptibility to diseases.

## Experimental Design

For fertilizer trials properly replicated applications (e.g., a factorial block design) are indispensable. Forest fertilizer trial designs are described, for example, by Binns (1976) and for sloping lands by (IBSRAM 1989). Details are described by Cellier and Oorrell (1984) and in view of statistical analysis by Little and Hills (1978). A brief handbook for field trial design and statistical interpretation has been published in several languages, for example, by the German Agency for Technical Cooperation (GTZ) (Rohrmoser and Wermke 1985). The homogeneity of the area must be checked by soil sampling before planting. Hurlbert (1984) discussed how pseudoreplications and wrong statistical conclusions can be avoided.

## Time of Fertilizer Application

Fertilizer application must be carried out at the beginning of the rains or toward the end of the rainy season, when it is already too late for planting, but the growth of many tree species reaches a maximum. During the peak of the rainy season, fertilizer application would probably interfere too much with ongoing planting work, and nutrient losses by rain will be high. Best conditions to apply fertilizers include periods of high root activity, moderate soil temperature, moist litter and soil, and a high probability of good rains soon after the applications of the product, like the ones found at the end or the beginning of the rainy season in tropical regions (Paudyal 2012). For some elements the response is best after thinning (Crane 1982) and results will be visible soon after the treatment is applied (Torres et al. 1993), particularly on low-fertility soils; the little response to the addition of N and P in very dense plantations is attributed to the lack of area for canopy expansion of fertilized trees; however, it should be remembered that when infertility is caused for other reasons than low nutrient contents (shallow soil, water deficit or excess, etc.), the problem cannot be overcome with additions of nutrients.

In trials with eucalypts in South Africa, the fertilizer was usually applied at planting or a few days afterward. There were declining effects from fertilizer the later it was applied after planting. A maximum tree height of 50 cm has been set as a criterion for a beneficial second application of fertilizer to *E. grandis*, possibly at slightly lower rates (Herbert and Schönau 1991). This second application should not take place after the trees have reached a height of about 1 m (Schönau 1984). Fertilizing at planting has little effect on site fertility, but promotes the development of a vigorous root system, which allows for continually improved growth (Herbert and Schönau 1991). Thus, responses increase with the effective rooting depth and soil water availability of sites, as well as being larger for the faster-growing species.

The situation regarding the time of fertilization for pines is slightly different. The controversy still rages whether a stand has to be thinned before a meaningful increase in growth from fertilizing existing stands is obtained. For most pine species on the other hand, fertilizing at planting gives responses when the correct fertilizer is used. As for the other species, early application after planting is essential for pines, as long as weeds are controlled. This is of far greater importance for pines than for the fast-growing eucalypts and acacias. It takes far longer for the slower-growing pines to reach and respond to the fertilizer, while in the meantime most of the advantage has gone to weeds which are then better able to compete with the trees for water and the remaining nutrients (Herbert and Schönau 1991). Nambiar et al. (1984) discussed some examples on the interactions of thinning, fertilization, and water stress. Various authors mention that fertilizer application particularly that of N and P will enhance forest plantations productivity when the product is localized at planting and one or two years later when 25–50 % of the trees are thinned (Sundralingam and Ang 1975; Prasad et al. 1986; Kishore 1987; Sein and Mitlöhner 2011). The frequency of pine fertilization depends on the natural fertility of the soils and silvicultural practices like pruning and thinning recommending to apply fertilizer at 0, 7, and 12 years when soil fertility is high; at 0, 2, 4, 7, and 12 years if natural fertility is medium; and at 0, 1, 3, 5, 7, and 12 years when natural soil fertility is low. For *Acacia mearnsii* the best results were obtained if the fertilizer was applied 6 months after establishment. Broadcast applications of up to 2 t superphosphate (11.3 % P) to wattle stands between 1 1/2 and 7 years old showed increased yields at harvesting. However, these increases have been small, probably due to weed competition (Herbert and Schönau 1991).

## Method of Fertilizer Application

A general comprehensive review on the subject for crops is available at IPNI (2012). Many different methods of applying fertilizers to eucalypts have been studied all over the world. Methods tested include applications in the planting hole, in a band, in a furrow, in or along the planting line, in one or more spots, in slots, in a circle or semicircle, uphill or downhill, in broadcast, 15–30 cm from the seedling, on or below the surface, covered or uncovered, mixed with the soil or concentrated, in a solution, and as a foliar spray. In large plantations fertilizers can be added with the help of tractors, helicopters, and small planes depending on the economics and type of topography (Fisher and Binkley 2000). When possible fertigation can be performed in dry areas (Sima 2010; Love-Myers et al. 2010). The results were variable and rather confusing, but depended on the type and quantity of fertilizer, texture and nutrient-fixing capacity of the soil, time of application, and weather conditions. Thus, fertilizers high in N should be placed in a radius of 30 cm to the seedling, but not in the bottom of the planting hole. Especially when the clay content of the soil is low, it is inadvisable to apply fertilizers with high nitrogen content in concentrated placing. Water-soluble P fertilizers should not be mixed in P-fixing soils but banded in a ring with a radius of 15–20 cm around the seedling or in two broad slots on either side; the larger quantities of rock phosphate should be spread over a wide area or broadcast. The depth of placement should be similar to that of the root plug (Herbert and Schönau 1991; Schönau and Herbert 1989).

Concerning pines the picture is even more confusing than for eucalypts. One of the various methods recommended is spot placement in a surface depression some 20 cm from the tree, which seems to be the most effective and practical technique. Other methods encouraged weed growth and increased phosphate adsorption (Herbert and Schönau 1991). In Queensland, if there is no aerial application or tractor, fertilizers are usually applied about in the tree base or as narrow bands along the planting row (Grant 1991).

Investigations on black wattle revealed the superiority of band applications 25 cm on the upper side of the tree rows after the first spacing and weeding when the trees were 30 cm tall. The change in wattle silviculture from line sowing to planting necessitated further investigations. These indicated that applications in a circle with a radius of 15 cm generally showed the best response. Only when the rainfall was of high intensity did superphosphate applied in the planting hole under the seedling give better results. Especially during dry weather it is essential to place the fertilizer about 5 cm into the mineral soil and to cover it (Herbert and Schönau 1991).

## Rates of Nutrient Application

The application rates depend on species requirements, stand age and density, expected competition by weeds, method of application, site characteristics (fertility, texture, etc.), and costs of fertilizer. Initial N rates may vary from 0 to 7–50 g per tree (12–80 kg $ha^{-1}$), P rates from 4 to 60 g per tree (7–100 kg $ha^{-1}$), and K rates up to 5 g per tree (8 kg $ha^{-1}$) (Pulsford 1981). Similar amounts (initial N rates 5–50 g $tree^{-1}$ and P and K 1–50 g $tree^{-1}$) are reported for experiments conducted in forest plantations in Latin America by Alvarado and Raigosa (2012) with a second application of N rates 5–30 g $tree^{-1}$, P rates 1–45 g $tree^{-1}$, and K rates 5–25 g $tree^{-1}$

**Table 10** The range of element rates used in commercial forest fertilization operations (After Ballard 1984)

| | Application at planting | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Application method | Rate of application | | | | | | | |
| | Unit | N | P | K | Mg | B | Cu | Zn |
| Banded | kg $\mathrm{ha}^{-1}$ | 30–50 | 50 | 50 | 30 | 8 | 5 | 5–10 |
| Spot | g $\mathrm{tree}^{-1}$ | 10–30 | 10–15 | 15 | 10 | 1 | 1 | 5 |
| Broadcast application in established plantations | | | | | | | | |
| Rate of application (kg $\mathrm{ha}^{-1}$) | | | | | | | | |
| | N | P | K | Mg | B | Cu | Zn | |
| | 100–300 | 50–100 | 50–100 | 30–50 | 8 | 5 | 10 | |

immediately after the first thinning. Lime requirements and response depend on the tolerance of species to soil acidity saturation and when required usually 1–3 t $\mathrm{ha}^{-1}$ is applied before planting. Alvarado and Raigosa's (2012) summary concludes (Table 11) that very adapted species responded to low to medium fertilizer addition of nutrients limiting growth; in contrast more demanding species responded better to the application of larger amounts of fertilizer. The best responses to low quantities of fertilizer added correspond usually to experiments established in the 50s and 60s and to larger amounts in more intense recent plantations aiming best economic returns. In regard to micronutrients Castaño and Quiroga (1990) conclude that most forestry conifer and eucalypt commercial plantations respond to the addition of NPK, but in soils deficient in B and/or Zn, the fertilizer mostly contains between 5 and 8 kg $\mathrm{ha}^{-1}$ of each element to maximize growth and survival of trees.

Table 10 gives information about the range of element rates used for different methods of application. In general, the upper levels are applied to fast-growing hardwoods and *Eucalyptus* species (Ballard 1984).

Depending on fertilizer solubility, frequency of application may have a more lasting effect over time than increasing the rate of fertilization. Additionally, the balance between the nutrients (e.g., N and P) should always be considered carefully and may be more important than the absolute amounts.

## Type of Fertilizer

Mineral fertilizers are widely used depending on availability, price, and effectiveness. According to Schönau and Herbert (1989), the most frequently used N fertilizers are water-soluble ammonium sulfate (21 % N) with an acid reaction; calcium ammonium nitrate (26 % N), which is much less acid; and the directly available form as urea (46 % N). P fertilizers are either natural rock phosphates or water-soluble superphosphates in a single, double, or triple form. In commercial forestry, triple superphosphate (ca. 19 % P) has largely replaced normal superphosphate (ca. 9 % P). The effectiveness of rock phosphate depends on its total P content, solubility in citric acid, and the degree of soil contact. The latter depends

**Table 11** Best response of tropical tree species to fertilizer application under various site conditions (Adapted from Alvarado and Raigosa 2012)

| | Best response to the addition of elements (g tree$^{-1}$) at | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | N | | P | | K | | Others | |
| Species | Planting | First thinning | Planting | First thinning | Planting | First thinning | Planting | Number of references |
| *Calophyllum brasiliense* | 5 | | 1 | | 3 | | | 1 |
| *Terminalia amazonia* | 5 | 6–8 | 5 | 1–5 | 5 | 5–6 | | 4 |
| *Cupressus lusitanica* | 5 | 30 | 10 | 5–10 | 5 | 20–25 | 3 borax | 4 |
| *Cedrela odorata* | 2–17 | 12 | 5–15 | 15 | 5–10 | 10 | | 7 |
| *Swietenia macrophylla* | 6–21 | | 3–11 | | 7–26 | | | 3 |
| *Pinus caribaea* | 6–46 | 6–22 | 2–18 | 1–20 | 1–20 | 6–20 | 5 borax | 19 |
| *Gmelina arborea* | 5–23 | | 13–20 | | 2–20 | | 10 borax | 5 |
| *Vochysia guatemalensis* | 10–20 | | 10–20 | | 7–14 | | 2 borax | 2 |
| *Cordia alliodora* | 20–30 | | 10–50 | | 20–35 | | | 3 |
| *Acacia mangium* | 20–40 | | 20–50 | 45 | 20–50 | | 1 t lime | 5 |
| *Alnus acuminate* | 30–50 | | 22–40 | 26 | | | | 3 |
| *Tectona grandis* | 10–50 | 31 | 3–5 | 30 | 6–9 | 25 | 0.5–2.0 t line | 11 |
| Range | 10–50 | 6–31 | 1–50 | 1–45 | 1–50 | 5–25 | | |
| Fert. formula | Nutrient applied with 100 g tree$^{-1}$ of fertilizer | | | | | | | |
| 15-15-15 | 15 | | 3 | | 12 | | | |
| 12-24-12 | 12 | | 11 | | 10 | | | |
| 10-30-10 | 10 | | 13 | | 8 | | | |

on particle size and form of application. Since rock phosphate is less soluble than superphosphate, it shows lower leaching losses and longer duration of response. Common K fertilizers are potassium chloride (50 % K) or potassium sulfate (40 % K). The latter is preferred in semiarid climates, since it causes lower salinity. Mg is usually applied as sulfate as well or as dolomitic limestone and Ca as limestone, if available, or as CaO or $Ca(OH)_{2.}$ In addition to the normal functions of Ca and Mg, these fertilizers (not in sulfate form) are important in their role of adjusting the soil pH through liming up to pH 6.5, but not above this value.

Many fertilization experiments were carried out with mixtures of N and P or the three primary nutrients N, P, and K, such as ammoniated superphosphates or mono- or diammonium phosphate (MAP, DAP), and other commercial NPK mixtures marketed either in granular form or in tablets. The latter often contain N in a slow-release form such as urea formaldehyde. Mono Amonium Phosphate (22 % P, 13 % N) reacts with acid, while DAP reacts with alkali. The kind and amount of nutrient element in NPK fertilizers are shown in the analysis printed on the fertilizer bags. The first figure indicates the percentage (by weight) of the first element available in the fertilizer (usually N), whereas the second shows the percentage of the second nutrient (e.g., P) and so on. Traditionally, the contents of P and K are expressed as $P_20_5$ and $K_20$, but relative amounts of the pure elements are possible as well. Micronutrients (Fe, Zn, Mn) are often applied as chelates (EDTA, EDDHA), B as borax, and Cu often as $CuSO_4^-$ $5H_2O$.

The figures (Table 11) of application rate of N (kg $ha^{-1}$) should be multiplied by 4.7 for ammonium sulfate, by 2.1 for urea arid, and by 3.8 for ammonium chloride, the P ($P_2O_5$) figures by 11.5 (5.0) for ordinary superphosphate and by 5.0 (2.2) for triple superphosphate, the figures of K ($K_2O$) by 2.23 (1.85) for sulfate of potash, and the figures of, for example, B by 8.8 for borax.

The choice of fertilizer may best be judged from the depth and organic matter content of the topsoil, the degree of weathering of the soil, the parent material from which the soil is derived, the soil texture, and the effective rainfall. Soils high in organic matter require approx. 10 g P per tree at planting in a fertilizer with low N/P ratio (viz., 1:3), as such soils contain considerable mineralizable N. Eucalypts planted on soils low in organic matter will respond best to N on its own (10–20 g per tree) or the fertilizer N/P ratio should be higher (viz., 2:1). Soils derived from the parent material low in K-bearing minerals, highly weathered soils, or soils in drier areas may also require K in addition to N and P. For these, the K/P ratio should generally not exceed 1.

More details on commonly used fertilizers in forestry are described by Pulsford (1981). Due to high precipitation and low absorption of, e.g., N, Ca, Mg, and K and high P fixation in many soils of the humid tropics as well as limited financial possibilities, research on the development of cheap, slowly soluble mineral fertilizers is strongly needed.

Fertilizer bags should be stored in a dry room with low air humidity on a wooden platform.

## Magnitude of Response

The magnitude of response of trees to fertilizing at planting varies depending on the site and species, type of site preparation, seedling quality, choice of fertilizer, time and method of application, and competition from weeds. It is estimated that roughly 10–20 % of applied fertilizer might be utilized by trees during the mature stage of growth; it is found that one fourth of the fertilizer is absorbed during the first years of growth, an equal amount is immobilized on micro-biomass or soil organic matter, and the rest is hard to measure or is lost by volatilization and leaching (Fisher and Binkley 2000). The residual effect of P fertilizer is considered to last up to 10 years and that of N up to 5 years (Dayson 1995). To better estimate the response to fertilizer additions, Paudyal (2012) recommends conducting an evaluation after a full expansion of canopy on variables such as foliar area, tree growth, mortality, diameter distribution, height/DBH, wood quality, susceptibility to pest and diseases, mycorrhiza development, and weed composition changes.

The length of the response to fertilizer addition depends on the natural fertility of the site, land preparation for planting, and growth pattern of the species. When the site's natural fertility is low, the response to fertilizers is immediate and long lasting. When a nutrient availability is moderate, the response to fertilizer addition cannot be estimated, but after the second year, it is due to factors like dilution of elements on the foliage, nutrient immobilization in soil biomass, or accumulation of nutrient in tissues like wood (Tanner et al. 1990). Under these conditions, empirical evidence shows that these sites will present disorders since the beginning of the plantation until harvest (Fisher and Binkley 2000). The correction and response to P fertilizer additions might by carried out as early as possible and will last until the first harvest, while N response might last only a few years and that of K is less frequent. Some authors mention 15–25 years of response after adding 50–224 kg P $ha^{-1}$ (Ballard 1978; Flinn et al. 1979; Trichet et al. 2009), while conifers reach a peak of response to N 2–4 years later after being added with a decline in response after 5–10 years (Mead and Gadgil 1978). Bonneau (1978) attributes the long-term response of trees to P and K additions to the low mobility and retention of P and K in the soil and to the large amounts of nutrients applied (50–100 kg P $ha^{-1}$) in relation to the needs of the trees (5–70 kg P $ha^{-1}$); on the contrary N mobility is by far larger than that of P and K causing a beneficial effect only for short to medium periods of time and sometimes being negative for those leguminous species that have the ability to fix N.

In Queensland, volume responses in the order of 75 % have been obtained in stands of average site quality, but on poorer soils, there have been responses in excess of 1,000 % (Grant 1991). Initial growth responses are not only maintained but also increase with time for eucalypts, pine, and wattle, as shown by Herbert and Schönau (1991) in South Africa. The final height responses tend to be greater for eucalypts than wattle (1.5–3.0 m vs. 1.0–2.0 m respectively), while both of these are larger than that for pine in the summer rainfall areas (0.5–1.5 m). The magnitude of the height response thus appears directly proportional to the species early growth rate and crown development. A similar situation exists for DBH. The absolute difference is maintained until harvesting up to 12 years after establishment. Consequently, the basal area and the volume per ha will show an increasing response with age. The response of eucalypts in additional MAI varies between 3 and over 10 $m^3$ $ha^{-1}$ in South Africa, the lower responses being mainly due to a poorer site quality and/or unsuitable fertilizers and poor experimental design and layout. Optimum nutrient application rates for *E. grandis* were 0–62 kg N $ha^{-1}$, 10–37 kg P per ha, and 0–40 kg K $ha^{-1}$ (Herbert and Schönau 1991).

The examples for pine fertilizer experiments show a range of MAI response similar to that for eucalypts. In the case of *P. patula*, additional MAI/PAI varies in South Africa between 1 and over 8 $m^3$ $ha^{-1}$. Optimum nutrient application rates for, e.g., *P. patula* at planting have been 0–18 kg N $ha^{-1}$, 20–70 kg P per ha, and 0–45 kg K $ha^{-1}$; in older stands, rates are 63 kg N $ha^{-1}$, 94 kg P per ha, and 63 kg K $ha^{-1}$. In Australia and New Zealand, long-term effects of P fertilizing, partly into the second rotation, are discussed by Turner and Lambert (1986).

In older *P. elliottii* and *P. taeda* stands, optimum application rates have been twice as large. Contrary to eucalypts, the higher responses of pines in the Cape seem to occur mainly on poor quality sites exhibiting acute P deficiencies. Trials with intermediate-aged pine stands in the summer rainfall areas do not exhibit acute nutrient deficiencies, and thus, nutrient balance becomes more important. Results to date suggest on strongly leached soils an increasing need for additions of N, P, and Ca for stands of pine 10–12 years after planting. However, gains from fertilizing appear greatest on good sites with deep soils and an adequate supply of soil water. Where soil water is limited, thinning may be unnecessary to boost the availability of water to individual trees (Herbert and Schönau 1991). Positive responses of refertilization of 14–22-year-old pine stands in Australia are reported by Grant (1991; see section "Fertilizer Recommendations for Plantations"). Fertilization studies on other intermediate-aged species are rare. Ten- and 20-year-old *T. grandis* plantations were fertilized over 5 years with urea (0–300 kg N $ha^{-1}$) and superphospate (0–150 kg P $ha^{-1}$) in Madhya Pradesh. A significant volume increase was observed in the younger plantation (Prasad et al. 1986). The additional MAI for the slower-growing *Acacia mearnsii* is less than for faster-growing eucalypts (1.0–4.6 $m^3$ $ha^{-1}$). These results were obtained by maximum application rates of 0–53 kg N $ha^{-1}$, 19–46 kg P $ha^{-1}$, and 0–126 kg K $ha^{-1}$. However, this is in agreement with the observation that the response is greatest for faster-growing species and on the best sites but that the percentage increase is greatest for slower-growing species on poor sites. The added advantage of fertilization of wattle is the concurrent increase in bark yields which represent about half the gross income at harvesting (Herbert and Schönau 1991).

There is a loose relationship between the type of response to nutrient additions and the amount of nutrients accumulated in tree bark of tropical tree species (Table 12). Some of the species of low accumulation (green) correspond to species that respond to small amounts of fertilizer added while some of those that accumulate larger quantities of nutrients in the wood (pink) correspond to species that respond to the application of larger amounts of fertilizers added. It is worth to mention that some of the tropical forest species adapted to acid soils (i.e., *Vochysia*

**Table 12** Nutrient content on the wood of 20 tropical species (nutrient export potential)

| | N | P | Ca | Mg | K | S | ME | Total |
|---|---|---|---|---|---|---|---|---|
| Species | % | | | | | | | |
| *Eucalyptus saligna* | 0.01 | 0.03 | 0.20 | 0.02 | 0.01 | 0.01 | 0.006 | 0.29 |
| *Eucalyptus deglupta* | Tr. | 0.06 | 0.17 | 0.05 | 0.10 | | 0.007 | 0.39 |
| *Quercus costaricensis* | 0.04 | 0.03 | 0.24 | 0.03 | 0.09 | 0.01 | 0.014 | 0.45 |
| *Alnus acuminata* | 0.06 | 0.04 | 0.20 | 0.05 | 0.15 | | 0.031 | 0.53 |
| *Cedrela odorata* | 0.01 | 0.03 | 0.37 | 0.02 | 0.08 | 0.01 | 0.012 | 0.53 |
| *Pentaclethra macroloba* | 0.18 | 0.04 | 0.21 | 0.03 | 0.10 | | 0.003 | 0.56 |
| *Carapa guianensis* | 0.05 | 0.04 | 0.29 | 0.08 | 0.11 | | 0.054 | 0.62 |
| *Gmelina arborea* | 0.10 | 0.04 | 0.23 | 0.05 | 0.33 | | 0.021 | 0.77 |
| *Cordia alliodora* | 0.21 | 0.04 | 0.32 | 0.09 | 0.10 | | 0.025 | 0.78 |
| *Swietenia macrophylla* | 0.11 | 0.10 | 0.29 | 0.03 | 0.23 | | 0.054 | 0.81 |
| *Enterolobium cyclocarpum* | 0.10 | 0.04 | 0.25 | 0.05 | 0.36 | | 0.021 | 0.82 |
| *Quercus copeyensis* | 0.03 | 0.02 | 0.36 | 0.08 | 0.11 | 0.02 | 0.248 | 0.87 |
| *Carapa guianensis* | 0.08 | 0.04 | 0.33 | 0.06 | 0.23 | | 0.170 | 0.91 |
| *Terminalia oblonga* | 0.09 | 0.04 | 0.72 | 0.04 | 0.26 | | 0.103 | 1.25 |
| *Vochysia guatemalensis* | 0.04 | 0.09 | 0.11 | 0.13 | 1.04 | | 0.035 | 1.44 |
| *Dipteryx panamensis* | 0.07 | 0.27 | 1.25 | 0.30 | 0.02 | | 0.036 | 1.95 |
| *Hieronyma alchorneoides* | 0.13 | 0.05 | 1.61 | 0.12 | 0.46 | | 0.015 | 2.38 |
| *Vochysia ferruginea* | 0.06 | 0.25 | 0.84 | 0.33 | 1.84 | | 0.032 | 3.35 |
| *Cupressus lusitanica* | 0.00 | 0.26 | 1.16 | 0.37 | 1.81 | | 0.040 | 3.64 |
| *Tectona grandis* | 0.12 | 0.27 | 1.01 | 0.23 | 2.16 | | 0.031 | 3.82 |

*guatemalensis* and *V. ferruginea* and *Hieronyma alchorneoides*) rank in the group of species with larger content of nutrients in the wood due to their ability to accumulate total K in this tissue.

## Fertilizer Recommendations for Plantations

***Eucalyptus***: Ward et al. (1985) summarized research findings from various authors who report that during the fast growth to canopy closure stages, the response of eucalypt to N is very common, to P is rare, and to K is limited; the response to the addition of micronutrients is even more limited although the response to Mg and Fe in alkaline and calcareous soils and B in East and Central Africa and Andisols and Oxisol of South America is common. A comprehensive review of research finding on various *Eucalyptus* species in Brazil can be checked in Barros and Novais (1990). Based on the research carried out by the Wattle Research Institute, now Institute for Commercial Forestry Research (ICRAF), Schönau and Herbert (1989) have given general recommendations for eucalypts at the time of planting in South Africa as follows (Herbert and Schönau 1991):

**Table 13** Plant height of four eucalyptus species after 100 days of growth under greenhouse conditions and 0–81 ppm of Al in nutrient solution (After Neves et al. 1990)

| | Al concentration in nutrient solution (ppm) | | | | |
|---|---|---|---|---|---|
| | 0 | 3 | 9 | 27 | 81 |
| Species | Plant height (cm) | | | | |
| *Eucalyptus urophylla* | 45.1 | 43.3 | 33.6 | 17.2 | 11.1 |
| *Eucalyptus paniculata* | 40.5 | 32.9 | 27.6 | 8.8 | 8.5 |
| *Eucalyptus grandis* | 26.4 | 21.3 | 14.9 | 5.8 | 4.4 |
| *Eucalyptus cloeziana* | 1.2 | 10.7 | 3.7 | 0.7 | 0.4 |

1. On most fully cultivated (plowed and harrowed) sites, 100 g ammoniated superphosphate per tree should be applied (fertilizer composition, 3.8 % N, 12.2 % P, 9.8 % S, 17.1 % Ca; Schönau 1984).
2. On sites prepared by ripping or pitting only, 100 g 2:3:2 per tree should be applied, this being changed to 100 g 3:2:1 on topsoils low in organic matter (<4 % organic carbon).
3. Fully cultivated granite-derived soils in the Transvaal and adjacent areas should receive 100 g 2:3:2 per tree, this being changed to 100 g 3:2:1 for other methods of site preparation.
4. Fully cultivated recent coastal sands (<15 % clay) of Zululand should receive 75 g limestone ammonium nitrate (LAN; 28 % N, 3.5 % Ca) per tree when they are well drained and the topsoils low in organic matter. The fertilizer requirements of the other coastal sands are insufficiently clear for a recommendation to be given, and extra emphasis should rather be placed on thorough weed control.
5. On land previously under leguminous crop, 135 g superphosphate (10.5 % P, 10.2 % S, 20.3 % Ca) per tree is recommended by Schönau (1984).

Tolerance to soil acidity of eucalyptus species (Table 13) follows the order *E. urophylla* > *E. paniculata* > *E. grandis* > *E. clöeziana* (Neves et al. 1990). Novais et al. (1979) found a positive response of *E. saligna* to the addition of 2 t of lime ha$^{-1}$ and of *E. grandis* to the application of fertilizer and lime with increments in tree height of 30–35 cm (check 1 cm) after a month of experiment establishment.

Fertilizer applications to older or coppiced stands have been investigated only in a few instances and are difficult to determine, varying with site, species, and stand development. A high rate of application could make this a doubtful financial proposition.

**Pines**: Foliar critical levels of P in pines range between 0.08 % and 1.40 % (Alvarado and Raigosa 2012), amounts that are easily fulfilled with a minimum concentration of soil P under tropical conditions (Corrêa and Bellote 2011), in the case of *P. taeda and P. elliottii* without showing foliar deficiencies (Reissmann and Wisniewski 2005). In South Africa and Swaziland, Carlson (2001) mentions that out of 71 fertilizer trials with *P. patula*, *P. elliottii*, *P. taeda*, and *P. caribaea* were P was added at planting, more than 80 % responded positively to the addition of 20 g P tree with a residual effect up to 9 years. However, the addition of 115 kg ha$^{-1}$ of various fertilizer formulas showed a positive response in commercial plantations of *P. radiata*, *P. elliottii*, *P. patula,* and *P. taeda* (Donald et al. 1987). Nitrogen becomes a must after various successive rotations (Bizon 2005). The relevance of micronutrient additions on conifers can be checked in the paper of Saur (1990). For a comprehensive discussion of nutrient needs and response to fertilizer additions of *P. radiata* in Chile, see Rodríguez and Alvárez (2010).

Generally accepted recommendations for fertilizing pines at planting in South Africa can be summarized as follows (Herbert and Schönau 1991):

1. At planting for all pines except *P. pinaster*, apply 10–25 kg P per ha. In the southern Cape this could be in the form of superphosphate (up to 200 g per tree), but in the summer rainfall areas, an application of 150–200 g 2:3:2 per tree is recommended.
2. After first thinning, apply 35–90 kg P per ha (greater amounts on better soils). In the southern Cape this could be up to 60 kg P in the form of superphosphate, but in the summer rainfall areas with higher rainfall, warmer climate, and ferralitic soils, one ton of 223:2 ha$^{-1}$ is recommended.
3. Manganese-deficient pines in the southern Cape should receive soil applications of $MnSO_4$ at a rate of 20–45 kg ha$^{-1}$ depending on the severity of the deficiency. In NE Australia 50 kg P per ha (superphosphate) is currently recommended for all pine plantations soon after planting (Grant 1991). Less fertile sites are partly refertilized with 50–60 kg P per ha in later years (e.g., age 14 years) (Maggs 1985). In South Australia, a second-rotation decline of *Pinus radiata* has been corrected with success, using a mixture of several macro- and micronutrients (Woods 1990).

***Acacia mearnsii***: The recommendations for black wattle are according to the annual reports of the ICFR (Herbert and Schönau 1991):

1. For seedlings, apply at planting 200 g per tree of a mixture made up of three parts superphosphate (10.5 % P) and one part potassium chloride (50 % K). When planting later than February, half of the mixture should be withheld and applied early in spring after the first rains.
2. For line sowings, apply 360 kg superphosphate mixed with 120 kg potassium chloride per ha after first spacing of trees to about 60 cm apart in the row.

## Fertilizer Recommendations for Natural Forests

### Fertilizer Recommendations for Tropical Lowland Forests

Very few articles on the use of fertilizers in tropical lowland forests are available. In general these ecosystems are dominated by evergreen vegetation that sometimes shed leaves along the year and grows in soils that might be very developed and low-fertility status or medium- to high-natural-fertility alluvial soils. In low-fertility soils MAI in diameter of trees increases with the addition of N, P, K, Mg, S, B, Cu, and Zn (Gerrish and Bridged 1984) or N (Vitousek et al. 1987; Cavalier 1992) or P (Santiago et al. 2005; Alvarez et al. 2013). Mirmanto et al. (1999) found that the addition of fertilizers containing N, P, and NP to the evergreen lowland forest at Central Kalimantan, Indonesia, significantly increased the mass of foliage deposition and its P concentration but not the diameter at breast height (DBH), indifferently of the type of fertilizer compared.

In Panama foliar concentration of P, K, Ca, and Mg decreases with rainfall precipitation, while the C/N ratio increased and the N/P ratio varied from 16 to 24 suggesting that P is limiting growth in these sites (Santiago et al. 2005). Again in Panama lowland semi-deciduous forest, Cavalier (1992) shows a reduction in root distribution with soil depth due to an N low availability in the subsoil. Alvarez et al. (2013) found in a lowland tropical forest of Costa Rica dominated by *Pentaclethra macroloba* and the palm *Socratea exorrhiza* a response in basal area (63–66 % without P to 63–77 % with P) after 2.7 years with the application of 47 kg P ha year of triple superphosphate, but not in basal area, litter production, or root growth with the additions of 100 kg N $ha^{-1}$ as ammonium nitrate and urea or the combination of N and P. Phosphorus addition doubled diameter growth rate of trees with diameters between 5 and 10 cm but not of those with a diameter of 10–30+ cm; the P addition also improved seedling survival from 59 % to 78 %. Alvarez et al. (2013) then conclude that P is a really limiting element for the forest community growth but rather in conjunction with other elements (heterogeneous nutrient limitation) affecting different taxa.

## Fertilizer Recommendations for Mountain Tropical Forests

Tanner et al. (1998) summarized literature to investigate the extent to which productivity of tropical montane rain forests is constrained by low nutrient supply. The authors mention that with increases in altitude foliar N decreases and P and K usually decrease, but Ca and Mg show no consistent trend. However, for a wide range of sites, N, P, K, Mg, and Ca show no trends. Litterfall contents of N and P and often K, Ca, and Mg are lower in montane forests than in lowland forests, mainly because of reduced litterfall mass, but N and P concentrations are also lower in forests above 1,500 m. Tropical montane soils usually have more soil organic matter per unit ground area; N mineralization levels are lower at higher altitudes in Costa Rica, and extractable and total soil P are lower in sites with lower litterfall P concentrations. Tanner et al.'s (1998) fertilization studies on volcanic ash-derived montane soils in Hawai‘i showed a trend for a switch from N limitation on young soils to P or N and P limitation on soils over older substrates. Jamaican montane trees were limited by N and by P separately. Venezuelan montane trees were limited by N. The sites in Jamaica and Venezuela have soils of indeterminate age. Taken together these results show that nutrient limitation is widespread in montane soils (all sites have responded to at least one nutrient) and that the particular nutrient(s) that limits production may differ for explicable reasons. First results from lowland forests on sandy soils in Kalimantan show N or simultaneous N and P limitation. Many more experiments, especially in lowland forests, are needed to test our speculation that P usually limits productivity in tropical lowland rain forests and that N limits productivity in tropical montane rain forests.

Kitayama and Aiba (2002) while measuring net primary productivity of the wet tropical forest in Borneo found that available P did not significantly change with elevation from 700, 1700, 2700 to 3100 masl. In the organic horizons of the soils of the Equatorial Andes, at elevations from 1,900, 2,400 to 3,000 masl Soethe et al. (2008) found high C/N ratios (25/1 at 2,400 and 34/1 at 3,000 masl) and C/P ratio (605/1 at 2,400 and 8/1 at 3,000 masl) values that suggest low rates of mineralization or residues and low availability of N and P al higher elevations; the same authors reported foliar N/P ratios of 11/1 at 2,400 and of 8/1 at 3,000 masl suggesting that at higher elevations N availability is more critical than P availability for forest development. Soethe et al. (2008) report a reduction in the maximum tree height from 19, 12 to 9 m while moving from a 1,900, 2,400 to 3,000 masl in the mountain belt at the Cordillera de los Andes, Ecuador, accompanied by a reduction of the leaf annual production rate in the order of 862 and 433–263 g $m^{-2}$ year in an elevation range of 1,900–3,000 masl. In the same Cordillera Zeaser et al. (1988) do not recommend planting trees for logging over 3,200 masl, when soil temperatures at 50 cm are below 10 °C, annual rainfall is less than 500 mm, slopes are over 70 %, and soil effective depth is less than 35 cm.

Vegetation composition of mountain tropical forests changes along altitudinal gradients (Holdridge et al. 1971; Grubb 1977; Soethe et al. 2008) making difficult to differentiate the effects of genetic and environmental factors on vegetation growth and diversity. From the nutritional point of view, nutrient absorption capacity of the trees decreases with elevation due to (i) a reduction of photosynthesis rates caused by cloudiness and low solar radiation, (ii) lower soil temperatures (Pregitzer and King 2005) and lower rates of respiration and transpiration, and (iii) lower nutrient availability at higher elevations due to low soil temperature and pH values that reduce rates of litter mineralization. In the cold tropical mountain forest environments, residues accumulate on the soil since their litter composition makes it hard to mineralize (Holdridge et al. 1971; Tanner et al. 1998; Montagnini and Jordan 2002; Santiago et al. 2005), there is a low population and diversity of arthropods to comminute the residues (Bruhl et al. 1999), and the presence of amorphous clays derived from volcanic ash depositions stabilizes organic compounds at middle elevations (Powers and Schlesinger 2002).

## Economics of Fertilizer Application

The true criterion is whether the additional investment of fertilizing earns a profit in real terms at harvesting including compound interest at present-day replacement costs and ruling timber prices. In South Africa, profitability of fertilizing eucalypts could be summarized as follows: the real internal rate of return on costs of fertilizing eucalypts varied between 15.4 % and 41.0 %. Fertilizing *E. grandis* with the relevant fertilizer improved the internal rate of return for fertilizing on its own amounting to approximately 25 %. Since nutrient extraction is species dependent, the economics of planting trees should consider where is more profitable to export large amounts of low-price wood of low quality (and nutrients) or small volumes of wood of high quality and prices (de Graff 1982); this is particularly relevant to avoid mining of nutrients and keep nutrient balance of the site (Mackensen 1999; Mackensen and Fölster 1999).

When plantations are established in good sites, the genetics of the species can be maximized and fertilizer responses are more likely to be profitable; choosing good land also reduces mortality and costs of land preparation and increases the possibility of commercializing some of the thinned trees with available technology. The abovementioned added to the fact that total felling in improved tropical forest plantations is being reduced to 7–8 years for *Eucalyptus*, *Gmelina*, and *Acacia* (Barros and Novais 1990; Mackensen 1999), 15–20 years for *Alnus acuminata* (Mena et al. 2000), and 20–25 for *Tectona grandis* and *Cordia alliodora* (Vallejos 1996; Montero 1999). After selecting sites and using clones of *E. urophylla* in Kandiustults, González et al. (2005) found an economically viable response to the addition of fertilizes only when two applications were made in the sandy soils of Brazil.

Because of their generally longer rotations, the profitability of fertilizing pines at planting is less evident than for eucalypts. Profitability studies of several fertilizing trials gave the following results: application of superphosphate to *P. canariensis* at planting gained 13.1 % after 18 years. The compound interest rate of return for *P. elliottii* 15 years after application was 21.9 %. Real rates of return on investment have been 11.5–19.6 % after 8 years for *P. radiata* and 5.8 %, 4.2 % and 11.7 %, respectively, after nearly 9 years for *P. elliottii*, *P. patula*, and *P. taeda*. A conservative assessment was made of the profitability of fertilizing pines at planting in the summer rainfall areas showing that relatively the real rate of return after 10 years would be 10.5 % per annum.

Fertilization of older pine stands is economically more attractive than that at planting, since the interest period is usually shorter, the quality of additional wood is better than that laid down before the first thinning, and the increment is added on to fewer trees, increasing size value of the logs and reducing harvesting costs. The internal rate of return for *P. radiata* in one trial was calculated to be 18.5 % per annum 10 years after application at 15 years and in another trial 58.0 % after a similar period. In the eastern Transvaal the first applications of 2:3:2 at 9.5 years earned internal rates of return of 10.7 %, 11.7 %, and 14.8 % per annum, respectively, for *P. elliottii*, *P. patula*, and *P. taeda* 8 years after application. In Australia refertilization of 14–22-year-old slash pines results in a yield increase of 6–14 % at the end of rotation, with real rates of return of 9–16 % of the money invested in fertilizing (Grant 1991).

Profitability of fertilizing black wattle at planting over a 10-year period exceeded 20 % per annum in real terms (20.1–30.2 %).It is noticeable that these figures show a slight but firm increase in profitability over the years. These consistent and high returns include the profits from increased timber yields as well as those from bark.

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