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REVIEW ARTICLE

Nutrient management of immature rubber plantations. A review

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Abstract

The rapid expansion of rubber tree plantations in recent decades has been accompanied by dramatic negative ecological and social impacts. Rubber sector stakeholders consequently engaged in sustainable production of rubber. Despite the lack of harvest during the immature stage following planting, this period plays a key role in future yields. Management practices, particularly fertilization regimes, are used by farmers to shorten the immature period as much as possible. This entails maintaining or even improving the productivity of existing plantations to face the demand for natural rubber. This review focuses specifically on the immature period of rubber tree plantations, as it is the most critical period for nutrient management. We reviewed available knowledge on fertilization practices, soil management, and nutrient dynamics in rubber plantations with the goal of developing a nutrient balance approach for this crop. Our review revealed (1) a notable difference between fertilizer recommendations made by technical institutes and those reported in the scientific literature; (2) that even though nutrient diagnostic methods could help growers adapt the fertilization of rubber trees more than 3 years of age, further studies are needed to adapt current methods to the wide range of cultivation areas; and (3) that the nutrient budget approach may be the best way to incorporate the variety of rubber tree cultivation conditions. In conclusion, the nutrient budget method is a promising way to improve the sustainability of rubber plantations through fertilization making it possible to increase nutrient use efficiency. A comprehensive approach based on nutrient budgets requires further in-depth studies to examine nutrient dynamics in a wide range of conditions, including intercropping and logging residue management between clearcutting and replanting.

Keywords Rubber tree · Immature period · Integrated nutrient management · Fertilization · Intercropping · Nutrient budget

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1 Introduction

Rubber tree (*Hevea brasiliensis*) plantations are the main commercial sources of natural rubber (NR), an essential raw material in several high-end manufacturing sectors, including the tyre industry (Vaysse et al. 2012). Although *H. brasiliensis* originates from the Amazon basin, Southeast Asian countries (Thailand, Indonesia, Malaysia, Vietnam) and India account for more than 90% of the 11.5 million ha of rubber plantations worldwide (FAOSTAT 2016). Contrary to common belief, most rubber farms are smallholdings rather than large estates belonging to agri-business companies (Bissonnette and De Koninck 2017). The NR sector is thereby an important source of income for millions of people as rubber harvesting and its initial transformation are labor intensive.

In the last 20 years, the growing demand for NR, mainly driven by the rapid growth of the vehicle fleet in China, has accelerated the expansion of rubber plantations outside the areas where rubber trees have traditionally been cultivated since the first half of the twentieth century (Fox and Castella 2013). This trend has been supported by an increase in the market price of NR since 2000, despite strong inter-annual fluctuations. The expansion of rubber plantations has mainly occurred in Asia with strong environmental and ecological impacts linked to the conversion of natural forests into monoculture plantations with over-use of agro-chemical inputs: loss of biodiversity (Hughes 2017), loss of soil carbon (de Blécourt et al. 2013), greenhouse gas emissions (Zhou et al. 2016), disturbance of the hydrological cycle (Guardiola-Claramonte et al. 2008) and soil erosion (Guillaume et al. 2015; Liu et al. 2017). In this context, the sustainability of NR production is of increasing concern for the stakeholders of the NR sector (Warren-Thomas et al. 2015; Kennedy et al. 2017; Kenney-Lazar et al. 2018). One of the main challenges is increasing the productivity of existing rubber plantations, because further expansion is very limited and only possible in less favorable environments (Fox and Castella 2013; Ahrends et al. 2015). However, increasing the productivity of rubber plantations has to be achieved through better use of available soil resources, as this would reduce mineral inputs and ultimately the environmental impacts of rubber plantations.

Most rubber plantations are monospecific stands managed as monoculture, except in Indonesia where rubber agroforest is the traditional cropping system (Feintrenie and Levang 2009). In monoculture plantations, latex is harvested for 20 to 30 years by regular tapping of the tree bark (Lacote et al. 2004; Michels et al. 2012), after an initial unproductive period of about 6 years called the immature phase. Improvement of tapping systems has been the main driver of rubber monoculture intensification since the release of high-yielding clones (Lacote et al. 2010; Chantuma et al. 2011). In particular, ethylene stimulation has allowed significant gains in labour and land productivity thanks to reduced tapping frequency and up to 78% increases in yield (Lacote et al. 2010). In comparison, nutrient management appears to be a secondary driver of rubber yield. The effects of fertilization on latex yield reported in the literature range from + 5 to + 10% (Karthikakuttyamma et al. 2000; Gohet et al. 2013; Watson 1989). In these conditions, fertilization of mature rubber plantation is only profitable when the price of NR is high (Chambon et al. 2017).

Even though no latex is harvested during the immature phase of a rubber plantation, appropriate management of the stand during this period is of great importance for the future yield and economic profitability of the mature plantation. Basically, this immature phase ends when 50% of the trees in the plantation reach a girth of 50 cm measured 1 m above ground level (Gunasekara et al. 2007). These trees are "tappable," meaning that they are ready for latex collection by regular tapping of the tree bark. Hence, intensification of rubber plantations during this period should seek to optimize tree growth in order to start latex harvesting as early as possible. In the current context of rubber cultivation in both traditional and non-traditional rubber areas, the management of soil fertility is the main challenge during the immature phase. In the past, applying fertilizer during the immature phase was not considered mandatory because plantations were established on fertile soils after deforestation (Bolton 1964). However, long-term rubber cultivation is likely to result in loss of soil fertility in traditional areas. Indeed, Cheng et al. (2007) reported a 48% loss in soil organic matter in the 0–40-cm soil layer after 40 years of rubber cultivation in Hainan Island, China. Aweto (1987) in Nigeria and Zhang et al. (2007) in China observed a significant decrease in soil pH (between 0.5 and 1.0 units) and a depletion of exchangeable cations in the topsoil. Zhang et al. (2007) also found an increase in soil exchangeable Al, which could impair rubber tree growth (Bueno et al. 1988). Moreover, export (Shigematsu et al. 2011) or burning (Yew 2001) of tree biomass after clear-cutting of old plantations before replanting may worsen the long-term soil nutrient depletion. In the last 20 years (Fox and Castella 2013), rubber plantations have been established in non-traditional areas that are considered sub-optimal (or marginal) because of poor soil conditions (low OM content and CEC) along with adverse weather conditions (e.g., a marked dry season with annual rainfall < 1500 mm and daily temperature > 34 °C) (Rao et al. 1993; Priyadarshan et al. 2005; Isarangkool Na Ayutthaya et al. 2011; Chandrashekar et al. 1998). In these areas, fertility problems may be accentuated by the previous land use. For instance, in the north-eastern provinces of Thailand, rubber plantations have been replacing other intensively managed crops, particularly sugarcane and cassava, which have already depleted soil nutrient stocks (Putthacharoen et al. 1998).

A wide range of recommendations exists for the fertilization of rubber plantations during the immature phase (Table 1). These recommendations vary along with the country, the region within the country and sometimes even with the soil characteristics or the cropping systems. Most of these recommendations are found in books dealing with rubber cultivation based on research carried out before the 1990s. These recommendations may not be suited to current conditions or answer the above-mentioned challenges facing rubber plantations. It is thus high time to review knowledge about nutrient and soil fertility management during the immature phase of rubber plantations. The ultimate objective of our review is to draw conclusions concerning specific management practices to be implemented to optimize rubber tree growth while minimizing environmental impacts. This objective matches the goal of the Integrated Nutrient Management (INM) approach. The INM concept has been developed and applied over the last 20 years in response to concerns about the consequences of the unsustainable use of inorganic fertilizers for the environment (Gruhn et al. 2000; Spiertz 2010; Wu and Ma 2015). Briefly, INM aims to increase nutrient use efficiency, minimize loss of nutrients to the environment, and improve/preserve soil resources (Wu and Ma 2015). To achieve this goal, the INM concept is based on three main principles: (i) reducing the use of inorganic fertilizers by promoting the use of all possible sources of nutrients; (ii) matching the soil nutrient supply and crop requirement over time and in space; and (iii) preventing soil degradation through soil conservation technologies (Gruhn et al. 2000). From a practical viewpoint, an efficient INM approach should combine advances in crop science and functional ecology, analytical tools, such as nutrient diagnoses and nutrient balances, and local knowledge stemming from farmers' experience (Doré et al. 2011)

The objective of this paper is to review available knowledge on fertilization management and nutrient dynamics in rubber plantations needed to design an INM approach for the immature period of rubber plantations. The different sections address the following questions: (1) What is the impact of fertilization on the rubber tree growth and the duration of the immature period? (2) Which alternative practices to mineral fertilization can improve soil fertility and nutrient management in immature rubber plantations? (3) Which tools exist to manage nutrient supply in immature rubber plantations? (4) What do we know (and do not know) about nutrient dynamics in immature rubber plantations? We conclude the review with recommendations for further research needed to design INM systems and develop tools to help rubber farmers implement such systems.

This paper focusing on tree nutrition contributes to the overview of knowledge on the management of rubber plantations (Fig. 1) provided by other recently published review papers on this tropical crop: Carr (2011) on water relations, Warren-Thomas et al. (2015) on biodiversity issues, Blagodatsky et al. (2016) on carbon balance and Langenberger et al. (2017) on intercropping. The conclusions of this paper could also be useful for better management of the immature phase of other tropical perennial crops such as oil palm.

2 Methodology

Due to the relatively poor scientific literature on the rubber tree plantations available on specific databases like "ScienceDirect" (Elsevier 2018) or "Web Of Science" (Thomson-Reuters 2018), the review was mainly based on Google Scholar requests to increase the number of documents searchable, especially those from grey literature. First, we used three books considered as references works in rubber tree production: Webster and Baulkwill (1989), Compagnon et al. (1986) and Sethuraj and Mathew (1992). For each section, the "immature" and "Hevea" keywords were used in Google Scholar. We then used the keyword "fertiliz*" to refine the results in Sect. 3; the terms "cover crop" and "previous crop residue" for Sect. 4; the terms "soil diagnosis," "leaf diagnosis," and "DRIS" for Sect. 5. This section was mainly based on the

Table 1 Standard fertilizer recommendations or traditional practices based on a tree density of 475 trees per hectare, in different countries during the six first years of the immature period (in g tree^{-1} year^{-1})

Country	Additional information	N	P_2O_5	K_2O	Mg_2O	References
Sri Lanka	Lateritic soil	433	578	311	100	Watson (1989)
	Micaceous soil	456	622	222	67	
	Quartzitic and alluvial Sandy soils	378	511	433	133	
Thailand	Low K	556	600	489	111	Watson (1989)
	High K	644	667	289	111	
	RRIT	360	60	216	–	RRIT (2011)
Indonesia	East Java	644	687	293	111	Watson (1989)
	West Java, Sumatra	558	609	482	111	
Malaysia	Low K, no legume	1422	556	378	111	Watson (1989)
	Low K, mixed legume	500	556	378	111	
	Low K, pure legume	67	556	378	111	
	High K, no legume	1467	578	200	111	
	High K, mixed legume	500	578	200	111	
	High K, pure legume	67	578	200	111	
	Loam and clay loam soils	82	146	28	18	Shorrocks (1965a)
	Sandy soils	72	127	64	18	
India	Legume	444	444	258	47	Watson (1989)
	No legume	578	489	231	47	
	Traditional region	120	120	48	18	Pushpadas and Ahmed (1980)
	North-eastern region	144	144	72	0	Debasis et al. (2015)
China		167	167	167	167	Zhou et al. (2016)
brazil	$P < 12$ ppm	473	473	473	–	Bataglia and dos Santos (1998)
	$P > 12$ ppm	473	182	473	–	
Liberia		500	500	556	444	Watson (1989)
Ghana		422	422	578	422	
Ivory Coast	South-east	103	67	84	–	Allé et al. (2014)
	South-west	57	95	30	–	

proposals found in (Pushparajah 1994), considered as a reference work.

Many results were returned by Google Scholar for each section; we selected only the most relevant, namely those which clearly described experimental results and provided information and knowledge related to the questions asked in the section headings.

Fig. 1 A 2-year-old rubber plantation intercropped with pineapple in Chachoengsao Province, Thailand

3 What is the impact of mineral fertilization on rubber tree growth and on the duration of the immature period?

The literature search using Google Scholar returned 1010 results. We selected only the most relevant. We found 26 articles reporting the results of field studies (three of the ones cited in Krishnakumar and Potty (1992) are no longer available) on the impact of mineral fertilization during the immature period of rubber plantations (Tables 2, 3, and 4). Years of publication ranged from 1966 to 2017. A total of 49% of these papers were published after 2000. A total of 48% of the studies were conducted in Southeast Asia. The studies all dealt with application of N, P, K, and sometimes Mg as a single nutrient or in combination at different doses. The results are analyzed in terms of the effect of fertilization on trunk girth growth, the

Table 2 Summary of experimental results of the effect of mineral fertilization during the immature period of rubber trees in South East Asia

Region		Clone	Soil	Cover crop	Nutrient	Main results	References
Malaysia	Skud ai	Tjirandji 1	Pot experiment, low P, K)	None	P, K, Mg	- Rubber growth increased linearly with application of K fertilizer. - K/Mg antagonism - K/P interaction	Bolle-Jones (1954)
	Selangor	RRIM 2000	Haplic Acrisol	None	N	- Urea performed as well as ammonium sulfate.	Mokhatar and Daud (2011)
		RRIM 2001	Oxisol	None	N, P, K, Mg	- Growth reached maximum at 150% of the rate recommended by the Malaysian Rubber Board. - K and Mg were deficient under standard recommendations	Mokhatar et al. (2012)
		RRIM 2001 RRIM 2025 RRIM 3001	Oxisols and ultisols	Unknown	N, P, K	- Munchong soil series and RRIM 3001 showed better performance than the Holyrood soil series and other clones. - Optimum fertilizer level was achieved at 150% of the standard dose (780 kg ha^{-1} of a blend of 10–16–9-2) - 200% appeared excessive for plants and had a detrimental effect.	Salisu et al. (2013) Salisu and Daud (2016)
	Melaka	RRIM 3001	Unknown	Unknown	N, P, K	- Height and girth increased with increasing fertilizer application rate whatever the form of fertilizer applied (yellow fertilizer (15-15-6-4) and/or mulching)	Razman et al. (2016)
		RRIM 3001	Unknown	Unknown	N, P, K, Mg	- Higher growth on Gajah Mati than on Jabil - More fertilizer (NPK yellow) was needed on Jabil (715 g tree^{-1}) than on Gajah Mati (658 g tree^{-1}) - From 37 to 49% extra fertilizer compared to the recommended rates was needed to achieve maximum growth	Zahidin et al. (2017)
Thailand	Nakhon Si Thammarat	RRIM 600	Pot experiment: “representative rubber soil”	None	N, P, K, Mg	- The limiting nutrients were N, P, and Ca (lime). Rubber growth in the field that received government recommended and omission-based fertilization did not differ.	Timkhum et al. (2013)
	Surat Thani	RRIM 600 RRIT 251	Pot experiment	None	N, P	- Although N and P uptakes of RRIM 600 and RRIT 251 did not differ, young RRIT 251 rubber trees had higher stem height. Considering N and P uptake related to biomass produced, these results suggest that nitrogen use efficiency by the RRIT 251 clone was higher.	Thitithanakul et al. (2017)
Indonesia	South Soumatra	PB 260	Ultisol Low OM, high Al	Unknown	N, P, K	- Field experiments showed that growing rubber stump of PB260 clone in peat + soil potting mixture combined with recommended rate of inorganic foliar fertilizer resulted in a better performance in the field.	Ardika et al. (2017)

Table 3 Summary of experimental results of the effect of mineral fertilization during the immature period of rubber trees in India and Sri Lanka

Region		Clone	Soil	Cover crop	Nutrient	Main results	References
India	unknown	RRIM 600 RRIM 605 PR 107 Tjir-1	Unknown		N, P, K, Mg	- RRIM 600 and RRIM 605 had the largest girths. - N fertilizer increased the girth in the 4th year but not in the 5th. - K increased girth, but at the highest rate, a decrease in girth was observed - P and Mg fertilizer had no effect - Interaction between N and P was observed at the earlier date (N increased tree girth only with lower P rate).	Kalam et al. (1980)
	Kerala	RRII 105	Pot experiment (low nutrient content)	None	N	- When N was not applied, more than half the total biomass was diverted for the development of roots. - When N was applied, a good share of it was translocated to the leaves. - Urea is the best form of nitrogen with respect to growth and apparent recovery of applied N.	Karthikakuttyamma et al. (1994)
		RRII 105 PB 235	High C (1.4%) Low P and K	*Pueraria phaseoloides*	N, P, K	- Adding 30 k ha^{-1} of N or P increased tree girth from the third year to the end of the immature period. - Adding 60 kg ha^{-1} of N or P did not produce an additional growth response.	George et al. (1997)
	West Bengal	RRIM 600	High C (1.6%) Low P and K	*Pueraria phaseoloides*	N, P, K	- P and K fertilizer did not increase rubber tree girth and tappability. - Tappability depended on N/K interaction (tappability increased linearly with K levels at lower N rates, but the effect of K was no longer significant with additional N)	Meti et al. (2002)
Sri Lanka	Unknown	PB 86 RRIC 100 RRIC 101 RRIC 102	Homagama series soils (quartzitic)	*Pueraria phaseoloides* *Desmodium ovalifolium*	N, P, K, Mg	- 310 kg N ha^{-1}, 160 kg P ha^{-1}, and 310 kg K ha^{-1} were sufficient for maximum growth - Fertilization with NPK reduced the unproductive period of RRIC 100 series clones by between 18 and 24 months.	Yogaratnam et al. (1984)
		PB 86 RRIC 100 RRIC 103 RRIC 121	Red Yellow podzol-quartzitic	None (pot experiment)	K, Mg	- PB 86 has lower K requirements (33 g K tree^{-1} year^{-1}) than RRIC 100 and RRIC 121 clones - soil K > 27 ppm was adequate. - PB 86, RRIC 100 and RRIC 121 had lower Mg requirements (22 g plant^{-1} year^{-1}) than clone RRIC 103.	Weerasuriya and Yogaratnam (1988)
		Unknown	Boralu series soils	Unknown	P	- The currently recommended rate of P was insufficient. - The efficiency of Eppawela rock phosphate (ERP) was similar to that of imported rock phosphate (IRP) and triple superphosphate (TSP).	Dissanayake et al. (1994)

Table 4 Summary of experimental results of the effect of mineral fertilization during the immature period of rubber trees in smaller areas

Region		Clone	Soil	Cover crop	Nutrient	Main results	References
Brazil	São Paulo	Unknown	Pot experiment (vermiculite)	None	Al	Aluminum content > 15 ppm reduced growth of rubber trees	Bueno et al. (1988)
		RRIM 600	Unknown	Unknown	N, P, K	- Highest responses were observed with K fertilization. - Negative effects of N and P fertilization were not rare.	Bataglia and dos Santos (1998)
			Red yellow podzolic soil	Unknown	N, P, K	- The immature period of the crop was only significantly affected by K fertilizers. - Unbalanced relations of NPK can delay the beginning of tapping by up to 15 months. - There was an antagonistic effect of N and P.	Bataglia et al. (1999)
	São Sebastião	RRIM 600	Red yellow podzolic soil	None	N, P, K	- Percentage of tappable plants increased linearly with N and K fertilization. - Under best NPK relations, the immature period was reduced by 8 to 12 months. - Fertilizer responses disappeared 1 year after applications of fertilizer ended.	Bataglia et al. (1998)
	Tocantins	GT1	Greenhouse, oxisol with a very clayey texture	None	K	- A rate of 170 kg of K_2O led to maximum production of DM - The use efficiency of K decreased with an increase in the rate applied.	Correia et al. (2017)
Côte d'ivoire	Gô	PB 235	Gravelly, ferralitic, highly desaturated, good water availability	*Pueraria phaseoloides*	N, P, K	Fertilization with half dose of fertilizer leads to stable physically improved soil in the long term. The vegetative behavior of PB 235 was satisfactory and showed that an application of manure of more than half the dose was not necessary.	Allé et al. (2014) Allé et al. (2015)

duration of the immature period, and/or number of tappable trees at the beginning of latex harvesting.

We selected ten studies on several rubber tree clones planted in contrasting soils and under different climates. The choice of these studies was mainly based on the availability of information like soil type and initial nutrient content. These studies showed that N, P, K, and Mg fertilization improved rubber tree growth and shortened the pre-harvest period. The studies also showed that rubber trees reach their maximum growth with a relatively small amount of fertilizer (Table 3), the amount of which varied from one study to another (Salisu et al. 2013; Bolle-Jones and Ratnasingam 1954; Shorrocks 1965b, 1965c). More precisely, in Sri Lanka, 50 kg N ha^{-1} $year^{-1}$, 20 kg ha^{-1} $year^{-1}$ of P_2O_5, and 50 kg ha^{-1} $year^{-1}$ of K_2O over the immature period increased final girth of a 6-year-old trees by 2 to 19% compared to the girths of unfertilized trees (Yogaratnam et al. 1984). In India, Meti et al. (2002) and George et al. (1997) reported that 20 to 30 kg N ha^{-1} $year^{-1}$, 30 to 40 kg ha^{-1} $year^{-1}$ of P_2O_5, and 20 to 40 kg ha^{-1} $year^{-1}$ of K_2O were sufficient to achieve similar rubber tree growth. These authors also emphasised that adding 60 kg ha^{-1} $year^{-1}$ of N or P_2O_5 did not increase the girth beyond that reached with the lower level of fertilization (25 and 30 kg ha^{-1} $year^{-1}$ of N and P_2O_5). In the case of potassium, the proportion of trees reaching maturity depended on N/K interaction. In several studies, the girth increased linearly with K levels when no additional N was added (+ 34 and + 37% when 20 and 40 kg ha^{-1} $year^{-1}$ of K_2O were added, respectively), but the effect of K fertilizer on girth was no longer significant with additional N fertilizer (Meti et al. 2002; Pushparajah 1973; Bataglia and Santos 1999; Bataglia et al. 1999; Bataglia et al. 1998). This underlines the importance of taking the balance between nutrients into account (Table 2). In their study, Yogaratnam et al. (1984) clearly demonstrated the interaction between fertilization and the clone with respect to tappability. For instance, they found that adding NPK had no significant effect on RRIC 100 tappability from the fifth to the seventh year, whereas adding 310 kg ha^{-1} of NPK increased the percentage of tappable trees from 40 (control) to 75% in the seventh year. These results are in line with those reported by Thitithanakul et al. (2017) who showed that N and P uptake were equivalent in the clones RRIM 600 and RRI 251 but that clone RRIT 251 had a higher growth rate

Most studies emphasized that using a blend of fertilizers (e.g., N-P, N-P-K) led to better growth than applying a single-nutrient fertilizer. Moreover, the use of a single N fertilizer may promote crown development over trunk growth, which is likely to increase the wind sensitivity of the trees (Watson 1989). In most South West Asian countries, fertilizer recommendations (Table 1) aim to guarantee maximum growth of rubber trees. The quantities of fertilizer recommended are higher than those in the scientific literature. For instance, in Sri Lanka, despite the fact that Yogaratnam et al. (1984) reported that 50 kg N ha^{-1} year^{-1} was sufficient for maximum growth of rubber trees, from 180 to 210 kg N ha^{-1} year^{-1} is recommended by the technical institute. In China, recommendations do not take into account the fact that nutrient requirements increase with the age of the rubber tree during the immature period: rubber plantations on Hainan Island receive a uniform yearly application of 1.1 to 1.2 kg of NPK fertilizer per tree from the planting to the start of latex harvesting (Chen et al. 2011). Finally, the new rubber tree cultivation zones in suboptimal areas are not necessarily managed differently from other rubber tree plantations even though fertilization needs to be adjusted to cope with the less favourable climate and soil conditions.

Although fertilizer recommendations provided by the technical institutes were expected to guarantee to reach a high proportion of tappable trees rapidly, the fact is, large quantities of fertilizers can increase the risk of over fertilization compared to tree requirements. This was confirmed by results in the scientific literature showing that in some cases; 50% of the recommended dose led to the same percentage of tappability (Allé et al. 2015). As a result, one can assume that a high proportion of the nutrients contained in fertilizer applied is lost to the environment, especially in soils characterized by low CEC. These nutrient losses can reduce the economic profitability of rubber tree plantations and, in addition, have a negative impact on the environment due to the risk of groundwater pollution or of the production of large quantities of NOx by volatilization. To limit the risk of nutrient losses, it is essential to adapt the recommendations to the difference between the nutrients available in the soil and those required by the trees, as supported by the INM.

According to current knowledge and the fact that some of the studies did not provide complete systematic information on soil properties (texture, nutrients status, etc.), we considered making recommendations derived from the results reviewed here risky. However, it is possible to provide some general basic guidelines: even when synthetic fertilizers are used, it is important to apply green manure to increase soil organic matter at the medium- and long-term scale. The frequency of application of synthetic fertilizers and green manure inputs should be determined based on soil proprieties, especially texture, to improve nutrient use efficiency.

4 Which management practices other than mineral fertilization can improve soil fertility in immature rubber plantations?

The INM approach relies on the use of all possible natural and synthetic sources of plant nutrients and the implementation of soil management techniques to avoid nutrient losses and to improve soil functioning (Gruhn et al. 2000). We found a few relevant papers dealing with the use of organic fertilizers in immature rubber plantation (Abraham et al. 2015; Ardika et al. 2017). In contrast, the management of the soil cover during the first years of a rubber plantation is well documented. A summary of the most relevant works is presented in Sect. 4.1. Another alternative to synthetic fertilizers was to use nutrients accumulated in the biomass of the previous crop; this practice can also to be included in an INM approach in the context of replanting. Even though the literature is scarce on this aspect, in Sect. 4.2, we analyze existing data on rubber plantations and other tropical tree plantations from which useful information can be extracted for the management of replanting rubber trees.

4.1 Intercropping management (Fig. 1)

Tree density in standard rubber monoculture is ca. 550 trees/ha with 6- to 8-m inter-rows, leaving 75% of the soil surface uncultivated. Furthermore, incident radiation in the inter-rows is sufficient during the first 4–5 years of the plantation for the development and growth of a soil cover of annual or perennial plant species (Paisan 1996; Langenberger et al. 2017). Three main soil cover management systems can therefore be considered: (1) management of spontaneous vegetation, (2) use of cover crops like legumes or grasses, and (3) cultivation of annual or perennial crops, also called intercropping.

Soil cover in inter-rows of immature rubber plantation is mainly recommended to avoid soil degradation and loss. Liu et al. (2016) showed an eight-fold reduction in soil loss by erosion in a 12-years rubber plantation with no control of the natural soil cover compared to plots where weeding was controlled by applying herbicides bi-monthly. However, rubber planters are usually not keen to let weeds grow for different reasons: competition with rubber trees which can delay the start of tapping, the risk of fire during the dry season, inconvenience for in applying other management practices, providing a habitat for dangerous animals like snakes (Liu et al. 2016; Bagnall-Oakeley et al. 1996). Hence, intercropping is an appropriate way to control weeds while providing other benefits (Bagnall-Oakeley et al. 1996; Watson et al. 1964a). Use of nitrogen-fixing legume species as a cover crop is by far the best soil management technique with respect to nutrient management during the immature phase. Broughton (1977) made a comprehensive review of work carried out in Malaysia between the 1950s and the 1970s on the effect of legume cover crops on rubber tree growth and soil fertility compared to other types of soil cover (grass and natural cover). More recently, Clermont-Dauphin et al. (2016) conducted a similar study with additional measurements to assess N transfer from *Pueraria phaseolides* to the rubber trees using the natural abundance of ^{15}N. The legume cover crop strongly increased tree girth from 11 to 29% in 4- to 6-year-old plantations compared with natural cover (Broughton 1977; Watson et al. 1964a; Clermont-Dauphin et al. 2016). Overall, the improvement in tree growth made it possible to shorten the immature period by 5 months to a year (Watson et al. 1964a; Watson et al. 1964b). Improved growth of the rubber trees can be explained by a better mineral nutrition, particularly nitrogen nutrition. Watson et al. (1964a) showed that legume intercropping significantly increased N contents (+ 5.5%) and P contents (+ 3.4%) in the foliage of rubber trees compared to a grass cover. Three years after establishment of the cover crop, Clermont-Dauphin et al. (2016) observed significantly higher nutrient contents in rubber tree leaves in plots with intercropped legumes in the inter-row (2.66% N, 0.19% P, and 1.62% K) than in plots with bare soil (1.69% N, 0.15% P, and 1.18% K). Broughton (1977) concluded that a legume cover crops act as a “bank” of nutrients because of its capacity to rapidly accumulate nutrients, mainly N, and to make it available to the rubber trees though the degradation of its litter. He assumed that the legume cover crop stimulates the proliferation of the rubber tree roots, thereby boosting nutrient recycling.

However, despite these advantages, legume cover-crops are seldom used in rubber plantations particularly in smallholdings. Smallholders usually prefer to grow annual or perennial crops for food or income during the unproductive period of the rubber plantations (Obouayeba et al. 2015; Langenberger et al. 2017; Min et al. 2017; Romyen et al. 2018). Few studies have reported the effect of intercropping on tree growth, soil fertility and nutrient management. The most comprehensive was by Rodrigo et al. (2005a, 2001, 1997, 2005b) on a rubber-banana system with different densities of banana trees. These authors showed that banana intercropping led to better rubber growth in terms of height and girth than rubber monoculture. After 6 years of growth, the percentage of tappable trees in banana-rubber systems was 10 to 20% higher than in the rubber monoculture (Rodrigo et al. 2005a). They also demonstrated that the better performance of the banana-rubber systems was due to better light and water use efficiency (Rodrigo et al. 2001; Rodrigo et al. 2005b) and better dry matter accumulation and partitioning (Rodrigo et al. 1997), but they did not investigate the nutrient use efficiency of the trees nor the nutrient status of the soil. Each banana tree was fertilized with a 750-g mixture of urea, phosphate, and potash at 4 monthly intervals, while the rubber trees were fertilized only at planting. Hence, it is likely that in the rubber-banana system, the rubber trees benefited from the nutrients supplied to the banana trees in contrast to the rubber trees under monoculture. Actually, most of the articles on intercropping practices during the immature phase of rubber plantation reported either no negative effect or a positive effect of intercropping on rubber tree growth compared to monoculture (Paisan 1996; Snoeck et al. 2013). Therefore, one can assume that, in a rubber intercropping system, the intensive management of the intercrops, including fertilization, weeding, and irrigation, also stimulates rubber tree growth.

The positive effect of the intercrop on the rubber trees could also be due to beneficial interactions between the rubber trees and the intercrop itself; for instance, an increase in soil P bioavailability in 10- and 22-year-old rubber plantations was recently demonstrated in the case of intercropping with understory tree shrubs (Liu et al. 2018). Yet, in the long term, the positive interaction between rubber tree and cover crops or intercrops can have detrimental effects on tree growth and survival. Clermont-Dauphin et al. (2016) showed that rubber trees stimulated by association with *P. phaseolides* were more sensitive to drought than trees grown with natural cover in the inter-row. This example shows that the choice of a cover crop or an intercrop must depend on local soil and climate conditions to avoid competition between the rubber trees and the companion crop. Planting density, spacing, and the length of the companion crop cycle must also be taken into account, and the management of the rubber plantation also needs to be adapted (Punnoose and Laksmanan 2000). In particular, the planting pattern of the plantation may differ from the standard single-row system (Rodrigo et al. 1997; Snoeck et al. 2013).

Cover crops appear to be the best soil management option for an INM in immature rubber plantations. Cover crops can help reduce N fertilization while stimulating tree growth. However, if intercropping is preferred for economic reasons, the management of the intercrops and the possible interactions between the intercrops and the rubber trees must be incorporated in the INM. Very limited quantitative information is available to allow more specific recommendations to be made at this time.

4.2 Replanting management

The end of the life cycle of a rubber tree plantation occurs when all the bark has been removed because of tapping. The trees are then logged, which happens approximately 30 years after planting. However, logging age varies with the country and with the rubber farm typology and ranges from 25 years in rubber smallholdings to 40 years or more in bigger estates in Thailand. Two practices are commonly used for the management of the biomass of the logged trees: either burning in the plot or harvesting the trunk to be used as timber or firewood. Both practices are implemented for economic reasons and, in some cases, for phytosanitary reasons as well. Burning limits field interventions, while trunk harvesting provides additional income (Simorangkir and Sardjono 2006). On the other hand, only a small amount of roots are left in the plot, which limits the development of white root disease (*Rigidoporus microporus*), which is responsible for annual mortality of 1 to 2% of trees in certain conditions (Martin and Plessix 1969). Even though no study has provided quantitative information on the link between the amount of biomass left on-site and the occurrence of white root disease, removal is strongly recommended for phytosanitary reasons (Mariau 2001; Nandris et al. 1987; Omorusi 2012).

On the other hand, it has been shown that both burning and harvesting biomass have negative effects on soil fertility (Karthikakuttyamma et al. 2000; Yew 2001). Intense fire is likely to cause serious changes in ecosystem functioning, modify microbial species composition, alter the C:N ratio, or increase mineralization and nutrient volatilization rates (Neary et al. 1999). When the biomass is harvested, the nutrients which accumulated in the tree during the plantation cycle are exported (Compagnon et al. 1986; Krishnakumar and Potty 1992). Burning harvest residues or harvesting the trunk are therefore likely to have a negative impact on the growth of young rubber trees due to a long-term decrease in soil fertility (Pollinière and Van Brandt 1967).

Alternatively, leaving residues of the previous crop on the soil surface is likely to enhance nutrient recycling and soil fertility. However, literature on this practice, called “residue management,” is scarce and no recent publications are available for rubber plantations (Shorrocks 1965a; Compagnon et al. 1986; Pollinière and Van Brandt 1964; Yew 2001). Nevertheless, insights into the potential benefits of residue management on the fertility of immature rubber plantation can be inferred from the literature on eucalyptus plantations. Eucalyptus plantations are an interesting model for immature rubber plantations since the rotation cycle for tropical eucalypt plantations is 6–7 years like the immature period of rubber plantations, and eucalyptus trees can grow on soils that are comparable with soils found in rubber growing areas. Residue management has been intensively studied in eucalyptus plantations all over the world. Results generally revealed a strong positive correlation between the quantity and quality of the residues left on the soil and the volume of wood at the end of the rotation (Laclau 2004; Rocha et al. 2016). This improvement in tree growth was linked with changes in nutrient cycling (Versini et al. 2014; Rocha et al. 2016) and an increase in organic carbon, nitrogen, and exchangeable cations when residues were retained in the plot (Hu et al. 2014). These findings for eucalyptus highlighted the possibility of reducing fertilizer applications on replanted plantations. Thus, in areas replanted with rubber trees, it would be very interesting to adapt this way of returning nutrients by increasing the volume of residues left in the plot, thereby simultaneously addressing economic and environmental concerns.

5 Which tools exist to manage nutrient supply in immature rubber plantations?

Strategies to develop INM often rely on a combination of soil and/or plant nutrient diagnostic methods and fine-tuned, site-specific knowledge about the crop requirements and the sources of nutrient inputs (Wu and Ma 2015). In this section, we start by reviewing available knowledge on the use of leaf and soil nutrient diagnoses in rubber plantations. We then review existing literature on a highly recommended method for the sustainable use of fertilizers, the nutrient balance (or budget) method (Öborn et al. 2003; Ranger and Turpault 1999).

5.1 Soil and leaf nutrient diagnosis

The basic principle of all diagnostic methods is comparing current levels of nutrients in leaves or soil samples with reference values or thresholds of nutrient concentrations (or ratios between nutrients) at which tree growth is optimal (Table 5). These methods are also based on a strict sampling protocol, which includes precise guidelines on how and when to collect samples. In their book on NR production, Compagnon et al. (1986) made a detailed review of the research conducted between 1940 and 1980 to establish leaf diagnostics for rubber trees. A dozen subsequently published papers dealt with the local adaptation of available knowledge on rubber leaf diagnosis (Suchartgul et al. 2012; Njukeng et al. 2013a, 2013b). Most of the papers dealt with the development of leaf diagnosis for mature rubber plantations. However, Compagnon et al. (1986) reported that the leaf sampling protocol used for mature trees could also be used for 3- or 4-year-old trees, which have already produced branches. This protocol advised collecting shaded leaves on the lowest branches 100 days after leaf emergence. In the case of young trees with no branches, the same authors suggested sampling leaves during the penultimate flush before maturation. The most widely used thresholds of N, P, and K concentrations for leaf diagnostics of mature rubber trees were established in Malaysia by Pushparajah (1994), in Cameroon by Njukeng and Ejolle

Table 5 Standard values for optimum satisfaction of soil and leaf macro-element requirements during the rubber immature period according to the main studies in the literature. Available P in the soil was determined using the Bray II method; exchangeable K, Ca, and Mg cations in the soil were determined using the Metson method. (Nd.: not determined; NP: not possible to determine)

Indicator	N	P	K	Ca	Mg	Country	Reference
Soil nutrient content (ppm)	Nd.	10 20	40 80	50 600	NP	Thailand	Suchartgul et al. 2012
	800 1400	5 8	40 60	Nd.	Nd.	China	Chen et al. 2011
Leaf nutrient content (%)	3.20 3.80	0.25 0.30	1.00 1.40	1.00 1.50	> 0.35	Thailand	Suchartgul et al. 2012

(2014) and in India by Pushpadas and Ahmed (1980). Only one study has been conducted on 4-year-old trees of the RRIM600 clone in Thailand (Suchartgul et al. 2012). To our knowledge, this is the only reference to a leaf diagnosis of immature rubber plantations. Some authors also explored the use of the Diagnostic and Recommendation Integrated System (DRIS) in rubber plantations: Njukeng et al. (2013c) in Cameroon; Chacón-Pardo et al. (2013) in Colombia; and Joseph et al. (1993) in India. The DRIS method (see Filho and Alves (2004) for a review) is based on ratios of pairs of nutrients in the leaves rather than on thresholds of individual nutrients. This method appears to be efficient to detect nutrient deficiencies in rubber leaves but requires a large database of leaf nutrient contents and ratios of nutrient concentrations along with crop performances. Furthermore, we found no publications on DRIS for immature rubber trees.

Information on soil diagnostics in rubber plantations is scarce both for mature and immature stands. Chen et al. (2011) and Suchartgul et al. (2012) proposed threshold values for some nutrients in the topsoil of mature rubber plantations in China and Thailand, respectively. In Malaysia, Pushparajah (1994) attempted to establish soil nutrient thresholds for the most common soil types. However, Guha et al. (1971) pointed out that these critical nutrient thresholds need to be systematically calibrated for each soil and climate condition. Like the DRIS method, soil diagnoses based on ratios or balances between nutrient concentrations rather than thresholds of individual nutrients have been successfully used on perennial crops like coffee and cocoa plantations (Jadin and Snoeck 1985; Snoeck and Jadin 1990). However, they have not yet been developed for rubber plantations.

5.2 Nutrient budget method

Nutrient budget methods for fertilization management are based on empirical models which calculate fertilizer requirements as the difference between the nutrients required by the crop to reach the target yield and the net nutrient supply to the tree from the soil (Öborn et al. 2003). In the case of rubber trees, the target was to rapidly obtain a high proportion of tappable trees in local conditions. The net nutrient supply is the result of a soil nutrient balance between different sources of nutrients (mineralization of soil organic matter, mineralization of residues and organic manure, atmospheric deposition, atmospheric nitrogen fixation, etc.) and nutrient losses outside the field (export at harvest, leaching, runoff, volatilization, etc.). Estimation of soil nutrient sources and losses requires information on the physical and chemical soil properties (mainly texture, organic matter, and clay contents), climatic variables (generally temperature and rainfall) and some characteristics of the crop such as the maximum rooting depth.

We found only one reference using a nutrient budget for rubber plantations, in Hainan Island (Chen et al. 2011). In this work, the authors tested a model to provide a site-specific fertilizer recommendation at Hainan State Farm. The model of nutrient budget was combined with leaf diagnosis and the use of a geographic information system to provide spatially explicit fertilizer recommendations. Although this method provided reasonable and reliable predictions of fertilizer needed, the authors underlined that nutrient accumulation in the trees was the main obstacle to the use of the model due to the relatively limited number of studies that quantify the accumulation of nutrients in immature rubber trees. Another limitation of this model was that soil nutrient availability was assessed through soil analysis only at planting but not recalculated each year taking the nutrient budget into account. Consequently, variations in nutrient availabilities and fluxes caused by extreme climatic conditions or agricultural practices like swathing or intercropping are not currently included in the model, which may reduce the accuracy of the predictions. A crop model, such as the Water Nutrients and Light Capture in Agroforestry Systems (WaNuLCAS) model (Van Noordwijk and Lusiana 1999), can be used to develop a nutrient balance method at field scale. WaNuLCAS has already been used to estimate girth and above-ground biomass of rubber trees in plantations (Pinto et al. 2005; Yahya 2007; Boithias et al. 2011) but not specifically to establish nutrient budgets.

5.3 Conclusion on tools for managing fertilization in immature plantations

The literature on nutrient diagnostics or nutrient balance methods for managing fertilization in immature rubber plantations is too scarce to design a generic method that could be applied in all situations. Table 6 lists existing methods and the main advantages and drawbacks of each method based on our literature survey. Leaf and soil diagnostics could be developed based on existing methods for mature rubber plantations or other perennial crops. However, these methods cannot be implemented without a well-documented database linking the nutrient values and the plantation performance (i.e., tree growth rates during the immature period) in different agronomic, soil, and climatic conditions. The sampling protocol needs to be adapted to the specific features of rubber trees during the immature period. Although some limitations are possible, the use of these methods in areas where they were already calibrated would help growers manage fertilization. In any case, nutrient diagnoses could only ensure that soil and leaf nutrient contents are maintained at optimum values for tree growth. Diagnostics are complementary tools to nutrient budget methods that make it possible to match fertilizer application and crop requirements while accounting for all possible sources of nutrients at field scale. For instance, leaf diagnostics could be used to check if the nutrient budget method does not deviate across years, e.g., due to over-fertilization. This set of tools is very important because, in the current context of the increasing demand for NR, the appropriate management of fertilization would make it possible to increase global production of NR by reducing the length of the unproductive period and maintaining soil fertility (then increase latex yield) while limiting expansion of NR production into new areas. In the following section, we review all the knowledge available on input and output nutrient fluxes in a rubber plantation with the aim of building a nutrient budget model.

6 What do we know (and do not know) about the nutrient dynamics in immature rubber plantations?

6.1 Growth and nutrient requirements

As nutrient dynamics at both tree and plantation scales are tightly linked to phenology and annual growth in all trees, including rubber trees, the timeline and the main features of qualitative changes are recalled below.

6.1.1 Phenology and associated qualitative changes in growth dynamics

Two phases can be identified after planting and before latex production: a juvenile phase (i.e., tree establishment and first year after planting) and an immature period (from 2 years old until 6- to 7-years-old, depending on the clone used and on the environmental conditions).

Juvenile phase From a development viewpoint, the juvenile phase is characterized by the high growth rate of the primary axis (stem elongation) (Pollinière and Van Brandt 1967). Stem growth results from successive leaf stages which occur during the rhythmic establishment of growth units (Hallé and Martin 1968): (i) apical bud break, (ii) elongation of the internode along with the growth of a leaf cohort, and (iii) leaf maturation with synchronic leaf growth within unit growth. Finally, axillary and apical buds become dormant. Regarding nutrient cycling, there is no leaf fall and therefore very small amounts of

Table 6 Main characteristics of existing diagnostic methods (soil diagnostic, leaf diagnostic, and diagnostic and recommendation integrate system (DRIS)) for fertilization management in immature rubber tree plantations. We provide a qualitative comparison of the reliability and the ease of each method using different criteria. The number of "+" indicates the number of times a criterion is taken into account in the method

Criteria	Soil diagnosis	Leaf diagnosis	DRIS
Knowledge and tool easily available?	+++ - Malaysia, China, Thailand	+++ - Malaysia, India, Ivory Coast, Thailand	++ - Brazil, Cameroon, India
Easy to use?	+++	+++	++ (local calibration needed)
Optimal period for use of the tool?	> 6 years Could be adapted for use before planting	> 4 years Could be adapted for use during the immature period	> 6 years Not adapted for use during immature period
Knowledge available to assess nutrients requirements and thresholds	+ Thresholds established during mature period, equilibrium less known	++ Well-known in different geographic zones and for different clones	
Suitable for all nutrients?	not for nitrogen and phosphorus	Not for phosphorus and calcium	Yes
Suitable for fertilizer recommendation based on diagnosis	++ - Only a few tables are currently available		

nutrients taken up by trees return to the soil. At this stage, the taproot of rubber trees can forage only to a depth of 1 m (Thaler and Pagès 1996b).

The high nutrient demand of rubber trees during the juvenile phase may result in nutrient shortages caused by the imbalance between nutrient accumulation in the trees (see Meti et al. (2002)), with no return to the soil, and an insufficient supply of nutrients in the soil. Low nutrient recycling through litter fall both by the individual tree and by the plantation as a whole as well as high growth rates means that fertilization is mandatory. To our knowledge, no information is available on root growth dynamics and the intrinsic capacity of fine roots to take up nutrients throughout the soil profile.

Immature period Two major events occur during the immature period. First, ramification starts concomitantly with acceleration of the stem diameter (Delabarre and Benigno 1994). Second, flowering and leaf fall start at age 4 or 5 (Compagnon et al. 1986; Watson 1989). Flowering occurs after leaf fall or during leaf emergence (Delabarre and Serier 1995). During refoliation, mobilization of N and C compounds stored in ligneous tree components sustain bud break and the early leaflet growth (Li et al. 2016). Root growth during this period parallels shoot growth, i.e., is rhythmic (Thaler and Pagès 1996a). The few available data suggest that the maximum root growth occurs during refoliation and that minimum root growth occurs during leaf senescence (Jessy et al. 2013; Soong 1976). A decrease in soil water content during the dry season may enhance root growth to improve withdrawing water. Indeed, soil water content has been shown to be a key variable explaining root distribution in the 0–10-cm soil layer (McGroddy and Silver 2000; Green et al. 2005). In line with their findings, Jessy et al. (2013) recommend applying nutrient fertilizers when root growth is maximum (i.e., concomitant with refoliation) to promote fertilizer uptake. A taproot can reach a depth of from 1.5 to 3.5 m depending on the proportion of stones, and the length of the fine lateral roots can range from 4 to 9 m in the fifth year (Watson 1989; Priyadarshan 2011). At least 50% of the fine roots (which are largely responsible for nutrient uptake) are located in the topsoil (0–20-cm layer) (Pollinière and Van Brandt 1964).

In conclusion, both leaf senescence and maximum root growth rates are critical events. It can thus be hypothesized that biomass accumulation by the trunk, twigs, leaves, and roots largely relies on both nutrient uptake from the soil and nutrient recycling within the tree, even though detailed biogeochemical studies have not yet been carried out in rubber plantations. Thus, satisfying N, P, K, Mg, and Ca requirements is of great importance to successfully increase stem growth, thereby reducing the length of the immature period.

6.1.2 Time course of nutrient uptake, allocation and recycling in rubber trees: what is known?

Only a few studies have assessed the time course of nutrient allocation and recycling in rubber trees over the immature period (Lim 1978; Watson 1989; Shorrocks 1965c; Samarappuli 1996; Chen et al. 2011). Nutrient accumulation in rubber trees from planting up to age 6 amounted to 700 kg ha^{-1} for N, 60 kg ha^{-1} for P, 300 kg ha^{-1} for K, and 120 kg ha^{-1} for Mg (Fig. 2; flux 1a in Fig. 3).

Nutrient accumulation is exponential during the first 2 years after planting: this pattern can be explained by the high concentrations of nutrients in growing tissues. Nutrient accumulation reaches maximum at around 4 years of age but varies considerably among clones (Fig. 2). This variability may partly result from different nutrient storage capacities of perennial tissues, mainly bark and roots, during leaf senescence (flux 1b in Fig. 3) (Zhang et al. 2015). For instance, it has been shown that 40, 57, and 53% of the N, P, and K stocks in leaves were resorbed by storage tissues at leaf shedding in 5-year-old rubber trees (Li et al. 2016). Resorption rates were higher in 13-year-old rubber trees (57–59, 73–82, 73–86, and 27% for N, P, K, and Mg, respectively) (Murbach et al. 2003; Pollinière and Van Brandt 1964). Once stored, nutrients can be remobilized for the benefit of growth in new organs (such as twigs, leaves, and flowers) in the re-growth period (Millard and Thomson 1989; Millard and Nielsen 1989). Nutrient resorption and remobilization are two aspects of internal nutrient recycling over the annual growth period. The role of nutrient remobilization in fulfilling the demand of new organs is well documented in young trees. In the case of N, this contribution ranges from 17% in ash (4 years old) to 100% in oak (1 year old) (Millard and Grelet 2010) during the early stages of their life cycle. Nutrient accumulation in rubber trees can reach maximum when latex production starts.

In conclusion, trees are highly dependent on nutrient availability before starting to produce latex. However, data are scarce in the literature and only a few experiments have been undertaken to estimate the nutrient demand dynamics of young rubber trees under controlled conditions (Aibara and Miwa 2014; Thitithanakul et al. 2017).

6.2 Sources of nutrient inputs

6.2.1 Nutrients provided by residues and cover crops

Harvest residues in replanting sites Under a zero-burning strategy, plant biomass is mineralized on site. Relatively low C:N ratios (< 100 in the whole plant) and lignin contents (30% of the dry matter) have been measured in rubber trees

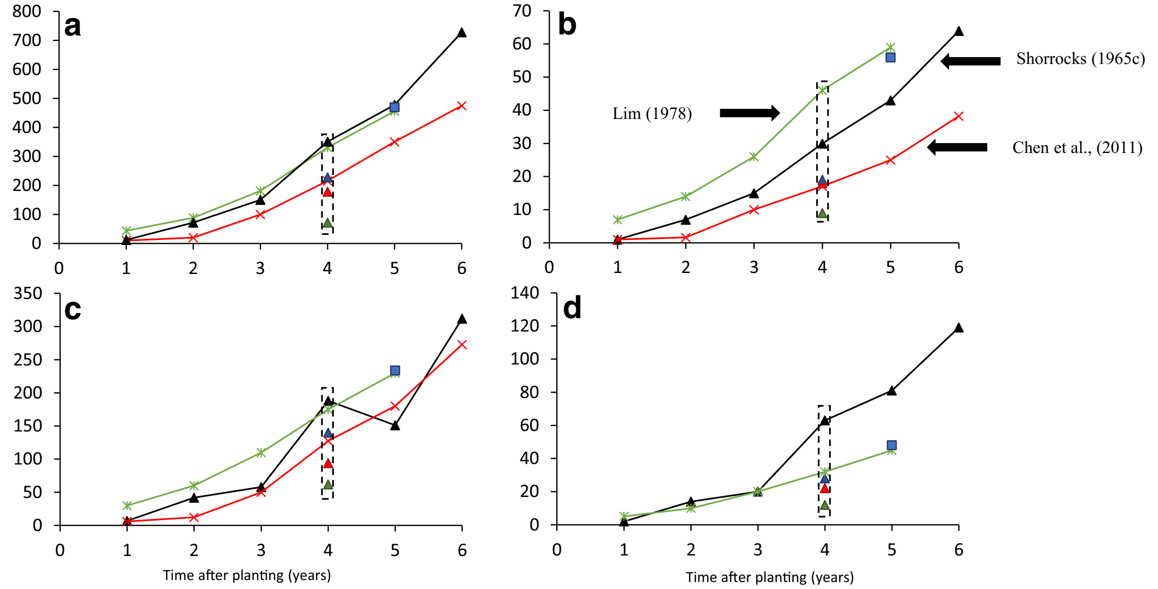

Fig. 2 Nitrogen (**a**), phosphorus (**b**), potassium (**c**), and magnesium (**d**) accumulation by rubber trees (kg ha^{-1}) during the immature period (0–6 years) in Samarappuli (1996) (Ski Lanka; blue square); Chen et al. (2011) (China; red line); Lim (1978) (Malaysia; green line); triangles are values reported by Shorrocks (1965c) (Malaysia) using different clones: RRIM 501 (black triangle and line); PB 86 (green triangle); GT 1 (red triangle); LCB 1320 (blue triangle)

compared to other perennial crops (Nizami et al. 2014). As a result, the decomposition rate is high, as measured by Gréggio et al. (2008), and nutrient release is expected to rapidly benefit young rubber trees. The amounts of nutrients returned to the soil at harvest depend on the stocks contained in the tree biomass left on site. The biomass of old rubber tree plantations is highly variable. For instance, in Malaysia, the aboveground biomass of 33-year-old rubber plantations amounted to 270 Mg ha^{-1} for clone Tjirl and to 530 Mg ha^{-1} for clone RRIM 501 (Shorrocks 1965c). In China, the aboveground biomass of 38-year-old rubber plantations ranged from 93 to 234 Mg ha^{-1} depending on altitude (Méndez et al. 2012). The amounts of N, P, K, Ca, and Mg immobilized in the biomass of 35-year-old rubber trees then released into the soil during the mineralization of residues after harvesting were 934–1779, 156–277, 592–1233, 2119–2179, and 417–560 kg ha^{-1}, respectively (Pollinière and Van Brandt 1964; Shorrocks 1965c; Yew 2001). Yew (2001) showed that 70% of the nutrients in harvest residues were released within 29 weeks and 100% within 129 weeks.

Intercropping (Fig. 1) During the first years after planting, cover crops develop rapidly in the inter-row, thereby protecting the soil against erosion and accumulating nutrients in their biomass (flux 2a; Fig. 3). Cover crops produce a considerable amount of biomass, especially in the first 2 years after establishment, from 5 Mg ha^{-1} year^{-1} for grass cover to 10 Mg ha^{-1} year^{-1} for *Pueraria phaseoloides* (Clermont-Dauphin et al. 2016; Watson et al. 1964a). Legumes, often *P. phaseoloides*, begin to fix atmospheric nitrogen after the first two to 3 weeks of growth, and litter fall begins about 6 months later (Broughton 1977). Canopy closure in rubber plantations leads to the gradual death of the *Pueraria* (flux 2b; Fig. 3).

The large amounts of nutrients contained in legume cover crops play a critical role in nutrient cycling to the benefit of rubber trees. The second year after planting, Watson et al. (1964a) showed that legumes contained 340 kg N ha^{-1}, 22 kg P ha^{-1}, and 80 K ha^{-1} by summing the amounts in the litter on the soil surface and in plant biomass. Legumes (a mixture of *P. phaseoloides*, *Centrosema pubescens*, and *Calopogonium mucunoides*) are likely to supply larger amounts of nutrients than non-fixing plants (a mixture of *Axonopus compressus* and *Paspalum*) + 151 kg ha^{-1} year^{-1} for N, + 10 kg ha^{-1} year^{-1} for P, and + 20 kg ha^{-1} year^{-1} for K in Broughton (1977). More recently, Clermont-Dauphin et al. (2016) showed that *P. phaseoloides* accumulated 250 kg N ha^{-1}, 10 kg P ha^{-1}, and 170 kg K ha^{-1} the first year after their establishment. These studies emphasize that large rapid-growth cover crops can supply additional nutrients to satisfy the high nutrient demand of immature rubber tree.

Legume litter accumulated on the soil surface is rapidly mineralized thanks to a low C:N ratio, thereby increasing nutrient availability for rubber trees before the latex production period begins (Broughton 1977). Indeed, most of the carbon and nutrients from the legume residues (70% of C and N, 60% of P, and 99% of K) are released into the soil 75 days after the cover is slashed and mulched (Clermont-Dauphin et al. 2016).

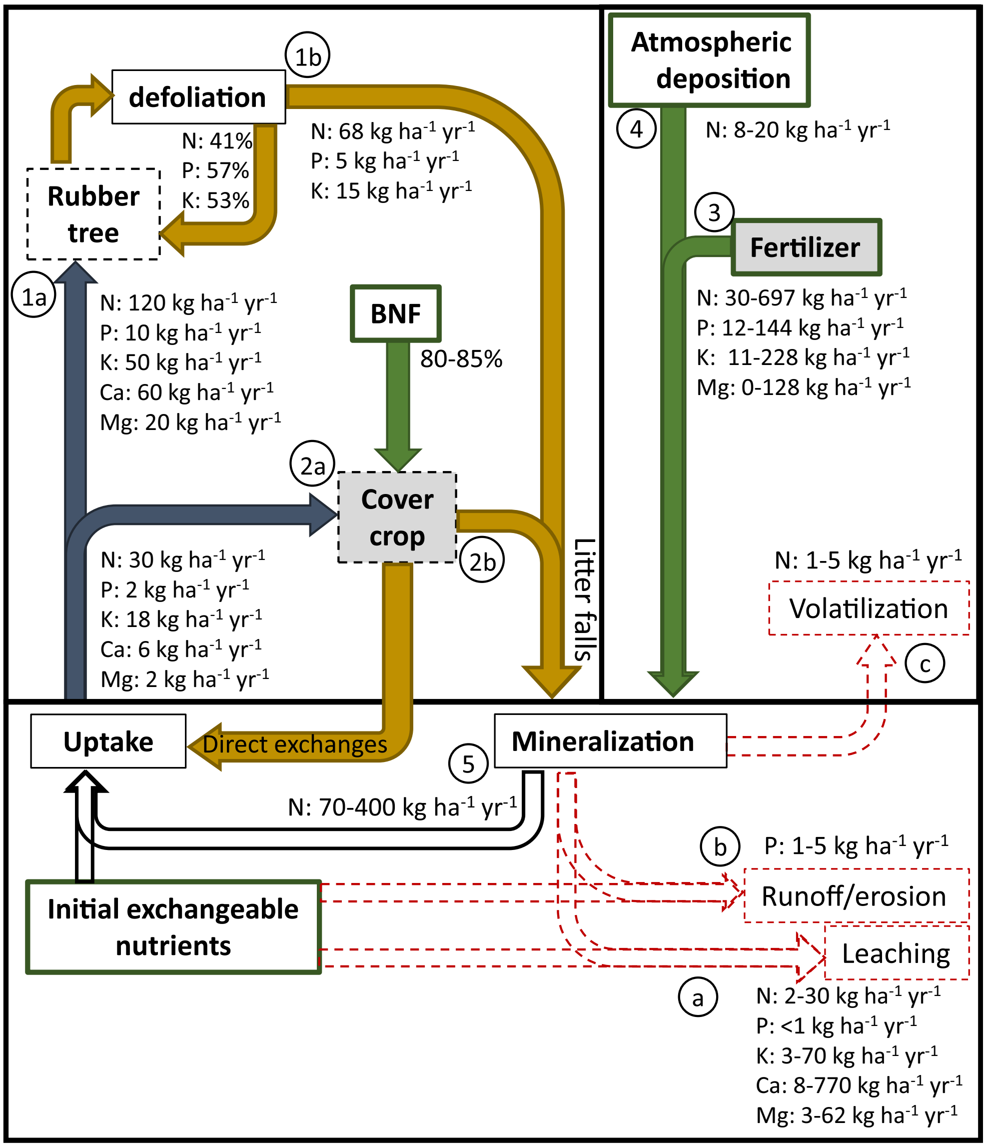

Fig. 3 Current knowledge on the nutrient budget in rubber plantations based on a tree density of 475 trees per hectare. Red dotted frames are outputs; green bold frames are inputs; gray frames represent sources of nutrients affected by management. Red dotted arrows represent fluxes of nutrient losses; yellow arrows represent the main fluxes in the biological cycle, including plant uptake (blue arrows). The references of the studies indicating the fluxes are indicated in each dedicated section. BNF: biological nitrogen fixation in cover crop; 1a: nutrient accumulation in rubber tree; 1b: nutrient internal recycling in rubber tree; 2a: nutrient accumulation in cover crop; 2b: nutrient restitution to soil due to cover crop death; 3: nutrient fertilizer; 4: N atmospheric deposition; 5: N and P release from organic matter mineralization; a and b: N, P, K, Ca, and Mg losses out from soil through run-off/erosion and lixiviation, respectively

6.2.2 Other contributions

Atmospheric deposition (flux 4; Fig. 3) is an additional source of nutrients, especially of nitrogen. To our knowledge, no specific studies have quantified atmospheric N inputs in rubber tree plantations. However, some studies in regions with large zones of rubber plantations reported atmospheric deposition of N ranging from 15 to 20 kg N ha^{-1} year^{-1} in Malaysia (Stevenson 1965) and 8 kg N ha^{-1} year^{-1} in Brazil (Trebs et al. 2006).

The release of inorganic nitrogen (NO_3^-; NH_4^+) and phosphorus ($H_2PO_4^-$; HPO_4^{2-}) from organic forms by mineralization of the soil organic matter (flux 5; Fig. 3) increases N and P inorganic availability in the soil (Tiessen et al. 2001). Mineralization can be estimated using field measurements, laboratory measurements, or by modeling. Soil nitrogen mineralization has rarely been measured in situ in rubber tree plantations. Values of between 70 and 400 kg N ha^{-1} year^{-1} have been reported in a few field experiments (Schroth et al. 2001; Ishizuka et al. 2002), suggesting a major flux of N in these plantations. To our knowledge, soil P mineralization has never been measured in rubber tree plantations.

6.3 Nutrient losses

We found only a few studies which quantified nutrient (N, P, K, Ca, and Mg) losses through leaching (flux a; Fig. 3) in rubber tree plantations. In a recent study in Sumatra, Kurniawan (2016) showed very limited leaching in 17-year-old rubber tree plantations established on loam and clay Acrisol (4, 3, 8, 4 kg ha^{-1} year^{-1} for N, K, Ca, and Mg, respectively). By contrast, nutrient leaching during the immature period of rubber trees generally appears to be high. For instance, on sandy loam soils, Pushparajah (1977) showed that after 20 rainy days (1 cm per day) from 20 to 80% of the amount of N added by fertilizer was lost by leaching in 1-year-old rubber plantations. Potassium leaching was assessed at between 20 and 45% of the amount applied as fertilizer. The fact that nutrient leaching is higher under immature rubber trees than under mature stands could be a result of lower root density and high fertilizer application on a small zone around the foot of the rubber tree, as reported for oil palm plantations (Pardon et al. 2016).

The litter layer also plays an important role in controlling soil erosion and runoff (flux b; Fig. 3). Practices like burning (Alegre and Cassel 1996) and absence of cover (Sojka et al. 1984), which are frequently observed in rubber tree plantations, decrease the litter layer and increase the risk of soil erosion and runoff. For instance, Rodenburg et al. (2003) showed that slash-and-burn land cleaning multiplied the runoff flux by 17 (P losses varied from 0.2 to 5 kg ha^{-1}). Liu et al. (2017) showed that the presence of a cover crop under immature rubber trees decreased runoff by 56% and soil erosion by 81%.

Gaseous losses (flux c; Fig. 3) are mainly due to volatilization of nitrogen in the forms of ammonia (NH_3) and nitrous oxide (N_2O). Some studies of rubber tree plantations showed that NH_3 losses ranged from 2.5 to 4.0 kg N ha^{-1} year^{-1} (Zhou et al. 2016), and from 9 to 24% of the initial amount of nitrogen in 1 week when urea was applied on the surface soil at a rate of 224 kg ha^{-1} (Watson et al. 1962). NO_2 losses represented smaller amounts of N, generally less than 1 kg N ha^{-1} year^{-1} (Ishizuka et al. 2002). These results largely depend on climatic factors, soil texture, the form of fertilizer applied, and agricultural practices like land clearing by slash-and-burn (Juo and Mann 1996; Kleinman et al. 1996). Overall, gaseous losses in rubber tree plantations have received little attention: as a consequence, estimation of this flux is limited.

7 Conclusions

Adding fertilizers during the immature period in rubber plantations has been shown to shorten the immature period and increase latex yield in the first years of production; yet, the amounts and dates of fertilizer application remain poorly documented. Current fertilization programs basically rely on extrapolated growth response curves to NPK application in local field trials, which likely lead to over-fertilization with respect to tree nutrient requirements and ultimately soil nutrient unbalance.

On the one hand, some improvement in managing NPK fertilization was thought depend on the use of efficient tools for nutritional diagnosis calibrated for mature trees. However, the use of these tools failed to generally improve NPK fertilization due to (i) lack of tools calibrated for the immature period (e.g., which leaf to sample for leaf diagnosis, when to sample) and (ii) the fact that although such tools do detect nutrient deficiency, they cannot provide information on the amount and on the date fertilizer should be applied. Thus, these indicators do not account for nutrient supply-demand schemes that may result in nutrient losses through deep leaching: imbalances between tree demand and soil supply have been widely reported. On the other hand, from a practical viewpoint, practices including the use of a cover crop, intercropping, and leaving crop residues on the ground are widely applied under immature rubber trees. Such practices have been shown to reduce the use of mineral fertilizer by up to 50% for equivalent growth rates (Pradeep and Manjappa 2015; Abraham et al. 2015). In the same line of thought, biomass return between two rotations also fulfills fertilizer requirements for equivalent growth (Yew 2001). However, no references are available about the amount, the rate, and the stage at which nutrients from cover crops, intercrops, and crop residues are taken up by immature rubber trees. These need to be accounted for, as this will reduce the amounts of mineral forms of NPK fertilizer used.

Based upon this literature survey, it is clear that nutrient management at the plot scale needs to be based on the combination of soil and leaf diagnoses and a balanced nutrient budget between soil NPK supply and NPK tree demand using agroecological practices, such as re-use of organic matter (cover crop and crop residues). Indeed, a soil diagnosis at the very beginning of the immature period would secure NPK supply during the first years of tree growth, while the nutrient budget would provide a long-term strategy for NPK application based upon predicted plant growth and soil functioning. Leaf diagnoses conducted throughout the period would identify NPK deficiencies. Then, recomputing the nutrient budget would provide information on how many NPK applications will be required to alleviate potential long-term effects of a NPK deficiency on growth during the immature period and on the yield of latex later on. Considering both long- and short-term nutrient management along with the use of dead and living organic matter is defined as INM.

However, using a decision tool based on a nutrient balance model requires a large dataset for calibration of the model and for optimal estimation of the parameters. In the case of rubber trees, in agreement with other conclusions in our literature review, Chen et al. (2011) pointed to the lack of experimental data to correctly assess nutrient fluxes, and in particular tree requirements to reach growth objectives. Only a few studies assessed nutrient returns to the soil during the early growth period of rubber trees (Yew 2001). The present review provides a baseline to develop a dual approach based on modeling the nutrient balance and field experiments. Current knowledge on nutrient budgets in rubber tree plantations is insufficient to correctly assess nutrient fluxes. The first modeling step is important to better identify knowledge gaps and to prioritize processes according to their relative importance in plantation fluxes. Additional field experiments are necessary to produce new references on the effects of the different practices (burning/ not burning; intercropping) on nutrient fluxes under rubber trees and also to improve the calibration of models based on smallholder and industrial practices.

Further investigations are needed to assess the effects of tree residues on rubber plantation functioning considering successive replanting cycles and the “zero-burning” practice driven by changes in legislation. Investigations are also needed to assess to what extent correct management of tree residues can address soil fertility decline, optimize fertilization, and the performance of tree-based cropping systems (Achat et al. 2015). The pertinence and the feasibility of leaving residues on site merit research on the trade-off between the amounts of residues left in the plot, tree growth, and prevalence of root disease (e.g., White root disease caused by *R. microporus*).

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Compliance with ethical standards

Conflict of interest The authors declare they have no conflict of interest.

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