FROM JUNGLE RUBBER TO RUBBER AGROFORESTRY SYSTEMS

History of Rubber Agroforestry Practices in the World

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Chapter 3

RAS in the rubber world: current agroforestry practices in various countries

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⏩ Origin and development of RAS

Before 1900, natural rubber was mainly produced by tapping *Hevea brasiliensis* rubber trees growing in natural forests in Amazonia, the homeland of rubber (Dean, 2002; Stanfield, 1998), and in West Africa, by exploiting common latex lianas, *Landolphia* spp. (Danthu et al., 2016). In Amazonia, rubber trees often grow at very low densities with only one or two tappable trees per hectare (Dean, 1987). In both cases, the practice is classified as "extractivism" from natural forests.

After rubber was introduced in South East Asia in the form of monoculture in large estates by colonial companies, it was rapidly and extensively adopted by local smallholders in the form of "jungle rubber", a diversified extensive system derived from swidden cultivation (Feintrenie and Levang, 2009; Gouyon et al., 1993). In the 1930s, some examples of smallholder intercropping experiments with coffee and tobacco were reported in Indonesia (Dickman, 1951) as well as some intercropping during the immature period (year 1 or 2), i.e., before natural forest regrowth makes intercropping impossible, resulting in jungle rubber. In the 1950s and 1960s in Malaysia and Thailand, and a little later, in the 1970s, in Indonesia, most farmers started using clonal rubber, originally as monoculture, because it was more productive than jungle rubber and because monoculture was the main technical practice promoted by extension services at the time. The next step was the development of rubber agroforestry systems based on clonal rubber (see chapter 2).

Intercropping with annual crops during the immature period boomed in Thailand and Indonesia between1970 and the 2000s with the expansion of clonal plantations. To a lesser extent, the same applied to associating rubber with tree crops during the mature period, which accounted for 10-15% of the cropped area in Thailand, for 40% in rubber development projects in Indonesia in the 1980s and 1990s (Chambon, 2001; Stroesser et al., 2018). On Hainan Island (China), in the 1970s and 1980s, intercropping was strongly promoted by the government during both the immature and mature periods to diversify the portfolio of agricultural products to reduce the impact of typhoon damage and hence to stabilise farmers' income (Langenberger, 2015, 2017). In contrast, in Thailand and Indonesia, agroforestry was not officially promoted but was developed by farmers themselves. It is clear that most RAS developed in this way, relying on the farmers' own experience and know-how.

In remote areas, crops including upland rice, maize, vegetables, peanuts and chilli peppers were primarily cultivated for home consumption. Where access to markets was good, for example in Sri Lanka and in Indonesia, cash crops like pepper (the spice, *Piper Nigrum*), banana and pineapple were grown in the immediate vicinity of big cities of Sumatra (Palembang, Pekanbaru, Medan) (Bagnall-Oakeley et al., 1996; Penot, 2001). In 2024, the associated crops used in RAS are market driven.

Smallholder use of cover crops has always been very limited, and when they are used, the aim is to prevent erosion or to control weeds. There are two major reasons why cover crops were not widely adopted by smallholders: (i) growing a non-productive plant was not considered favourably in the smallholder sector and (ii) successful management of cover crops is labour intensive.

Agroforestry during the mature stage of the rubber trees includes cash crops, e.g. tea (Sri Lanka), coffee, cocoa (with very limited success at normal planting density) but mainly fruit and timber trees (in Thailand and Indonesia) or spices (in India). Fruit/timber-based RAS have been developed in Columbia and Brazil with local specifically Amazonian fruits including pupuna, acai, castanhera, and copoadzu (*Theobroma grandiflorum)*. See the list of Amazonian species in appendices (Table S3).

Some farmers began to cultivate perennial crops when the rubber trees were big enough to provide shade, i.e., after 5 or 6 years, and continued growing the crop until the end of the rubber cycle, either on their own initiative (Thailand) or after government promotion (Sri Lanka, mainly cacao).

In some countries, RAS underwent a significant decline in the 2000s due to a more market-oriented policy (for instance in China or in some places in Indonesia, e.g. Jambi province), competition with oil palm (Indonesia), and in other countries, due to the diversification strategies of local farmers. In China, promising intercropping species such as medicinal ginger *Alpinia oxyphylla,* were rapidly abandoned due to low market prices (Zeng et al., 2012), the same was true of another ginger plant (*Amomum villosum)* in Yunnan, despite the fact it was strongly promoted for years (Zhou, 1993).

Incorporating livestock (sheep, chickens or cattle), in rubber plantations was also tested in North Sumatra, but poorly adopted by growers (Ng et al., 1997; Payne, 1985; Shelton and Stur, 1991; Waidyunatha et al., 1982). Some local livestock-based RAS developed in Vietnam (Penot et al., 2022) and eastern Sri Lanka (Penot et al., 2023a).

The key impact of shade

When clone rubber is grown at the normal density, in normal conditions, and in the absence of leaf diseases, shade generally reaches between 80% and 90%. Some clones such as RRIM 600, which is widely used in Thailand, provide limited shade, i.e., between 60% and 80%. Leaf diseases can reduce shade by as much as 50% (South Sumatra, Indonesia) depending on local conditions.

The results of the many experiments conducted since the 1990s indicate that cacao and coffee do not produce good yields under more than 80% shade in addition to strong competition with rubber roots in the upper soil layer. According to Wood (1985b), experiments using rubber at normal planting density as shade trees for cacao failed economically: the cacao trees survived in the shade but produced no yield, a fact that was confirmed in the Sri Lanka. Wintgens and Descroix (2009) claimed that rubber "has never been a successful shade tree for coffee". We can make the same claim for cacao, at least at normal rubber planting density. Timber trees are usually more suitable, as most species (for instance *Dipterocarpaces* species) are shade tolerant and may even require shade in their young stage.

A number of trials and surveys have shown that most fruit trees produce between 30% and 60% of their normal yield in the full sun (Penot, 2001; Stroesser et al., 2018; Penot et al., 2022). In sub-optimal and marginal growing conditions, shade may benefit certain plant associations, for instance, it can prevent overheating, which is a major advantage in the context of global warming, and in some species including coffee, fruit quality may even be enhanced if the shade is not too dense (Chaudhuri et al., 2013; Descroix and Snoeck, 2009; Muschler, 2009; Wintgens, 2009). However, shade normally considerably reduces the yield of associated plants. The solution is finding the right balance that will enable associated plants to be productive under a certain degree of shade. The shade threshold can differ from one location to another and more research is needed on that particular point. Some rubber clones are more suited to agroforestry with a canopy considered as "light" as it provides on average 70% shade (such as RRIM 600). The expansion of leaf diseases in many areas, in particular in Indonesia, also creates better conditions for agroforestry.

An alternative way to deal with shade constraints is to use double-row spacing, with a 15-25 metre inter-row, to guarantee sufficient light for the associated crops. Both coffee and cocoa succeed in such systems and we explore that possibility in a dedicated paragraph.

⏩ The situation in South and South East Asia

The two main countries with original or widely practiced agroforestry systems are Indonesia and Thailand (the latter was covered in chapter 2). Here we review other countries with rubber agroforestry systems: Indonesia, China, Malaysia, and Sri Lanka.

Indonesia

After having explored past experience with RAS in Indonesia in the 1990s, here we explore recent developments. In September 2022 and October 2023, two meetings were hold in Jambi and North Sumatra (GPSNR) on agroforestry practices gave us the opportunity to talk to local rubber smallholders about the current situation facing rubber, the serious impact of low rubber prices in the long run, the impact of the wide adoption of oil palm, and the need for income diversification, but also to discuss current agroforestry practices in these conditions. Oil palm has become the priority thanks its high margin/ha and excellent return to labour. In 2022, it is true that most farmers have already diversified with oil palm and do not need another way to diversify based on agroforestry with rubber. Agroforestry enabled the introduction of rubber in Indonesia through jungle rubber, and then through RAS in the 1980s and 1990s. But competition with oil palm and the long series of low rubber prices since 2012 seriously reduced interest in growing rubber and hence in any kind of agroforestry, particularly in Indonesia. Nevertheless, some farmers continue to practice agroforestry for economic or even social reasons. On the occasion of the GPSNR meeting, farmers who were still practising rubber monoculture, expressed their interest in the following aspects:

Fruit/timber systems based on the normal rubber planting density

– Local fruits such as Jengkol (*Archidendron pauciflorum*) and petai/stink bean (*Parkia speciosa*), which are easy to plant and grow (adapted to shade and already present in jungle rubber systems) and for which there are local markets and high demand for Jakarta. The same trend has been observed in West Kalimantan province in Borneo (Penot et al., 2019).

– "Alam" or local/traditional/robusta coffee grown from local seeds and sold on local markets, with also high demand from Jakarta as well as arabica coffee in North Sumatra.

– Mangosteen ("Manggis") which starts yielding four years after planting and produces a reasonable yield in the shade provided by rubber trees planted at their normal density.

– Local markets for sugar palm and lemongrass for distillation (North Sumatra).

– There is a strong demand for the development of associated trees nurseries to provide local farmers with high-quality plantlets of associated tree species.

– The main problems with grafted fruit trees like durian is finding good quality nurseries and the cost.

– There is a possibility of transition from the rubber-based system to durian-based system at the end of the rubber lifespan (currently between 25 and 35 years depending on tapping quality). According to the strategy used by local farmers, this is a good alternative following rubber. This idea is very similar to that of *tembawang*, the "fruit and timber tree" based agroforestry systems found in West Kalimantan.

Normal spacing vs. double spacing

– 3 x 7 m or 2.5 × 6 m is best for local fruit and timber species which can grow in the shade or the current situation of Indonesia with leaf diseases leading to a shade level of 70%.

– The choice depends on the farmers' strategies and level of intensification.

– There is a need for demonstration plots with different types of agroforestry systems based on demand from local markets.

RAS in Sumatra in 2023

A recent farming system survey of a sample of 100 farmers conducted by the Indonesian Rubber Research Institute (IRRI) as part of the Rubis project, reported that farmers still show a real interest in agroforestry practices with rubber in both immature and mature periods, particularly in South and North Sumatra provinces. In North Sumatra, 94% of farmers use RAS, 54% in South Sumatra and 41% in Jambi, confirming that RAS still interests most farmers despite the local interest in oil palm (source: Rubis project, Dr Dwi Shinta Agustina/IRRI, unpublished data, personal communication).

The boom in "Amorphophallus" in Indonesia

In Indonesia, we recently observed a boom in intercropping using "*Amorphophallus*": a tuberous plant that takes its name from its giant phallus-shaped inflorescence, and is called "porang" in Indonesia, named after the species *Amorphophallus muelleri*. It was ignored for a long time and then rediscovered, cultivated and massively exported for its glucomannan content, which is used for weight reduction. In 2020, Indonesia exported 32,000 tons of porang to Japan, China, Vietnam, and Australia, for a value of US$100,000. The plant is also widely used in industrial, food, and health products.

Agarwood

Agarwood oil, *or Gaharu*[61], often referred to as oud oil, eagle wood oil, or aloe wood oil is a resinous, fragrant high value heartwood. The essential oil is derived from heartwood infected by a fungus that produces a dark aromatic resin. The most popular species are *Aquilaria malaccensis, Aquilaria agallocha* and *Aquilaria crassna*. Agarwood oil is native to India and several countries in South East Asia including Vietnam, Philippines and Indonesia. Its extreme rarity in local forests makes it very expensive. In 2024, agarwood oil is obtained from cultivated trees and artificial infection and requires considerable investment per hectare. The essential oil is extracted by distillation in water and can be found in several quality grades that depend on the original grade of the wood and the length of the distillation period. Typically, the longer the distillation time, the higher the grade.

Agarwood oil is extensively used as a medicine (aid to digestion, to repair damaged skin, relieve allergies, treat insomnia and acne, relieve joint pain, and pain during and after birth, nausea and vomiting) as well as for spiritual purposes. The anticancer properties of agarwood oil have been investigated. It is also used in cosmetics, perfume and aromatherapy. The market for therapeutic and cosmetic applications is expected to increase in the very near future. Agarwood oil has long been used by Ayurvedic practitioners for spiritual and emotional applications. India, Indonesia, Singapore, Malaysia, and Sri Lanka are top exporters/manufacturers of agarwood oil followed by North America and Europe. The main importers ranked in decreasing order of importance are U.S.A., Germany, U.K., China, Saudi Arabia, and France.

China

Agroforestry has a long history in certain parts of China. According to Chen Yung's (1943) "History of Forestry in China and Administration of the Republic", agroforestry was already practised in Shanyang County 1,700 years ago. Records show that 300 years ago, some forest farmers planted agricultural intercrops under young plantations of Chinese timber that very closely resembles the Taungya system[62] (Sin et al., 1998) in Myanmar with teak. A civil officer, Zheng Hui, suggested planting a hedgerow of timber to overcome local timber shortages. The development of rubber in China had negative environmental effects due to extensive deforestation it caused. A controversy emerged on the sustainability of rubber farming in Xishuangbanna and other locations in South East Asia (Ziegler et al., 2009). Intercropping is one of the alternative ways of reaching both ecological and economic goals (Wu et al., 2001; Ziegler et al., 2009)

Hainan

Rubber with medicinal plants

Medicinal plants are very widely cultivated in China (Ghobarni et al., 2011).

Rubber plus *Amomum villosum* and *Clerodendranthus spicatus*. In the Xishuangbanna area of south-west China, intercropping rubber with medicinal herbs is regarded as

61. https://www.transparencymarketresearch.com
62. The Taunggya system was used in government teak plantations in Myanmar (still called Burma during the colonial era). The estate allowed local farmers to grow intercrops during immature period to reduce maintenance costs.

a promising way to reduce the negative hydrological effects of rubber monoculture and to improve the sustainability of old rubber plantations. Briefly, intercropping with shallow rooted medicinal herbs (*A. villosum and C. spicatus*) can help old rubber trees tap water in deeper soil layers, thereby hopefully helping the rubber tree and the intercrop create complementary water-absorbing patterns in the pronounced dry season. However, no real improvement has been observed to date, consequently intercropping rubber with medicinal herbs still needs more research, particularly soil water conservation and management.

Rubber plus Traditional Chinese Medicinal Models with *Alpinia/Oxyphylla* during the immature period. *Oxyphylla* c.f. and *A. villosum* (Zhou, 1993) belong to the ginger family (Zingiberaceae). This intercropping system was promoted in mountainous and hilly regions with fertile soils. Mountain slopes were terraced and rubber spaced 2 × 7 m or 2 × 8 m. Three years later, about 400 kg/ha of seeds were collected from each variety in the first harvest year and 400-500 kg/ha of the seeds were harvested in years 4 and 5 (Haishui and Kejun, 1991), which are reasonable yields.

*R*ubber plus *Morinda officinalis* during the immature period. The environmental conditions needed to grow *M. officinalis* resemble those of *Alpinia/oxyphylla*. Cuttings of *M officinalis* were planted under rubber trees in three to five rows with 0.5 x 0.8 m spacing. A yield of 250-300 kg/ha was harvested five years after planting.

Rubber plus *Amomum longiligulare,* adapted to shade*.* The best time to intercrop *A. longiligulare* is three or four years after planting rubber. 0.6 × 0.7 m spacing was used in this example. *A. longiligulare* took up 50% of the inter-row. It began fruiting three or four years after planting, when rubber was almost ready for tapping. The annual yield of *A. longiligulare* was 80-120 kg/ha which seems relatively low.

As most of these trials appear to have been abandoned or seriously reduced in recent years, yields and prices were probably not sufficient to maintain farmers' interest in such cropping systems.

Rubber plus lemongrass during the immature period

Lemongrass cannot grow well in the shade, so it was planted in the inter-rows at the same time as rubber trees with 0.8 × 1.0 m or 0.5 × 0.7 m between the rows of rubber trees; and harvested five or six months after planting, then once every four or five months. At each harvest, 10-15 tons/ha of fresh leaves were collected and turned into 100-150 kg citronella oil.

Rubber with tea

In Hainan province, most rubber is intercropped with tea, which is recognised as an effective way to reduce soil erosion (Guo et al., 2006).

Guo et al. (2006) conducted an economic analysis of rubber monoculture and rubber intercropped with tea using a large state-owned farm in Hainan, China as a case study. Whilst 7 × 3 m spacing was the normal density used for rubber monoculture, in the intercropped system, 12 × 2 m spacing was used for the rubber trees to accommodate 14,400 tea plants/ha (with 1.6 × 0.3 m spacing between tea plants). The loss rate of the rubber plants was 15% in both systems due to typhoons and/or temperature changes. The production cycle of rubber monoculture was 33 years and that of rubber intercropped with tea 34 years, and the first tapping took place in the 8th and 7th year, respectively. Normally, tea can be harvested in year 2. Using an interest rate of 5.76% as discount rate and the company's own cost and price record, the authors calculated the net present value (NPV) of the two systems and found that the rubber-tea intercropping system was consistently more profitable than rubber monoculture, and that the optimal rotation age was 29 years for rubber monoculture and 26 years for rubber-tea intercropping system.

The same authors, Guo et al. (2006), also conducted some sensitivity tests using different discount rates and fluctuations in the prices of tea or rubber and found that rubber monoculture would only out-perform rubber-tea intercropping if the price of tea decreased by 30%. The rubber-tea combination was more profitable because tea is a high value secondary plant and grows well under 30–40% shade. Intercropping also benefited rubber growth so rubber tapping was able start a year earlier and end a year later than rubber monoculture.

Production and cost data were collected for another trial with rubber plus black tea (Guo et al., 2006). The tea species selected for the study, *Camellia sinensis var. assamica*, which was widely planted in the past, was the right species for the Black Powder tea sold on the Chinese market. Rubber-tea intercropping is more labour intensive for both rubber and tea and thus depends on local labour availability. Intercropping under rubber is not feasible at high altitudes since rubber trees can be damaged by the cold. Because markets have changed in the past decade, black tea has been largely replaced by green tea.

The environmental conditions of more than half the rubber plantations in Hainan are similar to conditions in the plantation used for the study by Guo et al. (2006). However, the annual yield of latex, as well as stumpage may not be as high in some plantations because of stronger typhoons, lower temperatures or poor topographical and soil conditions.

Rubber and Alocasia

The effects of interspecific competition for nutrients on calla lily growth, development, and nutrient uptake when calla lily (*Alocasia macrorrhizos L.* or songe Caraibe/Alocasia/giant taro) were intercropped with rubber, were recently investigated in rubber systems (Sun Li-juan et al., 2019). Calla lily grows in shady environments. It reproduces rapidly and its tubers have high starch and sugar content. Whole calla lily plants also have medicinal and ornamental applications. Rubber tree/calla lily intercropping is a new and promising intercropping system suitable for implementation in shaded mature rubber plantations where the main product of the calla lily is industrial starch.

China: Yunan

In Xishuangbanna, rubber is mainly grown as a monoculture (Liu et al., 2006), although intercropping was previously recommended (Wu et al., 2001; Ziegler et al., 2009). In a case study of smallholder rubber farmers in Daka village in Xishuangbanna, Fu et al. (2009) identified several intercrops in rubber plantations including upland rice, taro and pineapple grown at normal rubber planting density. Leshem et al. (2010) analysed rubber intercropping practices in Xishuangbanna based on interviews with 15 experts and in-depth interviews with 25 farmers in two villages. They found that, depending on altitude and on the choice of crop, intercropping had positive economic and ecologic effects, for example, rubber intercropped with tea reduced economic uncertainty and improved the income of farmers in high altitude areas.

The Xishuangbanna Tropical Botanical Garden also conducts trials incorporating different tree and shrub species. The search for economic improvement has also led to the identification of "miracle trees", such as eagle wood (Aquilaria spp.) which is promoted for short-term production of agarwood. Agarwood is a highly aromatic and highly priced hardwood produced in old trees as a result of a fungal infection and related wood tissue reactions (Persoon, 2007). Agarwood is used to make incense and perfume. It is currently well developed in Indonesia as detailed in the previous chapter, and the market appears to be promising.

Another trial was conducted with native (indigenous) tree species in mature rubber plantations at normal planting density (Langenberger et al., 2017). The criteria used to select the species were: (i) it must be adapted to the prevailing environmental conditions, (ii) must be shade tolerant, (iii) its vertical growth must not be affected by light, (iv) conservation value, (v) economic potential, (vi) easy to manage. Rubber trees are usually planted in rows with 6-8 m between rows, with 2.5 to 3 m between rubber trees. The following species were selected for the demonstration sites: *Parashorea chinensis*, a valuable timber tree; *Taxus mairei*, a multi-purpose tree, providing good timber but also an anti-cancer drug, taxol; and *Nyssa yunnanensis*, selected for its conservation value. At the end of the economic life span of the rubber trees (about 30 years) there will be several options, but the three main options are: (i) the rubber plantation can be replanted, although the harvest of the *Parashorea chinensis* trees would be premature, while the *Taxus mairei* trees could be maintained through a new plantation cycle, (ii) both the rubber and the intercropped trees could be maintained for future timber and taxol production, and (iii) the plantation could be transformed into a managed sustainable forest scheme.

In Xishuangbanna, a study used cross-section data on 600 rubber farmers in Xishuangbanna (Min et al., 2017b), as a basis to develop four empirical models to analyse the adoption of intercropping at farm and at plot level. The study showed that only a small proportion of rubber farmers have adopted intercropping, tea being the most frequent intercrop. However, other studies indicate that intercropping remains an important source of income for households in the lower income category. The adoption of intercropping is affected by ethnicity, household wealth and family labour. On average, intercrops contribute 16.5% of the total household income, suggesting that intercropping is an important source of income for smallholder rubber farmers.

Malaysia

Rubber and livestock

Integrating animals in rubber plantations was found to be more profitable than rubber monoculture by both Majid et al. (1990) and San and Deaton (1999). Based on data collected from 51 farms and FELDA[63], Majid et al. (1990) found that the system based

63. Federal Land Development Authority (FELDA) was established on July 1, 1956 in Malaysia under the Land Development Ordinance of 1956 for the development of land and relocation with the objective of poverty eradication through the cultivation of oil palm and rubber.

on 50 ewes and one ram grazing in a rubber plantation from year 3 to year 25 was more profitable than rubber monoculture and the net present value (NPV) was 11.9% higher than rubber monoculture with a pay-back period reduced by one year to 8–9 years. San and Deaton (1999) assessed the feasibility of integrating sheep and soybean in rubber plantations based on data collected from 85 farms participating in Nucleus Estate Smallholder Scheme (NES) Development projects. Using a linear programming model, they found that the optimal combination of rubber trees with 16 remaining productive years (i.e. 22 years old) and sheep for a smallholder rubber farmer was 593 rubber trees with eight years of annual soybean production. Adding soybean was more profitable than rubber monoculture or only including sheep in the rubber plantation. Although no details on rubber planting density and yield were provided, having sheep graze rubber plantations would benefit rubber growth both by adding nutrients to the soil and by reducing the cost of weeding. However, it should be noted that these studies were conducted in the 1990s and the results may no longer be valid in the current economic situation.

Rubber and timber

A study was conducted by Yahya et al. (2023) on associating plantation crops like oil palm (*Elaeis guineensis*) and rubber (*Hevea brasiliensis*) and timber species like sentang (*Azadirachta excelsa*), a species usually found in secondary forest, and teak (*Tectona grandis*). The study involved government and private agencies and 50 farmers who practiced this type of agroforestry. The most frequent type of combination was found to be rubber and sentang used by smallholder farmers to supplement the low income they obtained from rubber particularly during the development stages when productivity is limited and when rubber is being replanted.

Rubber agroforestry systems in India

Unfortunately, very few publications are available to illustrate agroforestry practices in India even though India probably has the highest rate of agroforestry in the world and 80-90% of rubber is probably grown in association with other plants. In fact, as most rubber plantations are located in areas with a relatively high population density (i.e. more than 500 inhabitants per ha) there is a need for integrated, more economically efficient and more intensive agroforestry practices.

A high proportion of home gardens in Kerala have been converted into rubber plantations (Kumar and Nair, 2004). The cropped area of most smallholdings is less than 0.5 ha which has led to intensification through a combination of agroforestry and cropping, an important feature of Indian smallholder rubber (Menon, 2002). Banana, pineapple, different vegetables, cassava, tuber crops, ginger and turmeric are the intercrops most commonly cultivated in young rubber plantations (Jessy et al., 2017) using a normal planting density (6.7 and 3.4 m spacing). The probability of adoption of intercropping was highest for three crops (Rajasekharan and Veeraputhran, 2002): banana (*Musa* spp.), cassava (*Manihot esculenta*) and pineapple (*Ananas comosus*).

Shade tolerant medicinal plants like *Strobilanthus haenianus* (Karimkurinji), *Adhatoda vasica* (Valiya Adalodakam) and *Plumbago rosea* (Chuvanna Koduveli) can also be grown in mature rubber plantations without adversely affecting rubber growth and yield. The local marketability of such crops should be checked before large-scale cultivation is launched. Siju et al. (2012) conducted a study in central Kerala that revealed the growing popularity of contract farming with pineapple as intercrop in the immature phase at normal planting density. The results of their analysis highlighted the growing divergence between the recommended agro-management practices, and those actually adopted, for example, pineapple under contract farming, and the potential challenges this implies.

Rubber associated with *Garcinia*, vanilla and medicinal plants

Three experiments were conducted by the Rubber Research Institute of India in the period 2001-2014 with the aim to produce additional income and to improve small-holder welfare by integrating diverse crops in rubber ecosystems (Jessy et al., 2017).

In one experiment, coffee, vanilla with *Gliricidia sepium* as support stands, *Garcinia* and nutmeg (*Myristica fragrans*) were cultivated along with rubber at normal planting density. Three experiments were implemented to test other crops. Experiment 1 was based on intercropping rubber (clone RRII 105) using coffee, *Garcinia* (445/ha), vanilla and nutmeg (175/ha). Experiment 2 evaluated nine shade tolerant medicinal plants intercropped with mature rubber: *Adathoda beddomei, Alpinia calcarata, Andrographis paniculata, Asparagus racemosus, Desmodium gangeticum, Piper longum, Pseudarthea viscida, Rauvolfia serpentina* and *Strobilanthes cuspidal*. Experiment 3 tested short cycle vegetables during the wintering period of mature rubber using cow pea and *Amaranthus.*

Light availability was measured and subsequently reduced to 88%, 53% and 4.8% after respectively, 3.5, 4.5 and 5.5 years. The rubber yield was between 1,000 and 1,300 kg/ha/year, which is rather low compared to normal standards. The growth of rubber was significantly improved with intercropping and rubber yield was comparable to local monoculture systems. Soil moisture status in summer and microbial populations were higher in mixed planting systems and soil nutrient status remained stable. Yields of all the intercrops were good up to year 4. As the shade provided by rubber became more dense, *Garcinia* perished but vanilla and coffee continued to produce reasonably good yields. All the medicinal plants established well and produced reasonable biomass, but among the nine, the performances of *Strobilanthes cuspida* and *Alpinia calcarata* were comparatively better. Experiment 2 showed that short duration vegetables like *Amaranthus* and salad cucumber can be cultivated during the annual leaf shedding period in mature rubber plantations to meet part of domestic needs. The yields of coffee, vanilla and *Garcinia* obtained in experiment 1 are listed in Table 3.1 below.

Table 3.1. Yields of crops associated with rubber in experiment 1

Cropping year	2005	2006	2007	2008	2009	2010	2011
Yield of coffee as intercrop kg/ha	890	596	347	645	236	616	346
Yield of fresh vanilla beans/pl	0.42	0.36	0.5	0.38	0.28	0	0
Yield of *Garcinia* as intercrop kg/ha	13	35	394	503	521	245	89

Rubber and elephant foot yam

Trials were conducted in 2012/2013 at the Regional Centre of ICAR-Central Tuber Crops Research Institute, Dumuduma, Bhubaneswar, Odisha (India) with elephant foot yam (*Amorphophallus paeoniifolius* Dennst.), which is shade tolerant and can consequently be cultivated during the rubber mature period (Jata et al., 2018). The aim of the experiment was to study the efficiency of cropping systems with different treatments (irrigation, nutrient use efficiency and quality of elephant foot yam). The experiment used a split plot design with elephant foot yam plus green gram (*Vigna radiata* L.); elephant foot yam as the sole crop in the main plots with surface irrigation, drip irrigation at 100% cumulative pan evaporation (CPE), drip irrigation at 80% CPE, and drip irrigation at 60% CPE in the sub-plots. Five replicates were made of each treatment. Elephant foot yam plus green gram produced a larger yield of corms than the other treatments. Drip irrigation at 100%, 80% and 60% CPE resulted in respectively, 16.7% and 14.9%, 16.4% and 14.6%, 12.3% and 11.5% higher yield than surface irrigation. The highest nutrient use efficiency was obtained by intercropping elephant foot yam plus green gram with drip irrigation at 100% CPE followed by drip irrigation at 80% CPE. The combination of elephant foot yam plus green gram produced higher concentrations of protein and sugar in the corms than sole cropping. Optimum yields of elephant foot yam were obtained by intercropping elephant foot yam plus green gram with drip irrigation at 80% CPE, with an average yield of elephant yam of 30 t/ha.

Other crop associations

Intercropping a variety of crops before the rubber plantation reaches maturity provides the farmers with additional income. In a rubber-based multi-strata system, when the plantation reaches maturity, the canopy will be closed. Apart from food crops, medicinal and aromatic plants, for instance, medicinal yam (*Dioscorea loribunda*) can also be intercropped with rubber (Singh et al., 2021). Rubber trees can be associated with food and beverage crops including maize, cassava, sweet potato, coffee, tea, pepper, and lemon grass, and with fruit crops like banana and pineapple (Zheng and He, 1991). Combinations of crops grown under the rubber trees at different stages of development enable optimal use of land and water resources (Jiang et al., 2020) and also results in higher soil organic matter content (Xiao et al., 2019).

Fruit tree species associated with rubber are mango, sapota (*Pouteria sapota*), guava, citrus, custard apple, areca nut tree, banana, papaya, coconut, and drum stick.

Intercropping helps maintain the nutrient and moisture balance on the farm, provides a permanent ground cover, and helps increase farm yields while simultaneously enhancing soil productivity and preventing erosion. The selection of crops for intercropping will vary depending on regional preferences, climate conditions and market mechanisms.

Depending on local climate conditions, some of the tried and tested rubber-based agroforestry systems recommended in India (Kropf and Hoang (2012) cited in Singh (2018); reported in Table 3.2):

- jackfruit, acacia or mahogany can be grown as windbreaks for rubber trees;
- if the farm is located on marginal soils, elephant grass can be associated with rubber to provide fodder for cattle, buffaloes, goats and rabbits;

– food crops including peanuts, beans, sweet potatoes, taro, maize, or cassava can be associated with rubber in the first four years after rubber trees are planted;
– growing cassava with rubber in the first three years after rubber establishment can yield 14–18 tons of root tubers per hectare per year. No information was available on potential impacts of combining cassava and rubber on rubber growth or diseases;
– coffee and pepper can be intercropped with rubber trees in the early years of the rubber plantation.

Table 3.2. Comparison of contribution of rubber based agroforestry systems to income diversification of the community

Type of RAS	Tripura India		Assam India		Meghalaya India		Songhla Thailand	
	Income	Rank	Income	Rank	Income	Rank	Income	Rank
Monoculture	54,292	7	44,427	7	45,519	7	29,027	7
Rubber + fruit + agriculture	57,057	5	47,672	5	49,837	4	44,811	1
Rubber + poultry	55,715	6	45,807	6	46,764	6	31,314	6
Rubber + livestock	60,325	1	50,288	1	21,316	2	42,948	2
Rubber + rice	58,080	4	49,412	3	49,595	5	32,775	5
Rubber + fishery	58,466	3	47,733	4	51,502	1	40,476	3
Rubber + piggery	59,398	2	50,193	2	51,030	3	37,187	4

Source: extracted from Vishwanathan, 2008. The currency is Indian Rupiah.

Sri Lanka

The impact of shade is one of the main factors to take into account along with sufficient water for both rubber and the associated crop(s). Sankalpa et al. (2020), Penot and Ilahang (2023), and Chambon and Wibawa. (2023) identified the most common intercrops during the immature period to be peanut, maize, cowpea, chili and banana, and the most common intercrops during the mature period to be dairy cattle, pepper, cacao, Ceylon cinnamon (*Cinamomum* sp.*)*, passion fruit (*Passiflora)*, *Citronella* sp. (known locally as "pangiri"), and banana. Rodrigo et al. (2001) estimated that 25–50% of farmers in the traditional rubber growing areas in eastern Ski Lanka practice rubber-based agroforestry mainly combined with tea, banana, cinnamon, pepper, and pineapple during the mature period. Harvesting cassava or peanuts alongside clearing or burning weeds increases the risk of soil erosion whereas growing *Citronella* sp. reduces soil erosion.

Banana is the most widely reported intercrop (Rodrigo et al., 2001; Rodrigo et al., 2001) in Sri Lanka in both the established eastern rubber growing areas and in Moneragala/Ampara districts, which are new rubber growing areas in the west (Iqbal et al., 2006; Rodrigo, 2001) at normal rubber planting density (3 × 7 m or 2.5 × 8 m). The original planting design recommended in Sri Lanka for intercropping with banana was a single row of banana planted between rows of rubber trees planted at normal density (Rodrigo, 1997) to reduce competition for rubber as far as possible. In practice, it has been shown that banana planting density can be increased three-fold with no detrimental effect on rubber growth (Rodrigo et al., 1995; Senevirathna et al., 2010).

Sugarcane is a traditional high value crop in the dry and intermediate zones of Sri Lanka, particularly in Uva province where the market has been good for many years (Moneragala/Ampara districts). Sugarcane is grown under contract, i.e., local sugarcane companies provide inputs and contract to purchase the harvest. Intercropping rubber with sugarcane with rubber at the normal planting density in the first 5 years of rubber tree growth has been shown to improve the growth of rubber during the first 6 years as well as to protect the young rubber plants from drying out, which was confirmed by all the farmers in the area. Both the trunk girth and the height of the rubber plants were comparable with those in the traditional eastern humid zone (Rodrigo et al., 1995; Rodrigo et al., 2001).

Pueraria phaseoloides and *Calopogonium muconoides* are the most commonly grown cover crops. Farmers do not distinguish between the two species and locally refer to them both as “awarana waga” or “pohorawel”. Cover crops are apparently poorly adopted by local farmers.

The crops most often associated with rubber during the mature rubber period in the Moneragala/Ampara areas are cocoa, pepper and some timber trees at normal rubber planting density (Penot et al., 2023; Iqbal et al., 2006) and tea and cinnamon with double rubber spacing in traditional western rubber areas.

The association of rubber and tea with double spacing is quite common in the traditional western rubber growing area where tea is generally considered as moderately shade tolerant (Hajra and Kumar, 1999), but most of the tea which is grown as an associated crop is grown under full sun in systems with wide rubber inter-rows of between 18 and 25 m (Iqbal et al., 2016; Penot, 2004; Rodrigo et al., 2001).

In the eastern region, pepper is planted close to the rubber trees and uses the trunk of the rubber tree as a support, but according to recent survey conducted in 2023 with Laura Guilonnet (published in Penot et al., 2023), pepper is no longer popular because of severe local diseases particularly in Moneralaga, and because the local variety is not suitable for the local humid climate.

Some fruit and spice trees (soursop, mango, citrus, cinnamon) were tested with rubber in some demonstration plots at RRISL (Rubber Research Institute of Sri Lanka) but they were rarely adopted by the farmers as RRISL and DRD (Development of Rubber Division) had previously focussed on associating cocoa with rubber at normal rubber planting density. In practice, associating cacao with rubber at normal planting density does not provide good results because the shade provided by the rubber trees is far too dense after year 5. Timber trees, harvested before they are 10 years old, have been successfully associated with rubber in Uva province.

Countries where there has been no RAS in the mature period

Laos and Philippines have no experience of RAS as such, although some farmers may practice intercropping during the immature period. Cambodia and Myanmar have only used RAS in some trials conducted by researchers. In these countries RAS are not used either by smallholders or by estates.

In one province of Vietnam, there is some limited association of livestock with rubber in the immature period (Penot et al., 2022, FTA).

Cambodia

The rubber industry in Cambodia is currently expanding, with an increase in both smallholder plantations and private estates through "Economic Land Concessions" (ELCs), with almost 45% of plantations now owned by smallholders. This intensive development of rubber is a threat to the environment as most new plantations are created at the expense of local forests and cause soil degradation. ELCs and land ownership by smallholders are the main causes of deforestation in Cambodia (Diepart and Dupuis, 2012). Several tree species, timber and other species are under threat because of illegal logging and loss of forests. Ex-situ conservation of tree seeds began with Danida and Forestry Administration in the Cambodian Tree Seeds Project (CTSP, 2001-2006) with 21 species selected for planting in Kbal Chhay, Sihanoukville (Strange et al., 2007). The overall aim of the 2005/2008 study by Cirad and the Cambodian Rubber Research Institute (CRRI) was to reconcile associations of rubber and forest tree species and to expand the inclusion of timber trees in agroforestry. The specific goal of the study was to assess the long-term behaviour of simple associations of rubber and timber trees using double-row spacing but also to create a legal market for timber trees to compete with the illegal logging sector and combat deforestation, land grabbing, and soil erosion. The trial included rubber associated with 14 different tree species selected for their different characteristics and including high-value/endangered trees (particularly over-logged high-value species), well-known fast-growing trees in plantations plus trees that provide non-timber products. These kinds of plantations represent a long-term investment because many years pass before timber can be logged, and possible loss of rubber due to competition between species for water. High potential margins can be expected from timber trees, for instance, for *Dalbergia* sp., whose sale price can reach US$30,000/m3. The possibility of harvesting other non-timber products from the trees is also currently under study. Tree species that could be sources of complementary income are (i) *Dipterocarpus alatus* (oleoresin), but this species requires a long time before resin can be collected, (ii) *Moringa oleifera* (whose leaves and fruit are consumed as food supplements), and (iii) seeds of all the high-value trees that are collected to be sold. In 2023, the study is still underway on a 5.3 ha plot of the CRRI plantation at Chup (11° 57' N 105° 34' E), Kompong Cham Province, a historic rubber production centre in Cambodia. Maize was planted along with *Stylosantes guyanensis* in the first year after rubber was planted. *S. guyanensis* continued to be used as a regularly rolled cover crop from year 2 to year 5. Trees associated with rubber were planted in a 6.5 m × 6.5 m × 3 m pattern, while the rubber trees (clone GT 1) were planted using large spacing (16 m × 2.25 m) or rubber double-row spacing (14 m × 2 m × 2.5 m).

The tree species associated with rubber are (i) *Tectona grandis, Hopea odorata* using a simple (large) spacing pattern, and (ii) *Dipterocarpus alatus, Tectona grandis* using a double-spacing pattern. Other species used are *Adenanthera pavonine, Afzelia xylocarpa, Albizia lebbeck, Acacia auriculoformis, Coluta laccifera, Moringa oleifera, Sindora siamensis, troemia callyculata, Dalbergia bariensis, Pterocarpus macrocarpus, Dalbergia cochinchinensis* and *Xylia dolabriformis.*

A marked reduction was observed in the growth of rubber associated with *Acacia auriculoformis*, whereas when associated with teak plus a cover crop of *Stylosantes guyanensis*, rubber growth was only slightly affected. The observed effects of the growth of timber trees on young rubber trees differed: (i) small trees such as *Afzelia xylocarpa* and *Dalbergia bariensis*, had only slight effects on rubber tree growth, (ii) small trees such as *Hopea odorata*, had only slight effects on rubber growth, but their speed of growth increased when the rubber trees start to provide shade, (iii) medium size trees such as *Pavonina adenantera*, *Albizia lebbeck*, *Moringa oleifera*, *Dipterocarpus alatus*, *Sindora siamensis*, *Pterocarpus macrocarpus* had moderate effects on rubber growth, and (iv) fast growing trees, such as *Acacia auriculoformis*, had a major effect on rubber tree growth.

In the specific climatic conditions in Cambodia, where the "dry season" lasts 3 to 5 months, rubber production could be affected by the type of associated species. The length of the rotation remains an open question, since timber trees may have a longer lifespan than rubber. The economic perspective underlines (i) the extremely high performances of medium-term associations with high value timber species such as *Dalbergia* sp., which last 30 to 40 years, and (ii) the cost of leaving standing trees at the end of a concession. This possibility makes timber and rubber associations an attractive tool for afforestation, which could also be promoted by enforcement of a new law on ELCs allocations, requiring a minimum forest cover at the end of an ELC.

This trial has two probable main outcomes: (i) the need to carefully consider the planting design of rubber/timber trees in order to limit the risk of competition for water (and light) in a context of an increasingly constraining dry season under climate change, (ii) the possibility of creating a significant source of income at the end of the rubber lifespan to provide the capital required for replanting.

Myanmar

Some trials have been conducted in local research governmental stations. The rubber trees used in these trials are generally still young, i.e., in their immature period. The trials were designed as demonstration plots with the following combinations:

- coffee using normal and double spacing. In 2022, the coffee was not yet ready to be harvested;
- durian, banana and pineapple using double spacing;
- amarante (*Amarantgus* spp.), long beans, maize and food crops using normal spacing.

Conducting trials that include demonstration plots is a very promising way to convince local farmers of the possibility of developing RAS in Myanmar in the long run.

A study of rubber production in Tanintharyi region (Vagneron et al., 2017) reported some intercropping with rice when rubber was planted, followed in years 2 to 5 by cassava and pineapple. More rarely, the authors found areca nut (*Areca catechu*) and durian (*Durio zibethus*), during the mature period included in extensive agroforestry systems in the villages of Pyin Thar Taw and Thaung Thon Lon. In the moderately intensive systems in Thet Kal Kwat village, most farmers intercropped rubber with perennial cash crops such as areca and cashew nuts, with timber trees such as agar wood, and with fruits such as rambutan, banana and pineapple. Common intercrops in the intensive system in Pa Kar Yi village included rice at planting, followed by cassava and pineapple, or more rarely, by areca nut and durian.

Vietnam

Some preliminary trials were conducted in the 1990s in the area of Pleiku with rubber and tea but no monitoring was done. In the 2000s, a trial was conducted at the Rubber Research Institute of Vietnam (RRIV) in southern Vietnam using double spacing with 2 lines of rubber with 2.5 m between rubber trees × 4 m (between rubber rows) with an inter-row of 16 metres and one row of timber-rubber trees in between. The term timber-rubber tree refers to rubber trees selected for their better growth and capacity to also be used as timber at the end of their lifespan. No published data are available concerning that trial. Similar trials were conducted in Cambodia with other timber species.

⏩ The situation in Africa

Like in South East Asia, in Africa, rubber was introduced by colonial private estates primarily in the form of rubber monoculture. Smallholder rubber production developed later in the 1950s also based on monoculture, which was considered to be the best system for rubber. Farmers did not develop their own local agroforestry practices because extension services usually only permitted monoculture.

Côte d'Ivoire

Preliminary trials in the 1990s

The RAS trials in the 1990s at the National Rubber Research Centre of Côte d'Ivoire, (*Centre national de recherche Hévéa de la Côte d'Ivoire, CNRH*; Snoeck et al., 2013) included a comparative study of rubber as a monocrop with four rubber-based possibilities for diversification: rubber intercropped with coffee or cacao or cola or lemon, for which real data from a 17-year field trial in south-western Côte d'Ivoire were used. Rubber tree density for rubber monoculture was 510 trees/ha whilst that used in the intercropped system was 420 trees/ha. The density of the intercrops was 682 trees/ha for coffee and cacao (small shade tolerant trees), 55 trees/ha for cola and lemon (the trees are bigger and need more sunlight). Rubber tapping started in the 7th year. When Snoeck et al. (2013) calculated year-on-year cumulative return, defined as the sum of each year's gross margin, they found that, from year 3 to year 12, three diversified systems (rubber intercropped with coffee, cacao and cola) were statistically significantly more profitable than rubber monoculture from year 3 to year 12. The biggest difference was in year 10 when the cumulative return of rubber-coffee, rubber-cacao and rubber-cola was respectively, 98%, 65% and 22% higher than that of rubber monoculture.

From the 11th year on, the difference between the intercropping systems and rubber monoculture became progressively smaller and from the 13th year on, the rubber-cola combination became less profitable, but the rubber-coffee and rubber-cacao combinations remained more profitable using the double-spacing system than rubber monoculture although the difference was small. Intercropping rubber with lemon was less profitable from the 8th year on due to the sharp drop in lemon yield starting in year 6. Cola can be harvested between year 7 and 13 with peak yield occurring in year 10. This study (like other studies) showed that rubber latex yield actually benefited from the presence of intercrops, as the yield per tree was slightly higher than the yield obtained with rubber monoculture. However, the 17.6% reduction in rubber trees in the diversified systems needs to be offset by sufficient profit from secondary products. In the same RAS study, it was found that the growth of lemon and cola (both species need sunlight) was most adversely affected by shade from rubber and stopped producing in year 13, whereas coffee and cacao continued producing until year 17 although their yields peaked in year 7 and year 8, respectively. This explains why cola and lemon were less profitable than rubber monoculture, rubber-coffee or rubber-cacao combinations. However, it is possible that, if one considers the complete lifespan of rubber, the cumulative return of rubber monoculture is higher than intercropping with coffee and cacao.

Keli et al. (2005) studied both short and long-term intercropping. Data from 20 years of experimentation showed that intercropping food and industrial crops in the first three or four years after rubber planting was profitable. Food crops including upland rice, yam, groundnut, plantain banana, maize, and industrial crops like coffee, cocoa, oil palm, pineapple, coca and lemon trees, were found to be suitable intercrops. Rubber tree growth was improved by 29% under intercropping compared with growth in the control plot (rubber with a legume cover crop). The yields of the intercrops were moderate, but still profitable for the farmers. Some rubber-based crop rotation systems were thus recommended to small-scale farmers. The recommended three-year successions were yam – rice/peanut – maize/peanut, yam – rice/peanut – plantain, yam – yam – yam, plantain – plantain – peanut. The results confirmed the beneficial effect of food crops, in particular rice, peanut and plantain, on the growth of rubber trees, compared to the standard control rubber tree-*Pueraria phaseoloids* legume covercrop (Keli and De La Serve, 1988; Keli et al., 2005) Concerning light and shade, in some trials, measurements of the width of the crown of rubber trees indicated that five years after the rubber trees were established in permanent associations, 29% of the initial area reserved for crops (16 m) was shaded by the rubber tree canopy with the clone GT 1, while 38% was shaded by the PB 260 clone (Kouadio et al., 2021).

In this trial, the yields of associated crops were (i) low to mediocre for peanut (200 to 600 kg/ha) and yam (200 to 5000 kg/ha), (ii) average for maize (2,000 kg/ha) and (iii) satisfactory for plantain (7 to 21 t/ha), rice (800 to 3000 kg/ha) and cassava (10 to 30 t/ha). Then, after 6 years, the yields of both temporary and permanent crops grown in association with rubber dropped significantly. The authors concluded that increasing the width of the line spacing (16 m) was not sufficient to maintain the yields at a level that justify the cultivation of food crops in association with rubber (Kouadio et al., 2021).

Example of modelling rubber agroforestry

In Côte d'Ivoire in 2022, deforestation was almost complete. The role of cocoa as the main driver of deforestation and consumer of the "forest rent"[64] (Ruf, 1992) since the 1980s is well established. Surveys conducted since the 2000s found that rubber trees have mainly been planted on low-lying shrubby or fallow land, on land previously used for food crops, or in old cocoa and coffee plantations. The main constraint is

64. The forest rent is based on the fact that a new cocoa plantation will profit from net positive forest advantages in terms of soil structure and fertility and no diseases.

replanting cocoa once the forest rent disappeared, in other words once there is no more forest. Most rubber smallholders were cocoa farmers whose aim was to diversify by planting rubber.

Production of rubber by smallholders in Côte d'Ivoire proved to be enormously successful, approaching one million tons/year, with a boom in the last 15 years. A valid question is thus how diversifying to rubber affected the management of the "cocoa farms" and the changes this involved for their families.

As the economic results of growing rubber depend on rubber prices and the price of rubber has been very low since 2012, in December 2019, the authors conducted a survey of farming systems used by 150 cocoa/rubber smallholders in all the cocoa producing regions of Côte d'Ivoire, from Abengourou in the east to San Pedro in the west, with a focus on smallholders who lived in villages. Using the data gathered during this survey, several scenarios were designed to explore possible ways of improving the prevailing situation, including the adoption of rubber agroforestry (Biatry, 2021) through diversification with the aim of increasing the farmers' income. One limitation of the scenarios is the fact that it was only possible to interview a few local "absentee owners", especially the local elite, such as high-ranking civil servants, or lawyers.

The preliminary result of the survey confirmed that a major driver of diversification was the difficulty involved in replanting cacao on old cocoa cacao. Another result was that 25/35 years of rubber would make it possible to replant cocoa in better conditions than replanting cacao without a break. In this sense, choosing rubber can be interpreted not only as a mainstream strategy of income diversification but also a long-term strategy to make it possible to replant cacao in better conditions. In retrospect, if cocoa farmers had diversified with rubber, a "rubber cocoa complex" would have replaced the old "coffee-cocoa complex" that prevailed in recent decades.

Our scenarios show that diversifying as a way of facing the volatility of the price of natural rubber is the main advantage of the "RAS fruit tree" scenario, primarily aimed at improving sustainability. In 2023, the rubber industry in Côte d'Ivoire is facing several challenges: (i) the need for accurate estimation of the quantity of raw rubber material to be processed by local factories (because part of the rubber yield is exported as raw material), (ii) guaranteed access to Apromac[65] prices (the official price paid by local rubber factories), and (iii) promotion of further diversification through agroforestry practices in order to increase the gross margin of rubber plots and to maintain local farmers' interest in rubber despite lower prices.

Eight model farms representative of our sample of 150 farmers were therefore created together with their economic models using *Olympe* software (Penot, 2007). Different scenarios were tested to evaluate the impacts of price fluctuations, of changes in the type of labour used (family or hired), and of the implementation of rubber-based agroforestry systems. The results of the scenarios showed that the agronomic and economic performances of the farms varied, but that they still had many reservoirs of productivity. Payment at the official price, the use of family labour, and agroforestry systems are strategies farmers could adopt to stabilise and improve their agricultural income. The survey revealed that farmers frequently intercropped with food crops

65. Apromac : Association des Professionnels du Caoutchouc Naturel de Côte d'Ivoire.

(cassava, yam, peanuts, plantain, maize) in the first 1 to 4 years after establishment of rubber trees, which were planted at a normal density of 6 × 3 m.

Several model hypotheses were formulated involving different levels of certainty: (i) rubber cultivation occupies an increasingly essential place in farmers' income in Côte d'Ivoire and is a viable alternative to cocoa monoculture, (ii) the rubber marketing channel is one of the key factors that influences farmers' agricultural income, and (iii) rubber-based agroforestry systems are more profitable than monoculture and have positive environmental externalities.

Here we use the A2 farm type to illustrate the impact of all the scenarios. The A2 farm is representative of local farms in the area (see Biatry, 2021).

The RAS scenario with fruit trees

This scenario is based on the association of rubber and fruit trees:
– orange trees: 40 trees/ha producing a yield of 1,250 kg sold at 115 FCFA/kg (1 $US is 600 FCFA);
– cola trees: 30 trees/ha producing a yield of 300 kg sold at 350 FCFA/kg;
– mango trees: 30 trees/ha producing a yield of 900 kg sold at 110 FCFA/kg;
– avocado trees: 40 trees/ha producing a yield of 1,000 kg sold at 95 FCFA/kg.

To simulate the effect of competition with rubber for light, the fruit tree yields were reduced by 50% compared to those reported in the literature. Despite the relatively high production costs due to the use of inputs and hired labour, the adoption of RAS has a positive impact on agricultural income (Figure 3.1). Fruit trees represent a new source of diversification for rubber/cocoa planters and allow them to reach the threshold of 2,500,000 FCFA net agricultural income.

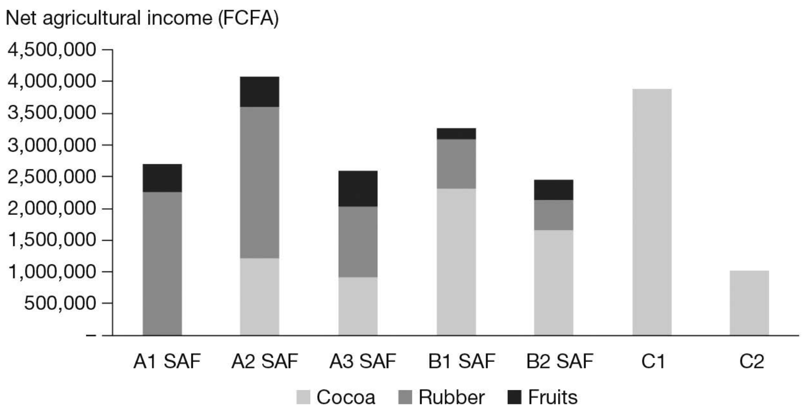

Figure 3.1. Net agricultural income from the different RAS cropping systems

The sale of fruits (oranges, mangoes, avocados, cola nuts) provides an extra gross margin/ha of 154,000 FCFA per hectare, thereby increasing the gross margin of the farm. The proportion of income represented by each type of fruit ranges from 21% to 33%: 33% for oranges, 24% for cola nuts, 22% for mangoes and 21% for avocados. The sub-types of farms (A3 and B2) which sell their raw rubber at the prices offered by "collectors" have a relatively low gross margin per hectare, and adding fruit trees increases their margin by respectively, 52% and 68% (Table 3.3). However, it is certain that the farm types based on rubber trees, and which are already present in the official Apromac sales channels (A1 and A2) are those most likely to be established (Table 3.3).

Table 3.3 Comparative analysis of the economic performance of each type of RAS farm

Farm Type	GM/ha rubber monoculture	GM/ha fruit based RAS	Difference (%)	Current agricultural income	Agricultural income Fruit based RAS	Difference (%)
A1	775,840	929,840	19.8	2,249,936	2,696,536	19.8
A2	768,085	922,085	20.0	3,596,064	4,073,464	13.3
A3	298,900	452,900	51.5	2,021,931	2,591,731	28.2
B1	642,830	796,830	24.0	3,086,910	3,271,710	6.0
B2	227,800	381,800	67.6	2,133,009	2,456,409	15.2

From the rubber tree's point of view, agroforestry is a "neutral" crop association: unlike agroforestry systems based on cacao, where shade can sometimes reduce the production potential of the cacao tree, rubber is not penalised by the presence of fruit trees, as when a maximum of 250 trees are associated with rubber per ha, it continues to dominate the canopy. In fact, it is the yield of the fruit trees that is negatively affected by the shade provided by the rubber trees compared with the yields of fruit trees growing in full sun.

The usual RAS scenario is based on the following items:
– rubber with 1 associated tree species (fruit tree, timber tree, coffee, cacoa) which produces a yield during the tapping period of the rubber tree (Snoeck et al., 2013). In this case, rubber is planted at the normal density (6 × 3 m);
– annual food crops can be planted between the rows of young rubber trees during the immature period, i.e., during the first 3 or 4 years.

The choice of associated crop focusses on the "best-bet" alternative between rubber trees and perennial crops. This is how the "AF/fruit tree" scenario was chosen, with fruit trees in the inter-row of rubber trees, with rubber planted at normal density. For this scenario, the species of fruit trees were selected because in a previous study on agroforestry practices in Côte d'Ivoire (Sanial, 2018), they had been observed growing in the cocoa plots. Cola, orange, mango and avocado trees were selected in addition because there was already a market (even if limited) for these products. Data on the yields and costs of the crops were taken from the *Agronomist's memento* (Cirad and GRET, 2006). To account for the effect of the shade provided by the rubber canopy on the fruit tree, yields of fruit were reduced by 50% compared to yields obtained in a conventional plantation.

A variant of this scenario was created that incorporates teak timber trees in the plantation. Teak requires little maintenance, and has the advantage that it can be exploited when the rubber trees themselves reach the end of their lifespan. The data were taken from a teak planting guide published by the National Agronomic Research Centre (CNRA) of Côte d'Ivoire (N'guessan et al., 2023).

The hypotheses in this agroforestry scenario are agronomic, economic and social:
– the inclusion of other trees has no impact on rubber yield as long as the density of other trees is less than 200 trees/ha and there is no canopy above that of rubber

(Penot, 2001). The neutral effect on rubber tree yield has been reported in other countries (Indonesia, Thailand) but remains to be confirmed in the case of the fruit trees selected in the scenario described here;

– structural market conditions may change in response to the supply of fruit. With the population of Côte d'Ivoire predicted to double by 2050, and a strong trend towards urbanisation, the market for fruit will probably increase;

– assimilation of the techniques used by planters and tappers in agroforestry cropping systems. In the past, companies did not recommend associating other crops with rubber, consequently industry players will need to play an active role in setting up this type of system.

Case study based on the A2 farm

The reason we chose to use the study of the A2 planter as an example was because it is the most "representative and balanced" farm, in the sense that the areas under rubber and cacao are almost identical. Above all, it represents a possible future for a large number of farms, with agricultural income primarily coming from rubber trees (raw rubber sold at the official price), and cacao representing diversification to face the risk of volatile rubber prices. This is the type of farm on which the most scenarios could plausibly be tested, with different variations (Figure 3.2).

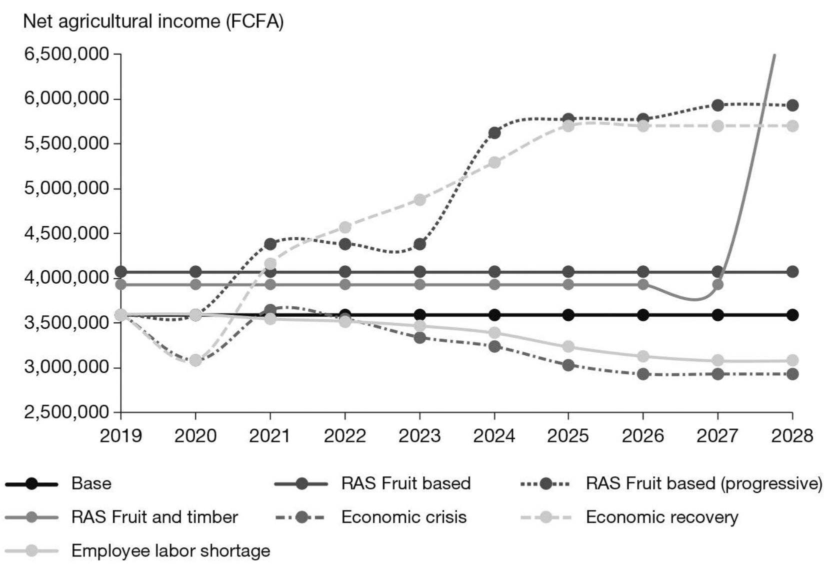

Figure 3.2. An example of one type of A2 farm: net agricultural income varies with the RAS scenario tested

The diversification of farm income for better resilience against fluctuating prices for natural rubber is the main asset of the "RAS Fruit tree" scenario, and this type of system could improve the sustainability of the rubber value chain in Côte d'Ivoire. The impact of the lack of a structured rubber industry is highlighted by the "collectors" price offered by sales intermediaries, which is the main factor explaining the different economic performances observed. This could happen again if rubber prices rise again and trigger a wave of new rubber plantations.

In 2024, the Ivorian rubber industry faces new challenges, in particular, (i) the real accurate estimation of the quantities of raw rubber material in order to adapt the potential quantity that could be processed by local factories, (ii) the guarantee all producers are going to be paid with the Apromac price, and (iii) promotion of more diversification through agroforestry practices.

Ghana

Many Ghanaian smallholders intercrop young rubber trees with shorter duration cash crops to increase their income (Tetteh et al., 2019; Malézieux et al., 2009; Langenberger et al., 2017). A promising species is *Thaumatococcus daniellii* which provides an extremely efficient sweetener with zero calories. It has been tested in African rubber plantations in Ghana with good results (Waliszewski, 2010).

In the 2010s, a trial was conducted with plantain banana at two different locations in the Western Region of Ghana. The first trial was conducted at the location of the Council for Scientific and Industrial Research-Crops Research Institute (CSIR-CRI) in Ellembelle district. The second on-farm farmer participatory trial, Tikobo No. 2 – Ehiamadwen, was conducted in Jomoro district. The conditions used were plantain monoculture (P) and three others, one with one row of plantain, one with two rows of plantain and one with three rows of plantain intercropped. The results showed that the system with three rows of plantain and two rows of rubber produces the highest yield for banana

Nigeria

In the 1990s, there were around 300,000 ha of old more or less abandoned rubber plantations (clonal or not), similar to jungle rubber. Today (2023) nobody can say how many of these old plantations still exist.

The main intercrops used during the immature period of rubber planted at normal density that have been recorded since then are cassava, maize, millet, plantain, yam, pineapple and leaf and fruit vegetables. The most common fruit crops grown with rubber in Nigeria are cherry, cola nut, bitter kola, pear, and *Irvingia*, as well as the rubber-livestock system, i.e., raising rabbits, snails, goats, sheep, pigs, and bees in mature rubber plantations.

In 2006, a study was conducted by Timothy U. Esekhade on rubber intercropped with melon/maize/cassava in year 1, melon/maize/yam/cassava in year 2, and melon/pineapple in year 3. This trial was an extension of an experiment started in 1993 (Esekhade et al., 2003, 2012). At the time the smallholders lacked extension services and access to technical information.

Later, another trial was conducted with the following crops: cherry (*Chrysophyllum albidum)* and avinger (*Irvingia gabonensis)* in the inter-rows of rubber (Wudpecker, 2014). Among the intercropping systems tested, rubber intercropped with cassava and plantain reached maturity earlier than rubber planted as sole crop or with tree crops (avinger and cherry) as intercrops.

Another experiment conducted by Esekhade (published in 2003) intercropped one, two, three and four crops selected among cowpea, soy bean, melon, maize and cassava with young rubber. The most robust girth of rubber samplings was observed in the rubber/soybean/melon and rubber/melon/maize systems, in the 1998 and 1999 seasons. Young rubber in the rubber/cow-pea system had the highest height increment rate. The area harvest equivalent ratio (AHER) revealed the comparative advantage of multiple cropping over monocropping. Rubber with melon had the highest AHER of 2.41 while rubber with soybean had the lowest AHER (1.20) of the intercrops.

A study by Mesike et al. in 2019 based on a survey of 200 smallholders on the adoption of rubber agroforestry in Nigeria reported positive differences in income for intercrops and mini-livestock but not for fruit trees in the rubber mature period.

Other countries in Africa

Except for temporary intercropping with annual crops in the first 3 years of rubber, no RAS is reported in Cameroon or Republic of Congo.

⏩ The situation in South and Central America

No RAS is reported in Mexico, but RAS is known to exist in Brazil and Colombia.

Brazil

Michelin conducted trials with palmito (*Bactris gassipaes*) in Brazil in the 1990s, but the results were not published. A similar system was tested in Guatemala on a private estate, apparently sucessfull but not published. Some rubber systems were transitioning to fruit based agroforestry systems in Tome-Acu in the 2000s, where rubber was associated with pupunha/palmito/chontaduro *(Bactris gasipaes*), at a density of 150 vines/ha including acai palm trees *(Euterpe olearacea)* and andiroba timber (*Carapa* spp.).

Another interesting association is rubber with acai/cupuaçu. These two fruit trees can be grown together perfectly as they occupy a different stratum and the acai palm provides a little shade for the cupuaçu (*Theobroma grandiflorum*). Other fruits can be associated with them: banana during the immature period of the cupuaçu, and pineapple during the first two years after rubber is planted. A third stratum could be occupied by slow-growing timber trees such as mahogany, teak, or ipe.

Other fruit trees mentioned by local farmers were Roocou/Achiote/Urucu (*Bixa Orellana*), guarana (*Paullinia cupana*), araçá/guave/cherry guava of China (*Psidium cattleianum)* — a different variety from the one observed in Colombia, which is called araçá for which there is a large juice and pulp market, comparable to the market for cupuacu in the Brazilian Amazon.

Columbia

Diversifying agricultural crops, including rubber, as alternatives to growing coca was a priority of the 1998-2005 Plante project in the Colombian Amazon, a pioneer area in the uninterrupted war waged by the government on drug lords and local guerrilla (FARC) until 2016. Plante was a presidential project launched in 1998 to offer local smallholders reliable and appropriate alternative crops to replace illicit crops and to put a halt to the associated violence. Rubber was identified as one of the most attractive and competitive crops for the purpose, as it is a reliable source of income since a good local market already exists for the product. It enables farmers to accumulate capital while simultaneously allowing them to invest in other diversified cropping or livestock systems (in particular fish ponds). In the 2000s, there was a fundamental change in societal demand in areas where colonisation is already past history and land-use has stabilised. The social cost of coca was considered unacceptable by local communities which led to a shift to less risky and less politically sensitive, but of course also potentially less profitable crops. Efforts have focused on competitive rubber monoculture or rubber-based agroforestry systems in partnership with the local rubber growers' association. The approach produced real social mobilisation and innovation capacities to cope with the social violence resulting from the cultivation of illegal crops and led to the adoption of more diversified and sustainable farming systems in the province of Caquetá.

Although cultivating coca originally provided a significant income, in the 2000s, this income no longer seemed sufficient for many producers located near cities who have other options, which is the case of rubber growers in Caquetá. The price of coca fluctuated considerably, an indirect effect of fumigation (undertaken to destroy the coca crop) and the social cost of coca. Most producers were looking for the return of social peace with guaranteed sales of their products (mainly fruit, milk and meat), fish farming, fruit crops, palmito, rubber, and to a lesser extent palm oil. These crops are profitable alternatives for agricultural development, and an elegant and sustainable solution for disengagement from — and ultimately the disappearance of — prohibited crops. Colombia has a long experience of what is historically and sociologically referred to as "Violencia".

The advantage of perennial crops, and in particular of fruit trees, is that a market already exists, particularly for "palmito/chontaduro" (depending on its use as a fruit or for heart of palm), and for the fruit trees that are typical of the region. For example, although *Bactris gasipaes* is successfully cultivated in Brazil for the production of palmito (Michelin perfectly mastered its cultivation in the Mato Grosso trials), this species requires careful management (between 3 and 15 years of age) for the production of chontaduro in Colombia, because *Bactris* grows much faster than rubber, overtakes it and can then quite simply prevent rubber growth from the 4th year on. Identifying the right species and the optimal densities can be achieved by setting up a full-scale experiment with small planters, with varying planting densities and different types of associations.

A participatory workshop was organised in 1999 with 4 groups of equal size in which the participants made suggestions for technical reference systems and associations of crops/intercrops with rubber for future experiments to test the technical feasibility of their proposals (Penot et al., 2012). Data from previous trials implemented by CORPOICA (the Colombian Corporation for Agricultural Research) were also used. In a plenary session, each group presented its results, which were then discussed by the group as a whole. The plenary session concluded that the interest of agroforestry practices, in particular the combination of rubber and Amazonian fruit trees, depends on the following criteria: (i) diversification of sources of income, (ii) flexibility of the system as a whole in the event of an excessive drop in the price of one or the other associated crops (in particular rubber), (iii) optimisation of work productivity, (iv) reduction in the overall cost of maintaining the agroforestry system (compared to the cost of running two monocultures), (v) the beneficial effect of the appropriate intercrop on rubber tree growth during the immature period, (vi) fighting *Brachiaria* spp. at the lowest cost (growing *Bracharia* spp. as an intercrop delays opening of the trees and tapping by 2 to 4 years), and (vii) priority in terms of growth in the immature period for rubber. The species tested in the above-mentioned trial are listed in Table 3.4.

Fast-growing timber trees (that are cut between 7 and 15 years of age) can be included in the system, but care must be taken to limit competition with rubber. Fast-growing timber species can be very aggressive, and it may be necessary to put off planting them until the second or third year after planting rubber. Non-climbing cover legumes, such as *Flemingia congesta* or similar plants, can be used to protect the soil, in anti-erosion lines, or along contour lines, or to fill the "gaps" between fruit trees.

The local shrubby legumes (*Albizzia falcataria*, cambullo (*Erythrina fusca*) including *Flemingia macrophylla*, which were tested by CORPOICA, were clearly too aggressive. Likewise, trees of the *Acacia mangium, Gmelina arborea* type should be avoided because they grow too fast. Although these tree species have advantages, for example, as a way to rehabilitate soils compacted by livestock farming, they are not right for associating with rubber, as we saw during our visits to the trial at the Macagual station in Caquetá in 1999 and 2001.

The association of rubber producers and the efforts to improve the technical itineraries of rubber-based agroforestry systems made in the early 2000s in order to compete with coca are evidence for this dynamism, for the strong capacity for social mobilisation and for the innovative processes underway in this region. The resumption of the war in 2003 put a temporary stop to the process. A peace agreement was reached in 2016. We have been unable to check if the agroforestry trend is still underway, but it remains an important source for successful diversification and an opportunity to break the vicious circle of coca cultivation, at least for local rubber growers.

⏩ Double-spacing systems: an alternative system for full-sun species associated with rubber

The double-spacing system could be a way to limit excessive shading of associated plants. Double spacing is based on a larger inter-row to optimise plant access to light for longer than the original 4-5 years with normal planting density. The system is based on double, or triple rows of rubber separated by 8, 10, 15, 20 or even 25-metre inter-rows. The wider the inter-row, the longer the associated crop can benefit from light and will produce more when subsequently shaded by the rubber trees. Several inter-row spaces have been tested (i) 12-15 m for cacao or 25 m for tea in Sri Lanka, (ii) 16 m with a double row of cacao with good yields for the first 12 years in Côte d'Ivoire (Snoeck et al., 2013), (iii) 20 to 25 m for 15 to 20 years of light for timber, fruit trees (Cambodia, Vietnam) or rice (Indonesia).

Double spacing systems generally contain fewer rubber trees per hectare (350 to 500 trees/ha) which, in some conditions, may reduce the rubber yield. Double spacing systems were not widely promoted by extension services until very recently (since 2020) when the search started for systems with a better gross margin per ha than standard monoculture.

Double spacing in Indonesia

All the double-spacing systems in Indonesia have only been tested in trials in research stations and have not been adopted by smallholders so far.

Since 2011, there have been significant changes due to low rubber prices, which seriously affected smallholder farmers' incomes and triggered the need for diversification. Some smallholders converted rubber plantations into oil palm or coffee plantations or grew annual crops such as maize and upland rice. Intensification through agroforestry is a potential way of preventing further conversion away from rubber to other crops. A study including a demonstration plot with double-row spacing was conducted in Tanah laut District, in South Kalimantan Province (700 ha) and in the Musi Rawas District, South Sumatra (400 ha). The study began in 2009 and ended in 2016 (Sahuri, 2016). The double-spacing system used wide row spacing (18 m × 2 m) × 2.5 m and a density of 400 trees/ha. Smallholders were thus able to cultivate intercrops such as maize, paddy, or cassava in wide inter-rows with sufficient light to obtain normal yields. The planting distance of maize as an intercrop was 40 cm × 10 cm, for paddy it was 75 cm × 20 cm, and for cassava 100 cm × 100 cm. The rubber clone used was PB 260. A survey of 50 smallholders showed that the rubber trees grew well. The trees could be tapped at the age of 55 months whereas in Indonesia, tapping usually starts at 60-70 months. The average yield of rubber was 1,500 kg/ha/year, which is quite satisfactory in Indonesian conditions. The yield of hybrid maize in the third year reached 5,000 – 5,500 kg/ha, that of Dayang Rindu upland rice varieties 2,000 – 2,250 kg/ha, peanut yield was 2,000 – 2,200 kg/ha, and cassava yield 16 to 19 t/ha. From an economic point of view, double spaced RAS with annual crops such as rice, maize or cassava is profitable as long as there is a strong demand for the crop concerned and, in the case of upland rice, if it can compete with irrigated rice.

The results of the study showed that with single-row spacing, the growth in the first year of tapping was slightly better than with double-row spacing but that the yield of latex from individual trees was the same in the two. The yield/ha of rubber was thus higher with standard single-row spacing because the planting density was higher.

Double spacing in China

Rubber and medicinal plants

A field experiment was conducted at the Experiment Farm belonging to the Chinese Academy of Tropical Agricultural Sciences, in Danzhou, Hainan, China, using the Reyan 7-20-59 rubber clone and two planting patterns: (i) single-row (SR) avenue planting 3 m × 7 m, and (ii) double-row (DR) avenue planting pattern (2 m × 4 m) × 20 m (Lin Weifoo, 1991). Although relatively fewer rubber trees were being tapped per unit area in the DR system, with 98% of SR, the yield per hectare was not significantly affected due to ithe higher yield per tree. In addition, the double-row system allowed more light to penetrate. When the overall performances of the two planting patterns were compared, the double-row system proved to be more suitable for long-term intercropping in rubber plantations. Due to the lack of markets, sales of some intercrops including *Alphinia* and *Oxyphylla* gradually decreased (Lin et al., 1999).

Rubber with tea, coffee and other crops

Combining rubber and tea was successful with large double spacing. Limited light penetration had previously been a major constraint to maximising land use using intercropping in conventional single-row rubber plantations. In 2002, a long-term field experiment based on a double-row pattern using the CATAS 7-20-59 rubber tree clone was set up to investigate whether land use efficiency could be increased by using double spaced intercropping. At the end of the experiment, the results showed that with the improved double-row system, 42-50% of the total land area could be used for intercropping with more crops (Huang et al., 2020).

Both annual and perennial crops were tested in the experiment: yam bean (*Pachyrhizus erosus* [L.] Urb.), peanut (*Arachis hypogaea* L.), maize (*Zea mays* L.), soybean (*Glycine max* [L.] Merr.), elephant grass (*Pennisetum sinese* Roxb.), ginger (*Zingiber officinale* Rosc.), common bean (*Phaseolus vulgaris* Linn.), arrowroot (*Maranta arundinacea* L.), coffee (*Coffea arabica*), cinnamon (*Cinnamomum cassia*), and cacao (*Theobroma cacao* L.) were planted when the rubber trees were mature. In China, 99% of coffee beans are arabica, which are mainly grown in high-altitude regions (700–1,840 m above sea level) throughout Yunnan Province. Robusta coffee is mainly planted in low-altitude regions (normally < 200 m) on Hainan Island (Liang et al., 2014; Zhang et al., 2014; Yang et al., 2021).

Among the annual intercrops tested, yam produced 74% of the yield it produces in monoculture. Peanut produced the lowest yield at only 38% of its yield in monoculture. Yields of intercropped arabica coffee (Catimor variety), which was introduced from Yunnan province, and local robusta coffee (Reyan variety) were recorded. Robusta coffee produced 1,226 kg/ha, equivalent to 35% of its yield in monoculture. Arabica coffee produced 1,319 kg/ha, close to its yield in monoculture. Double-row planting increases the light available to annual crops and other crops which, like coffee, require at least 70% light. Under the double-row system, Catimor arabica coffee is more suitable than robusta for intercropping with rubber.

The rubber/yam bean and rubber/Arabica coffee schemes were the two most promising intercropping patterns.

Impact of double spacing on rubber yield

In terms of rubber yield potential, Rodrigo et al. (2004) and Snoeck et al. (2013) reported that the rubber tree yields obtained using the double-row system were 77.1% and 87.7% of those obtained using the conventional single-row system. Similarly, from 2010 to 2018, the yields obtained in the double-row plot were 89% of those obtained in the single-row plot, due to lower rubber tree planting density. Although, from 2010 to 2018, the double-row system produced a significantly lower total yield of rubber (1,296 kg/ha) than the single-row system (1,445 kg/ha), there was no difference in rubber yield per tree between the double-row and single-row systems, confirming the results of other similar experiments.

⏩ Timber species

Timber as a challenge

The main challenge in timber RAS is including more trees in the different types of AFS in order to produce more timber and fuelwood at marginal cost because timber species actually profit from maintenance of both the main crop and of other associated trees. Most valuable timber species require the shade that is provided by AFS. In other words, it is far easier to include 5 to 10 additional timber trees in existing AFS that taken together add up to millions of ha (and will produce millions of albeit scattered individual timber trees) than to create new productive forests to grow valuable timber species which require high initial investment and continuous maintenance for 40/50 years.

AFS therefore offer a real opportunity. It should also be noted that farmers need trees in their production model, because even at a small scale, growing trees is advantageous because trees and agriculture are complementary, and because of the robustness of AFS in terms of technical itineraries. Indeed, at the scale of the planet, more trees are needed because of their role in mitigating climate change. Indeed, in some countries in West Africa, for instance in Côte d'Ivoire, the medium-term consequences of climate change for cocoa production are a cause for concern. Finally, farmers also have a financial need for timber trees as a source of income which can be exploited for the purpose of investment at the end of the lifespan of the main crop or when the farmer needs cash (with trees cut at 5, 8, 12 or 15 years like teak). But farmers can also use timber trees themselves, notably for building and construction.

AFS farmers could thus be the next timber producers: in terms of resources (low cost, low maintenance, good integration in AFS), they are the best placed to take up the challenge. Government policies should be aware of this opportunity and create favourable contexts and regulations to boost timber production. An appropriate regulatory framework is essential to secure farmers' investments and to guarantee the wood produced in tree plantations will continue to be used in the future.

During the period when the timber represented by rubber trees at the end of their lifespan was changing from being considered a waste product to becoming an economically important component of rubber plantation management (Killmann and Hong, 2000; Shigematsu et al., 2011, 2013), there were also reports of timber trees being included in RAS (Jongrungrot and Thungwa, 2014; Jongrungrot et al., 2014; Somboonsuke et al., 2011; Penot, 1997). In Thailand, the main tree species cited in the reports (Somboonsuke et al., 2011) were teak (*Tectona grandis*) and neem (*Azadirachta indica*). Since teak requires light, it needs to be incorporated during the early establishment stage of rubber and requires an appropriate light regime throughout the rotation. Many different timber species are associated with rubber in Indonesia. A wide range of spontaneous timber tree species associated with rubber were identified in the 1997 Cirad/ICRAF/SRAP trials (Table 3.5).

Since that 1997 survey, some of these species have been recently re-introduced in agroforests in the 2020s (Table 3.6), in particular in *tembawang* systems, or are protected when they emerge in natural regrowth in jungle rubber and RAS systems.

Table 3.5. Spontaneous timber species maintained in local agroforests and their uses

Local names	Latin names	Uses
Leban	*Vitex pinnata*	Timber, wood, spice, medicinal
Medang	*Litsea elliptica*	Timber, latex
Ramboutan	*Nephelium lappaceum*	Fruits, timber
Jengkol	*Pithecellobium jiringa*	Fruits, vegetable, timber, medicinal
Durian	*Durio zibethinus*	Fruits, timber
Pingam	*Artocarpus* sp.	Fruits, timber, vegetable
Cempedak	*Artocarpus integra*	Fruits, medicinal, vegetable
Lengsat	*Lansium domesticum*	Fruits, medicinal, handicrafts
Pekawai	*Durio* c.f. *dulcis*	Fruits
Mentawa	*Artocarpus* c.f. *anisophyllus*	Fruits
Nyatuh	*Palaquium* spp.	Timber, latex
Owan		Timber, handicrafts
Bungkang	*Polyalthia rumpfii*	Timber, spice
Belian	*Eusideroxylon zwageri*	Timber
Ubah	*Glochidion* sp.	Timber
Kemenyan	*Styrax benzoin*	Timber, latex, livestock feed
Tantang	*Buchania sessifolia*	Timber
Bidara	*Nephelium maingayi*	Fruits

Table 3.6. Useful spontaneous vegetation in rubber gardens in West Sumatra and Jambi that is not cleared by the farmers (1997 survey)

Fruit tree species		Medicinal plants	
Durian	*Durio zibethinus*	Sicerek	*Clausena* c.f. *excavata*
Nangka	*Artocarpus heterophyllus*	Sidingin	*Kalanchoe pinnata*
Rambutan	*Nephelium lappaceum*	Jirak	*Eurya acuminata*
Macang	*Mangifera foetida*	Sitawa	*Costus speciosa*
Mango	*Mangifera indica*	Bidaro	*Eurycoma longifolia*
Langsat and Duku	*Lansium domesticum*	Daun kasai	*Pometia pinnata*
Jambu	*Eugenia aquea*	Sikarau	*Cyrtandra* sp.
Petai	*Parkia speciosa*	Kunyit	*Curcuma domestica*
Mangosteen	*Garcinia mangostana*	Kunyit balai	*Zingiber purpurteum*
Jengkol	*Pithecellobium jiringa*	Sikumpai	Not determined
Kabau	*Pithecellobium bubalinum*		
Timber species		**Plants with other uses**	
Sungkai	*Peronema canescens*	Rimbang	*Solanum torvum*
Meranti	various genera and families, but esp. *Shorea* spp.	Daun kayu sibuk	

	Timber species		Plants with other uses
Kulim	*Scorodocarpus borneensis*	Damar	*Dipterocarpaceae*
Petaling	*Ochanostachys amentacea*	Kopi	*Coffea robusta*
Kumpabok	Indet.	Jambu monyet	.
Maraneh	*Elaeocarpus palembanicus*	Sitarak	*Macaranga* c.f. *nicopina*
Tamalun	Indet.	Dalo	*Macaranga javanica*
Kawang	Indet.		
Madang	Various genera and families but esp. *Lauraceae*		
Surian	*Toona sureni*		

In a survey conducted in 2022, as part of the Rubis project/RRII, other species were identified: kernang, a rattan like specie, gaharu (agarwood), various types of meranti, pulai (*Alstonia scholaris*), coconut tree and durian.

Potential timber trees in South East Asia

Malaysia

According to the Malaysian Timber Council (MTC, 2015), the eight recommended fast growing multipurpose trees species in Malaysia are *Acacia mangium* (acacia), *Khaya ivorensis* (African mahagony), *Tectona grandis* (teak), *Neolamarckia cadamba* (kelampayan), *Azadirachta excelsa* (sentang), *Octomeles sumatrana* (binuang) and *Paraserianthes falcataria* (batai).

Indonesia

Several timber species were cited by Jambi farmers during a GPSNR agroforestry workshop held in Jambi in September 2022 (Penot et al., 2022 GPSNR):

– Pulai *Alstonia angustiflia* (with FSC certification)

Similar to *Acacia mangium* in terms of uses. The wood is creamy white to pale yellow in colour, and slightly lustrous. The grain is straight and the texture medium. The grain is sometimes irregular or oblique. Latex canals are present. Density at 12% moisture content is 0.45 g/cm3. The blunting effect is normal; peeling is reported to be good but slicing is not recommended or is of no interest. Tools need to be kept sharp to avoid fuzzy surfaces. Filling is recommended for a good finish. Nailing is not good but gluing is satisfactory, although the glue dries rapidly and there is a risk of a blue stain appearing during drying. Pulai is not resistant to fungi and is susceptible to dry wood borers. Pulai can be used for several applications e.g. boxes and crates, matches, veneer, panelling, furniture, joinery, moulding.

– Medang *Litsea leytensis* Merr.

Good quality: but now rare since most forests have disappeared (Source ITTO).

Other names: Theptharo (Thailand); Medang serai (Indonesia); Medang lesah (Indonesia); Medang busok (Indonesia); Laso; Keplah wangi (Malaysia); Kepaleh;

Kayu gadis; Kajoe lada; Kajoe gadis; Gadis; Chintamula hitam; Safrol laurel (United Kingdom); Re huong (Vietnam); Thep tharo (Thailand); Karawa (Myanmar); Ki sereh (Indonesia); Safrol laurel (United States of America); Bunsod (Sabah); Keplah wangi (Sarawak); Medang kemangi (Malaysia); Rawali (Borneo); Selasihan (Indonesia); Teja (Sarawak); Teja (Malaysia); Huru (Indonesia); Medang (Indonesia). The Scientific Name Synonyms: *Cinnamomum sumatranum* (Miq.) Meissner; *Cinnamomum porrectum* (Roxb.); *Cinnamomum glanduliferum* C. Nees (Roxb.). The uses are: general housing, panelling, furniture and cabinets, luxury furniture, plywood and veneer, turning, tools, agricultural tools, containers, truck bodies, naval construction, other and musical instruments, handicrafts, shoes, coffin, moulding. Essential oils are obtained by steam distillation of medang. (Source ITTO).

– Mahang *Macaranga* spp.

A light density wood of poor quality. *Macaranga* spp. is a small tree which can grow up to 25 m in height and has a diameter at breast height (DBH) of 30 cm. This is an early successional tree that grows mainly in swamps up to 100 m above sea level. *Macaranga* spp. comprise 250 species, of which 30 grow in tropical Africa and Madagascar, and the rest in tropical Asia (from India to Indo-China, China, Taiwan and Ryukyu Island), throughout the Malaysian region, northern Australia and the east Pacific up to Fiji. Most of its diversity is found in Malaysia, where some 160 species grow, with an exceptionally high number of endemic species in Borneo and New Guinea (Sosef et al., 1998). Mahang wood is traditionally used for temporary constructions, especially for the parts of native houses which are not in contact with the ground. It can also be used for light frames, interior trim, moulding, shingles, packing cases and match splints. In the Philippines, mahang wood is a favourite material for wooden shoes. *Macaranga* produces high quality pulps and particle boards, cement-bonded boards and wood-wool boards. It is also suitable for the production of plywood, and is known to make good fuel wood.

– Berumbung/*Adina minutiflora*

Used for housing/doors and windows, etc.

– Nyatoh

Nyatoh is the trade name used for wood of a number of hardwood species of the genera *Palaquium* and *Payena* growing in rainforest environments in South East Asia, particularly in Indonesia and the Philippines. Nyatoh wood is reddish and most species are easy to work with and stain and polish well. It has a tight straight grain that resembles cherry wood. The surface is dark brown/red in colour. Nyatoh is generally considered to be a sustainable resource, but several species of related genera *Palaquium* and *Payena* are on the IUCN Red List due to overexploitation and an alarming reduction in their habitats. Rated as non-durable and as susceptible to insect attack. Common uses: furniture, plywood, interior joinery, and recently building solid-body electric guitars (Source Wikipedia).

– Mahoni

There are two types of mahoni: (i) *Swietenia macrophylla*, commonly known as Honduras mahogany, or big-leaf mahogany, is a species belonging to the Meliaceae family. It is one of three species that yield genuine mahogany timber (*Swietenia*), the others being *Swietenia mahagoni* and *Swietenia humilis*. Mahoni is native to South

America, Mexico and Central America, but naturalised in the Philippines, Singapore, Malaysia and Hawaii, and cultivated in plantations and as wind-breaks elsewhere. Unlike mahogany sourced from its native locations, trade in plantation mahogany grown in Asia is not restricted, and in 2024, the mahogany timber grown in these Asian plantations is the main source of international trade in genuine mahogany. The Asian countries in which the majority of *Swietenia macrophylla* grow are India, Indonesia, Malaysia, Bangladesh, Fiji, Philippines, and Singapore; and (ii) *Swietenia mahagoni*, commonly known as American mahogany, Cuban mahogany, small-leaved mahogany, or West Indian mahogany, is a species of *Swietenia* native to South Florida in the United States and islands in the Caribbean including the Bahamas, Cuba, Jamaica, and Hispaniola (this species is not grown in Asia).

Among the very durable heavy hardwoods are: balau (*Shorea* spp.), belian (*Eusideroxylon zwageri*), traditional in old jungle rubber, giam (*Hopea* spp.), malagangai (*Eusideroxylon malagangai*).

The majority of the light hardwood falls in either the moderately durable or the non-durable category.

Among the non-durable commercial timber species whose applications are limited to indoors or to environments where they will not be in contact with the soil or moisture are: light red meranti (*Shorea* spp.), jelutong (*Dyera costulata*), sesenduk (*Endospermum diadenum*) and mahang (*Macaranga* sp.).

List of Non-durable plantation species (10-year-lifespan):
- Acacia mangium,
- Acacia crassicarpa,
- *Acacia auriculiformis*,
- *Gmelina arborea* (yamane),
- *Azdirachta excelsa* (sentang) or neem tree.

Conclusions concerning the role of timber species in RAS

The main benefits of timber species in RAS are: (i) beneficial effect on the environment, better adaptation to climate change with more trees/ha that might mimic forest, improve animal biodiversity, (ii) good water conservation, prevent erosion, retain soil moisture, (iii) create capital for replanting at the end of the rubber lifespan, (iv) easy to integrate, and (v) local markets exist for use in housing, boat building.

There is a need for a more organised timber marketing chain: farmers do not receive their fair share of the margin along the value chain. It is important to promote optimisation of the timber chain such that farmers receive more of the profits. Some farmers prefer fruit trees, others may choose timber depending on their strategies. Tables S4 and S5 (Appendices) are a complete list of timber species that can be included in RAS for example, in Indonesia.

Incorporating native trees in rubber monoculture is another option that has already been tested. The aim is to mitigate negative environmental impacts and to provide alternative sources of income for farmers.

⏩ Conclusion

Farmers almost everywhere practice intercropping during the immature rubber period to ensure an income during the first 5-7 years when rubber is not yet productive.

It can be concluded that to be adopted at a large scale, and to permanently include other plants, intercropping must either to be very profitable or at least require little labour, as labour availability is becoming a real problem in many rubber producing countries. For rubber-based intercropping systems, profitability is closely linked to the following biophysical and economic factors (Langenberger, 2017; Penot, 2020):

– Biophysical interactions between rubber and inter-crops

Some species benefit from the shade provided by rubber trees (Guo et al., 2006). This is true of certain timber species and medicinal plants, but for most associated plants, shade is a real constraint. Other shade tolerant secondary species are (i) coffee and cacao (Snoeck et al., 2013) but with at the most, 30-40% shade, which is not compatible with the degree of shade provided by rubber planted at normal density, (ii) bamboo (Charernjiratragul et al., 2014) but which could compete too strongly for water, (iii) the leaf legume *Gnetum*/pak Lieng (Simien and Penot, 2011), and (iv) species such as camphor reported in Winarni et al. (2018), and cardamom. Species to avoid in RAS are those which require a lot of sunlight (citrus, some fruit trees (Snoeck et al., 2013), as well as species which grow taller than rubber.

– Lifespan of secondary species

The best-bet species are those whose lifespan resembles that of rubber. Some species live much longer than rubber (i.e. more than 35 years) including durian, petai, most tropical fruit trees and many timber trees. This may lead to a different strategy at the end of the rubber lifespan, i.e., the decision to change from rubber to long-term fruit/timber agroforestry systems. Examples of profitable combinations of rubber with durian and/or petai are reported in studies conducted by Somboonsuke (2001), Simien and Penot (2011), Stroesser et al. (2018), Winarni et al. (2018) and Wulan et al. (2006). The same applies to timber trees. Fast growing timber trees were generally found to be less profitable, as they have to be cut and replanted two or three times during the course of one rubber lifecycle (Wulan et al., 2006).

– Regularity of production of intercrops

The number of harvests ranges from almost daily (pak Lieng), two or more times a year (annual crops), once a year (most fruits and nuts) to one-off harvesting at the end of the lifespan (timber trees).

Regular harvesting implies higher labour costs but can improve the cash balance particularly for smallholder farmers with limited land resources. Timber trees harvested at the end of lifespan provide sufficient capital to cover the cost of replanting. But harvesting after 35 years is not a solution for rubber farmers who require a regular income (Stroesser et al., 2018).

– Planting density for rubber and secondary species

The standard planting density for rubber monoculture (7 × 3 m spacing), has traditionally been used by smallholders because most crop associations that use this density did not adversely affect rubber yield (Charernjiratragul et al., 2014; Penot, 2001). The optimal density of different species in a rubber agroforestry system needs to account for individual farming households' multiple goals (Gosling et al., 2020) as well as for the wider socio-economic-ecological environment. Double spacing systems enable higher productivity of associated crops in large inter-rows.

– Market value of rubber and associated species

To combine rubber with high value timber and fruit trees with good market stability is probably the best way to cope with fluctuating rubber prices. Durian (Simien and Penot, 2011) and tea (Guo et al., 2006) have been found to withstand price fluctuations. Durian has been identified as a desirable plant to complement rubber in both Thailand (Simien and Penot, 2011) and Indonesia (Winarni et al., 2018) as there are many stable markets for durian. However, what works in one region or country may not work in another area for environmental, political and socio-economic reasons. Despite the positive ecological benefits (Drescher et al., 2016), rubber agroforestry is still not widely used, particularly after the end of the immature period (Langenberger et al., 2017).

Additional income from intercropping, cash availability and improved return to labour are key requirements to increase the adoption of agroforestry (Penot, 2001; Gosling et al., 2020). Most current rubber agroforestry systems include both indigenous trees, as well as a range of livestock species but more rarely than plant production. Constraints reported in the literature are the additional labour requirements and local labour shortage (Guo et al., 2006; Snoeck et al., 2013; Stroesser et al., 2018), the necessary agroforestry knowledge and related skills (Somboonsuke, 2001; Penot, 2001), government policies (Penot et al., 2019), potential pests and diseases associated with the intercrop (Somboonsuke, 2001; Langenberger et al., 2017). Resilience is becoming a major concern for producers. RAS can contribute to economic and environmental resilience. Rubber-based agroforestry clearly has the potential to reduce most smallholders' vulnerability to rubber price volatility.

To promote RAS requires a reasonable understanding of the diversification processes used by smallholder farmers (Barrett et al., 2001) and of producers' strategies concerning tropical tree crops (Schrott and Ruf, 2014). More research is required on optimal density and density patterns, the proportion of different species of secondary crops combined with rubber linked with existing markets (Zeng et al., 2012; Zhou, 2000) and soil/climate conditions. Intercropping is currently purely market driven. Economic development linked with the proximity of cities and industrial centres also increases the availability of off-farm income options to the detriment of RAS. Table S6 (Appendices) summarizes the current situation of RAS in rubber producing regions worldwide. And Table S7 (Appendices) displays the total species encountered in RAS.