FROM JUNGLE RUBBER TO RUBBER AGROFORESTRY SYSTEMS

History of Rubber Agroforestry Practices in the World

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Chapter 1

Definition and history of RAS

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⏩ Rubber in Southeast Asia from 1900 to 2023

The rubber boom and the development of jungle rubber

This section has been originally published in 2004[8].

Rubber *(Hevea brasiliensis)* was introduced in Indonesia from Malaysia by the Dutch at the turn of the 20th century in North Sumatra and was originally cropped in private estates in the form of monoculture in the "estate belt", following the trend observed among English estates in the western part of Malaysia. At that time, the market for natural rubber was booming due to a constant increase in demand and is still sustained in 2024 by a permanent demand for around 14 million tons per year (world consumption in 2022). In the 1910s and 1920s, Sumatra and Kalimantan were sparsely populated, with 1-4 inhabitants per km^2. Shifting cultivation was the usual practice involving slash and burn of primary forest or old secondary forest[9], one or two years of upland rice cropping followed by a long fallow lasting up to 30/40 years depending on land availability. Land was plentiful and there was no particular pressure to force farmers to change to another system. The system was sustainable as long as the population remained relatively stable, which was not the case in Java. In Sumatra in the 1910s, rubber seeds were collected from estates in the north and then distributed or sold by Chinese traders and missionaries in the south (Riau, Jambi and South Sumatra provinces) creating a tremendous demand for rubber in pioneer zones. In Borneo, the first seedlings were introduced in 1882 (Treemer, 1864, cited in Dove, 1995). Seeds were distributed to the indigenous population in 1908 by the Sarawak government. In Kalimantan, rubber seeds were introduced in 1909 (Uljee, 1925, cited in King et al., 1988) and were spread by Chinese merchants and Catholic missionaries in the Kapuas river basin.

Farmers immediately saw rubber as a new source of income, and in addition, it was easy to integrate in their existing agricultural practices. They began to collect seeds from surrounding estates or existing plantations and started their own rubber plantations. Rubber was cultivated in a very intensive way on the estates using fertilisers and

8. Didier Babin (ed), 2004. *Beyond tropical deforestation. From tropical deforestation to forest cover dynamics and forest development,* UNESCO/Cirad, 488 p.
9. At the turn of the 20th century, the peneplains in Sumatra and Kalimantan were still largely covered by primary forest.

continuous weeding that required a high investment in labour and capital. Local farmers, along with spontaneous migrants, some of whom came from the estate sector, adopted their own system, according to their limited cash and labour resources. They planted rubber trees with rice after traditional slash and burn (*ladang*). Rubber trees then grew among the secondary forest. No weeding or inputs were required. This system is called jungle rubber (*hutan karet*). A higher planting density than that of estates is used in order to compensate for the loss of trees due to competition and depredation (between 800 to 2000 seedlings/ha). Eventually, after a longer immature period (8-15 years for jungle rubber compared to 5-7 years on estates), the number of trees that can be tapped (between 350 and 500/ha) is comparable. From the point of view of the estates, whose objective was monoculture, unselected rubber proved to be perfectly suited to this "new environment" (agroforestry), whereas in its original habitat in the forests of South America monoculture is not possible[10].

The emergence of the jungle rubber system

The jungle rubber system has been well described (Gouyon and Penot., 1995; Penot and Ruf, 2001) and from a botanical point of view, is defined as a "complex agroforestry system" (de Foresta and Michon, 1995). Originally this system implied fallow enriched with rubber trees. The lifespan of rubber (35 years) is the same as the traditional fallow period necessary to restore soil fertility and get rid of weeds. The Kantus Dayaks, considered jungle rubber (or rubber gardens) as "managed swidden fallows" (Dove, 1993). "*Swidden cultivators use simple land and labour resources within the swidden system to cultivate rubber*" as explained by Dove (1993). The suitability of rubber seedlings for agroforestry, with no inputs required, only marginal labour requirements at planting, and very limited risks are the factors that triggered the rubber boom. Labour requirements shifted from cyclic (a period of four months a year for upland rice) to permanent for rubber (from 6:00 to 11:00 a.m. every day) although with no competition between the two systems. The afternoons are still available for *ladang* activities (rain fed upland crops such as rice or groundnuts). Rubber proved to be the perfect crop to grow with rice. Beside land, labour is the main available factor of production. The main limiting factors are capital and technical information, but these were not necessary in the initial stages of setting up jungle rubber plantations. Thus, in the original farming system, rubber and *ladang* rice could be grown together satisfactorily. Rubber was never seen as an alternative to rice, although this is becoming less and less true due to intensification and the increasing pressure on land in some provinces as was the case in North and South Sumatra in 2002. In 1997 already and still in 2024, rubber, and in particular clonal rubber, provide income and return on labour far above that of upland rice (return on labour was 4 times that of rice in 1997, idem in 2022).

From a historical point of view, farmers changed to rubber not because they were obliged to (as were many farmers during the "forced crop" period from 1830 to 1870 under the Dutch) or were under pressure to change to another more intensive system

10. The rubber tree is a forest species whose original habitat is the Amazon Basin in Brazil. In this respect, farmers in Indonesia gave rubber a second chance to grow in its original environment: the forest. This was possible because there is no leaf blight (*Microcyclus ulei*) in Southeast Asian forests thus enabling wide dispersion of rubber throughout the sub-continent. In Amazonia, rubber trees only survive if they are isolated in forests and cannot be grown in pure plantations.

(as were Javanese farmers during the green revolution) but because it suited the local environment and was sustained by a constant market. It proved to be a safe and easy way to increase farm income without fundamentally disturbing local farming systems, at least in the beginning. Rubber enabled local farmers to improve their standard of living and welfare. At the same time, it enabled increasing numbers of migrants to settle permanently in these areas, either on a spontaneous basis or through transmigration programmes. These changes in both autochthone and allochthone populations triggered a change in population density and eventually led to increased pressure on available resources. The average population density in Sumatra was already at 35 inhabitants per km^2 in 1997 (30/50 in West Kalimantan), 120 in 2024, and land is becoming scarce in some provinces (North and South Sumatra, Jambi, Lampung).

The average area of jungle rubber per family is between 2.7 and 4 ha (Barlow et al., 1986; Gouyon, 1995). Rubber generates 55% for Barlow in 1982 to 80% for Gouyon in 1995 (Penot and Ruf, 2001) of the total farm income. Jungle rubber and shifting cultivation are not at all antinomic, as both systems can co-exist in local farming systems. The notion of "composite system" was developed by Dove (1993): *"there is little analysis of the relationship between the 2 systems (rubber as swidden agriculture with rice) and thus little understanding of why this combination historically proved to be so successful".*

Farmers profit from a no input/no labour rubber cropping system. During the immature stage, planting jungle rubber requires four days of additional work (Levang et al., 1997), which involves a certain amount of income diversification as the jungle rubber system also yields fruits, nuts, timber for housing a well as other products such as rattan and non-timber forest products (NTFP)[11]. The cost advantage of smallholders vs. estates in setting up a rubber plantation has been assessed at 13 to 1 during the colonial era (Dove, 1995), at 6 to 1 vs. estates in 1982, and between 3 to 1 and 11 to 1 vs. government rubber schemes (Barlow et al., 1982, 1989), showing that farmers always had very competitive cost advantages with rubber.

The fact that production per hectare of unselected rubber seedlings is very similar in monoculture and agroforestry systems shows that unselected rubber can compete and maintain its yield in association with a relatively high density of other trees (200 to 300/ha). However, this needs to be verified with improved agroforestry systems using clonal rubber. In the case of jungle rubber, the advantages are quite clear: no establishment costs (the use of unselected seeds with no monetary value, and no fertilisers), low labour investment (only a few additional days to plant the rubber as the land has been already cleared for upland rice) and no maintenance during the immature stage. These three components explain the success of jungle rubber, which became the biggest source of income for most smallholders in inland Sumatra and West Kalimantan. The disadvantages of jungle rubber compared with clonal plantations are the delay in production due to the longer immature stage and relatively low productivity.

The success of jungle rubber and the future of this cropping system

Jungle rubber was in fact very well suited to the situation farmers faced in 1900. Five conditions triggered the replacement of shifting cultivation by a sustainable rubber cropping system that was still being used by more than 1.2 million farmers in Indonesia

11. NTFP: medicinal plants, *gaharu*, resins, local vegetables, etc.

in the 1990s: (i) land was plentiful and unspoiled (primary forest; in this respect farmers profited from the "forest rent" theory proposed by Ruf in 1987)[12] and jungle rubber conserves soil fertility and biodiversity, enabling renewal of the system every 30 or 40 years. Land opportunity cost was low, and remains low in remote or pioneer areas on the outskirts of traditional rubber areas; (ii) the particularly satisfactory adaptation of unselected rubber to the forest environment in complex agroforestry systems; (iii) a labour pool was available in Java that enabled land colonisation by both local Dayak or Malayu farmers as well as Javanese transmigrants, who originally came as tappers for estates or sharecroppers for local farmers; (iv) the sustained demand for rubber and the pricing policy was almost always positive for farmers with continuous incentives for the further extension of land and an increase in production. In this respect, Indonesia is still very well placed on the world market with low labour costs and the capability of significantly increasing its production if more farmers change to clonal rubber. Demand is still sustained and will probably continue for the next 20 years as substitution with synthetic rubber is not possible for at least 10% of the total demand for rubber; the demand requires natural rubber with specific characteristics in terms of heat and shock resistance for the tyre industry; (v) no real alternatives were available up to the 1980s.

The ecological advantages of jungle rubber

It is clear that rubber initially triggered deforestation (Prasetyo and Kumazaki, 1995). Timber concessions (see the example of South Sumatra) originally had less impact on forest cover than any other land use. The paradox lies in the fact that in areas where the forest has disappeared, jungle rubber is now the main reservoir of biodiversity (de Foresta and Michon, 1995). In comparison with other land-use systems based on oil palm, coconut, coffee, cocoa or pulp trees, rubber agroforestry systems are among the best adapted to maintaining a certain level of biodiversity. Jungle rubber proved to be better adapted to this "new" environment than estates, especially as yields were comparable, with 500 kg/ha/year of rubber[13] (Djikman, 1951) as long as both farmers and estates used the same unselected rubber planting material, which was the case up to the 1930s.

Conservation of biodiversity is a spin-off of jungle rubber. Plant biodiversity in a mature old jungle rubber system is close to that of primary forest or old secondary forest (de Foresta and Michon, 1992, 1995). Environmental benefits in terms of soil conservation (Sethuraj, 1996) and water management due to its forest-like characteristics are also significant. The biomass of a 33-year-old rubber plantation (444.9 t/ha dry weight) is similar to that of humid tropical evergreen forest in Brazil (473 t/ha, from Jose et al., 1986, cited in Wan Abdul Rahaman Wan Yacoob et al., 1996, or Sivanadyan, 1992) or in Malaysia (475-664 t/ha, from Kato et al., 1978, cited in Wan Abdul Rahaman Wan Yacoob et al., 1996).

According to Sethuraj (1996), the potential photosynthetic capacity of rubber leaves is comparable to or even better than many forest species (about 1,150 g/m^2/year in a well-managed plantation). A total area of 10 million ha under rubber worldwide would fix about 115 million tons of carbon annually (of which 1/3 in Indonesia). Soil fertility is

12. See Clarence-Smith and Ruf, 1996.
13. Rubber yield is always presented as Dry Rubber Content (DRC) 100% and not as kg of raw material (rubber sheets or cup lumps) or litres (latex).

maintained or even improved (Sethuraj, 1996; Dijkman, 1951) as rubber increases the nutrient content of the upper layer of soil due to leaf litter (4 to 7 tons/year/ha; Sethuraj, 1996). Of course, removing rubber trees for timber implies considerable nutrient exports that must be replaced through equivalent fertilisation rates at replanting. Soil moisture is very high under rubber, which probably also leads to a faster rate of decomposition and better nutrient turnover. From a nutritional point of view, mature rubber is a self-sustaining ecosystem, unlike oil palm for instance. Nutrient cycling is likely to approach that of forest ecosystems (Shorrocks, 1995, cited in Tillekeratne, 1996). Farmers do not view these benefits as main components of the system but rather as incidental “gifts”, comparable to the “gifts” provided by the long-term fallow in the original system (“slash and burn, S&B). These “gifts” may be included in what Ruf called “forest rent” (1994), which provides advantages comparable with planting tree crops in a forestry or agroforestry environment as oppose to degraded land or land which is already cropped.

Historically, forest products formed the basis of commercial exchanges between “farmers-gatherers” and foreign traders like the Chinese as early as the 5th century AD, or the Arabs after the 9th century, for various products including resins, spices, nuts, or latex — gutta-percha[14] — for insulating marine telegraph cables in the 1840s (Dove, 1995). In the 19th century, rubber was also the product extracted from various other plants including creepers. Conserving biodiversity in agroforests is still considered to be a useful by-product by many farmers, in addition to the fact that agroforestry practices enable savings in both labour and inputs. This is particularly true in degraded and depleted areas like the low altitude mountains in West Sumatra in the Pasaman area or land that has been invaded by *Imperata cylindrica* (such as the West Kalimantan plains), as agroforests are a source of seeds for valuable fruit and timber trees. But of all these potentially profitable products, only rubber triggered the very large-scale development of agroforests (of which there were more than 2.5 million ha in Indonesia in 1997). Rubber became a strategic product as early as 1839 with the discovery of vulcanisation by J. Goodyear, and, later on, with the development of the tyre industry, which began in 1888, and accounted for 78% of world consumption of natural rubber in 2020.

Jungle rubber sustains development in pioneer zones

Four factors explain the rapid change in local agrarian systems and the adoption of rubber by more than 1 million farmers in Indonesia[15]. The first reason was the availability of rubber seeds on a large scale and at no cost (from estates and an increasing number of smallholder plantations) and the perfect adaptability of rubber as an enrichment species for fallows. The second reason was the apparently endless amount of available land and the possibility to extend plantations at a very large scale, originally using the river network. Rubber is not perishable, so its transport and sale is problem free. The third reason was the availability of labour from a reservoir of migrants from

14. Gutta-percha is a natural latex obtained from trees of the species *Palaquium spp*. Like natural rubber (from *Hevea bresiliensis*) from the rubber tree, gutta-percha is a polyisoprenoid, very rigid and partly crystallized at room temperature, which makes it much less elastic than natural rubber. It was used at the beginning of the 20th century to make golf balls.
15. Contributing to 3 million ha of which 2.5 million ha were under jungle rubber in 2001.

over-populated Java encouraged by estates contracting labour for their plantations and also spontaneous migration, which was later followed by official transmigration programmes[16]. The last reason is the fact that planting rubber represents a land-acquisition process that gives the planter land and tree tenure very similar to that of full ownership, at least under the traditional law ("*adat*" in Indonesian).

These factors relate to pioneer zones. Land and labour being almost inexhaustible (at least so it seemed up to the 1990s), success was guaranteed by a plant that required no capital investment or major labour at planting and could easily be integrated in local farming systems along with agroforestry practices that had already been developed in other agroforestry systems (such as *tembawang*[17] in Kalimantan or durian or durian/cinnamon and damar agroforests in Sumatra).

The three stages of jungle rubber development

Historically, rubber expansion can also be characterised in three stages. The first stage, from 1900 to the 1930s, was the enrichment of fallow with unselected rubber (improved fallow). Rubber was considered as a source of income but for obvious reasons connected with the need for a food supply, priority was still given to rice as the main staple food in shifting cultivation. Farmers rapidly shifted to the agroforestry rubber-cropping system and rubber became their main source of income as a result of the constant improvement due to selected farming practices. The second stage, from 1930s to the 1990s, was the shift from an improved fallow based on rubber to a real rubber-based complex agroforestry system that integrated some cultivation practices: planting in line, selective weeding at specified intervals, selection of associated trees, etc. The third stage, from 1990s to the present day, was when external technical innovations (such as clonal planting material, use of herbicides to control *Imperata cylindrica*, pesticides and fertilisers) were integrated in jungle rubber in order to improve land and labour productivity. In this way, jungle rubber was progressively transformed by some farmers into improved Rubber Agroforestry Systems called RAS.

In the 1980s, only 8% of rubber farmers were affected by government rubber programmes, vs. 16% in 2002 (unknown in 2024). A total of 350,000 ha has been planted or replanted as productive plantations in 1998. Meanwhile, 94% of intensive irrigated rice farms were involved in government programmes during the green revolution (Booth, 1988). Consequently, the diffusion of techniques, skills, and information on improved rubber was perhaps limited, although all farmers knew about and wanted to acquire clonal rubber. The commodity system did not benefit from a "first priority" government development policy, as was the case for rice with the objective of self-sufficiency. One major challenge is to ensure the diffusion of certain technical innovations, in particular clonal planting material, to farmers irrespective of the rubber cultivation system they use (monoculture or agroforestry), which would result in the full recognition of the advantages of agroforestry practices as a true component of cropping systems.

16. Some of which focused on tree crops and particularly rubber (NES: Nucleus Estate Scheme programme).
17. Tembawang are local timber/fruit-based agroforestry systems developed by Dayaks people in west Kalimantan and are still very popular in 2024.

During the colonial era, each time a natural resource was the subject of a commercial boom, active restriction measures were taken by the government to control and restrict its exploitation (Dove, 1995). Spices in the 18th century, in particular *jelutong* (from *Dyera* spp.), rubber (through the "international Rubber Regulation Agreement" from 1934 to 1944), as well as other timber such as teak (in the 1820s) are examples of such policies. In 1997, farmers did not have the right to exploit, cut and sell their timber trees if the land was classified as "forest area". Forests officially cover 74% of Indonesia and are under the control of the forestry department. This "tree tenure" policy was clearly restrictive and did not provide any incentive for the improvement or optimisation of timber production in agroforests outside the estate sector. Consequently, timber products from agroforests, and in particular in the jungle rubber system, could not be adequately valorised, underlining the fact that agroforestry practices were not officially considered to be "modern and efficient". By comparison, oil palm monoculture, which uses large quantities of fertilisers and capital, is considered a "modern" tree crop. Tree tenue was modofoed in the 2010s and farmers have in 2024 the right to cut and sell timber trees which changes drastically farmers strategies on timber.

Rubber drove "*a shift from a tribal political economic formation to a peasant formation*", as defined by Dove (1995) in Kalimantan. In other words, technically, it implied a shift from gatherers to real rubber planters after a stage of extensive rubber cropping through a fallow enrichment process. Politically, this situation led to a "contest" between the State and farmers in 1997, which in 2024 is still reflected in policies concerning rubber, wood, timber, oil palm, and in policies implemented in transmigration areas where tree crops were forbidden (such as food crop-based transmigration schemes in West Kalimantan until 1991). These policies did not take into account the fact that local traditional systems have proven their sustainability and their ability to adapt to economic development. In this respect, they are in fact "modern", at least in the opinion of the authors of this work. Policies have been focused on monoculture (oil palm, rubber, coconut, etc.) as they are far easier to develop using the well-known "technological package" concept.

It is important to note that, historically, farmers moved to rubber not because they were forced to in any way or were under pressure to move to another or more intensive system (like Javanese farmers during the green revolution), but because it suited the local environment and was sustained by a constant market, and consequently offered farmers the opportunity to easily increase their income. Rubber has given local farmers an opportunity to improve their livelihoods. At the same time, it enabled migrants to settle in these areas in increasing numbers thereby triggering a change in population density and putting pressure on available resources. Average population density in Sumatra is in 1997 35 inhabitants/km^2 and land is becoming scarce in some provinces (North and South Sumatra, Lampung).

According to Dove (1993), "*the comparative ecology and economy of rubber and upland swidden rice result in minimal competition in the use of land and labour, and even in mutual enhancement, between the two systems.* The notion of "composite system" was developed by Dove (1993).

The consequences of this low-level farm management are (i) slow and heterogeneous rubber growth and long immature period or late reaching tappable size (8 to 12 years after rubber planting), and (ii) rapid forest regrowth.

Rubber and fertility

Rubber increases nutrient content in the upper soil layer due to leaf littering (4 to 7 tons/year/ha; Sethuraj, 1996) and low nutrient export through latex (Between 20 and 30 kg N.P.K.Mg/year/ha; Tillekeratne, 1996; Compagnon, 1986). Of course, rubber wood extraction involves high nutrient exports that will need replacing through high fertilisation rates at replanting. Soil moisture is very high under rubber, probably also accelerating decomposition and improving nutrient turnover. Mature rubber is a nutritionally self-sustaining ecosystem, unlike for instance, oil palm. Nutrient cycling is likely to approach that of forest ecosystems (Shorrocks, 1995, cited in Tillekeratne, 1996).

Biodiversity

With rapid deforestation underway in Sumatra since the 1970s, rubber agroforests are becoming the most important forest-like vegetation cover in substantially large areas in the lowlands (Joshi et al., 2000). While jungle rubber cannot replace natural forest in terms of conservation value, the question whether such a production system could contribute to the conservation of forest species in a generally impoverished landscape is very relevant. Jungle rubber is itself a major reservoir of forest species and provides connectivity between forest remnants for animals that need larger ranges than the remaining forest provides. This leads to a diversified tree stand dominated by rubber, similar to a secondary forest in structure (Gouyon et al., 1993).

Michon and de Foresta (1996) concluded that overall, vegetation diversity is reduced to approximately 50% in agroforest and to 0.5% in plantations (Figure 1.1); but these estimates are based on plot-level assessments. Similar findings were reported for plants, birds, mammals, canopy insects and soil fauna by Gillison and Liswanti (2000), who, in their investigation, covered a wider range of land-use types, from forest to

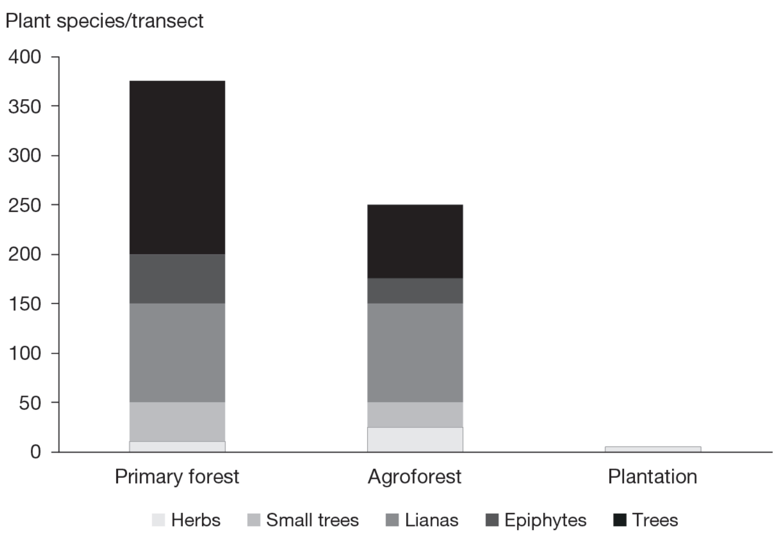

Figure 1.1. Comparison of plot-level plant species richness in higher plants between natural forest, rubber agroforest and rubber plantation (de Foresta and Michon, 1995)

Imperata grassland. Studying terrestrial pteriodphytes, Beukema and van Noordwijk (2004), also found that average plot-level species richness did not differ significantly in forest, jungle rubber and rubber plantations, however at the landscape level the species-area curve for jungle rubber had a significantly higher slope parameter, indicating higher beta diversity.

Of all the plants that are abundant in traditional rubber gardens, be they spontaneous or managed, about one third are used (Table 1.1), including timber species and non-timber forest products (Table 1.2). "Timber" uses are divided into fuelwood (mainly low-quality timber) as well as house construction and furniture making. In areas where there is no more natural forest within reach of the villages, however, traditional rubber gardens have become the main source of timber for the local population (de Foresta, 1992a). In these areas, timber from rubber gardens is already being sold, pointing to a prospective source of income that could be increased by the planting of valuable timber species.

Non-timber uses include food (i.e. fruit and vegetables: edible shoots and pods). Planted fruit tree species include durian, petai/stinkbean, jengkol, rambutan, mango, jackfruit and mangosteen (see Table 1.2 for Latin names). Petai and jengkol, both members of the family Mimosoidae, do not yield sweet, juicy fruits, but pods whose seeds are eaten raw or cooked as a vegetable. Legumes and many fruits fetch high prices in urban markets and could probably be sold if transportation could be provided. Some fruit tree species, like langsat and carambola, are only planted in the village area because they are said not to grow well in shady forest conditions. In Sumatra, as opposed to Kalimantan, some mango species (macang, kwini, mangga golek, mempelam) were also mainly found within the village area.

Other NTFPs are medicinal plants and handicraft materials, especially rattan, pandanus and tree bark, but also timber used to craft special items (e.g., machete sheaths). Latex and resin from rubber agroforestry systems are also sold (e.g., Hevea-latex, the latex of some Sapotaceae (nyatoh/*Palaquium* spp.) and Apocynaceae (especially *Dyera costulata)*. Apart from these, few products are harvested to sell for cash. Worth mentioning, however, is tengkawang, or illipe nut, harvested from Dipterocarpaceae and cultivated in West Kalimantan by the local Dayak population. Forest gardens, including tengkawang, are named *tembawang.* They usually contain fruit trees and sometimes rubber (Penot et Werner, 1997). Other uses of plants growing in rubber gardens are for ceremonial purposes, as ornamentals, thatching materials for field huts, fruits used as fish feed, or latex used to trap birds.

The data presented above prove the strong relationship between rubber garden bio-diversity and the presence of useful species. About two-thirds of all species present in rubber agroforestry systems have one or more uses. In the quest to increase the yield of rubber gardens, it is therefore important to search for systems that provide optimal growing conditions for improved rubber varieties, but still allowing a major part of the biodiversity of traditional gardens to persist: one of the objectives of SRAP activities Cirad/ICRAF (1994/2007).

Modern rubber agroforestry systems have to be able to integrate local wisdom about useful plants because in times of shrinking forest reserves, these systems might soon be the only ones still harbouring these species over large areas. Preserving biodiversity, therefore, also means guaranteeing the access of local people to these plant resources for their daily needs (Werner, 1993).

Table 1.1. Number of useful plants found in traditional rubber gardens in Jambi, West Sumatra and West Kalimantan

Province	**W-Sum**	**Jambi**	**W-Sum**	**Jambi**	**Jambi**	**Jambi**	**Jambi**	**W-Sum**	**Jambi**	**Jambi**	**W-Kal**	**W-Kal**
Plot N°.	LM 9	DB 2	LM 7	P 8	P 9	DB 16	P 5	LM10	P 6	P 16	E 1	S 1*
Plot age	65	25	20	20	60	50	20	65	60	60	60?	70?
Cleared/not cleared	(yes)	yes	yes	no	no	(yes)	no	(yes)	no	no	no	no
TIMBER												
Construction, furniture	3	6	3	5	6	6	6	5	8	9	17	35
Fuelwood	3	14	14	6	3	20	6	11	6	6	n.a.	n.a.
NON-TIMBER												
Fruits	7	2	3	8	5	2	6	7	8	11	20	25
Vegetables		1	2	2	3	1	1	1	2	2	1	4
Medicinal	4	2	6	2	3	5	4	12	3	4	2	3
Handicraft		1			2	1	2	1	3	2	5	4
Latex and resin	1	1	1	2	2		2	1	2	2	5	-
Sold for cash						1					1	1
Other	7	7	5	10	8	9	9	10	11	12		1
Total**	**23**	**30**	**30**	**33**	**32**	**37**	**35**	**44**	**40**	**45**	**37**	**49**
Total Biodiversity	**40**	**40**	**48**	**48**	**50**	**61**	**55**	**73**	**61**	**73**	**69**	**126**

*Plot size 2,500 m^2 as opposed to 1,000 m^2 for other plots. *Tembawang*, no abundant rubber. **Less than the sum of uses, because some species have more than one use.

Table 1.2. Useful spontaneous vegetation found in rubber gardens not cleared by farmers in West Sumatra and Jambi

Fruit tree species		Medicinal plants	
Durian	*Durio zibethinus*	Sicerek	*Clausena* c.f. *excavate*
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	indet.
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	indet.
Kulim	*Scorodocarpus borneensis*	Damar	*Dipterocarpaceae*
Petaling	*Ochanostachys amentacea*	Kopi	*Coffea robusta*
Kumpabok	Indet.	Jambu monyet	indet.
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*		

Jungle rubber is a balanced, diversified system derived from swidden cultivation, in which man-made forests with a high concentration of rubber trees replace fallows with a structure and biodiversity similar to that of secondary forest. Jungle rubber has accommodated increasing population densities, while preserving a forest-like environment. Yet farmers' income from jungle rubber has been declining since the 1990s due to the exhaustion of forest reserves, reduced land availability, low rubber prices, low yield and competition with oil palm. Short-term, small-scale credit schemes could help farmers adopt high-yielding rubber varieties which already emerged as a real necessity in 1997 with the introduction of oil palm in rubber areas. New options are thus needed to improve farmers' incomes with minimal call on government funding. In fact, the Indonesian government already stopped providing any help in 2001 at the end of the SRDP[18]/TCSDP rubber development projects. This led to the development of research on RAS based on clonal rubber which could be achieved by trying to preserve some of the advantages of jungle rubber including low maintenance and income diversity.

⏩ The development of clonal rubber-based agroforestry plantations: a new challenge

From improved or enriched fallow to a complex agroforestry system: the importance of rubber planting material

In 2002, as since the beginning of the 1900s, most farmers still relied on unselected rubber seedlings for their jungle rubber system, whereas estates and project farmers had all started using clones. Rubber clones[19] have proven to be the best planting material in terms of yield and secondary characteristics[20].

In the 1930s, researchers tried to compare "estate" monoculture and smallholder jungle rubber. Some even tried to integrate limited weeding through the "bikemorse system" in Malaysia (cited by Sivanadyan et al., 1992) or through "jungle weeding" in Indonesia (mentioned by Dijkman, in 1951, referring to a researcher with a private company in the 1930s). Experiments of this type were considered as failures in both cases, which resulted in rubber monoculture being considered as the only relevant technology for both estates and smallholders. This was the prevailing view until today in most private and public research centres.

The importance of the adoption of clones

Yields of clonal rubber obtained by estates in Indonesia or by the best farmers in the SRDP rubber scheme (In South-Sumatra, Prabumulih, DGE) ranged between 1,400 and 1,800 kg/ha in 1997. In 2024, non-project farmers who use clones obtain yields ranging from 800 to 1,500 kg/ha/year depending on tapping quality and leaf diseases impact on their plantations.

Other improved rubber planting material available in the 1990s were clonal seedlings (seeds from plots planted with 1 clone), which are not often used due to poor performance, and polyclonal seedlings (seeds from an isolated garden planted with several selected clones). In Indonesia, there is only one estate (London Sumatra in North Sumatra) able to produce real polyclonal seedlings (BLIG)[21]. Polyclonal seedlings (from Bah Lias Isolated Garden in North Sumatra) , which were popular with

18. SRDP: Smallholder Rubber Development Project, a World Bank scheme that lasted from 1980 to 1990 and was replaced by TCSDP: Tree Crop Smallholder Development Project (same scheme) from 1990 to 1998.
19. Rubber clones have been selected in national research stations (Bogor, Medan in Indonesia, Prang Besar and RRIM in Malaysia and RRIC in Sri Lanka are the best known). The minimum required for the multiplication of clonal planting material through grafting is a budwood garden, a rootstock nursery and grafting skills.
20. The first "generation" of clones was released in the 1930s, the second in the 1950s, the third in the 1960s and 1970s. The fourth generation of clones, which was released in the 1990s, is still under investigation or undergoing preliminary small scale testing by estates. Currently, estates and rubber development projects are still using the best third generation clones, such as RRIM 600, PB 260, RRIC 100. However the most widely planted GT 1 clones in Indonesia date from the first generation (released in 1922 in Bogor).
21. BLIG: Bah Lias Isolated Garden, London Sumatra, North Sumatra.

the estates in the 1950s and 1960s, have generally been abandoned and replaced by clones, which are more homogeneous, better adapted to high levels of production and which have good secondary characteristics (resistance to diseases), in particular the clones of the 3rd generation that have been available since the 1970s. Clonal rubber is therefore the first most important innovation to be adopted by farmers (also the case for improved varieties used in other systems). In other words, the IGPM (Improved Genetic Planting Material) revolution has not yet stopped giving rubber farmers a reliable reservoir of productivity.

A key question: Is there a specific best clone for RAS?

Historically, there has been no choice of a specific clone best adapted to agroforestry. Most farmers developed their RAS with locally available clones, mainly GT 1 and PB 260 in the 1980s and 1990s. This is still the case in 2024 as one of the the main constraint is still clonal planting material availability and clone adaptability.

In 2024, varietal improvement is focused on two major objectives, improving yields on the one hand, and on the other hand, sustainable production, i.e., resistance to disease and reduction in the length of the immature period. It takes about 25 years to recommend new clones. Adaptation to new climate conditions and in particular drought during the dry season through the global climatic change might be also a new priority. The main problem for smallholders when replanting, aside from choosing the right clone for their local conditions, is universal access to good quality clonal planting material, and for nursery owners, access to good quality clonal budwood gardens. In the meantime, farmers need more information about new clones or those more adapted to RAS, climate change, etc.

Rubber breeding has been devoted to promoting latex and latex/timber clones for monoculture through selection based on latex yield, tree growth to reduce the immature period, and disease resistance. There are several obstacles to the development of efficient rubber production systems: (i) the low level of adoption of innovation by farmers; (ii) the low quality of planting material available to farmers compared with that available to estate plantations; (iii) the long process of breeding and recommendation of clones (25-30 years); (iv) the spread of diseases (old and new) and climate change.

For these reasons, breeding programmes need to undertake multi-disciplinary research and to use participatory approaches to improve the design of solutions for smallholders and the impact of innovations as well as to speed up long conventional breeding programmes.

Rubber-based agroforestry systems have higher land productivity and biodiversity than monoculture but little is known about their adaptative capacity in response to climate change. Competition with associated crops may increase in the future. Consequently, breeding for RAS should integrate the most advanced technologies to predict the potential of rubber clones in such a system.

Use of physiological traits for early selection of rubber clones for agronomic traits

High-yielding clones are identified after five years of production in small-scale clone trials (SSCT). If the 5-year immature period is included, SSCT last 10 years.

Application of the latex diagnosis-based clonal typology is an interesting tool to predict both the production potential of clones and the appropriate frequency of ethephon stimulation[22] for each clone (Gohet et al., 2003).

Predicting susceptibility to tapping panel dryness (TPD) is another challenge. A small percentage of TPD-affected trees are identified every year, but after 10 or 15 years of production, this can reach up to 30% (Okoma, 2011). Putranto et al. (2015) showed that early TPD occurrence can be induced in TPD-susceptible clones after six months of tapping under a severe harvesting system (Herlinawati et al., 2022; Putranto et al., 2015). These two methodologies are being tested in 2023 in the framework of the Rubis Project[23] with the aim of reducing the duration of SSCT from 10 to 6 years and obtaining reliable results more rapidly.

Modelling tree architecture

Knowing the architecture of rubber trees is essential to predict timber production, the capacity to provide shade for associated crops, and resistance to wind damage. The Water, Nutrient, Light Capture in Agroforestry Systems (WaNuLCAS[24]) model was used to evaluate and understand the impact of crop management on inter-cropping scenarios and competition between rubber and associated annual crops. Improvement of such modelling systems is necessary using architectural traits such as height, girth, branching and canopy typologies. The susceptibility of rubber clones to wind damage was determined using ground-based mobile LiDAR[25] (Yun, 2019). These technologies have to be implemented in breeding programmes to select rubber clones that are resistant to the extreme natural disturbances linked to climate change, and also to better estimate the wood production potential.

The need to study eco-physiological traits

The frequency and intensity of El Niño and La Niña make water stress an important selection criterion for future rubber clones. The competition for water between rubber and associated crops in RAS will be further exacerbated in the future.

Many studies have been conducted to characterise drought tolerant rubber clones. Clone RRIM 600 is one of the best clones planted in drought areas in North East India and Thailand, for instance. The development of simple, robust and rapid methods of selection is necessary. In this perspective, some authors reported that the drought factor index (DFI) could be used for early selection of drought tolerant clones and contribute to adaptation to climate change (Cahyo et al., 2024). Rubber clones with high DFI need to be proven to be drought tolerant through large-scale clone trials and through characterisation using the LI-6800 Portable Photosynthesis System, which simultaneously measures photosynthetic gas exchange and chlorophyll a fluorescence.

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22. Stimulation with etephon chemical product is necessary for rubber when reduced frequency of tapping is adopted (with D3, D4 and more) according to clone typology.
23. Rubber agroforestry breeding initiative for smallholders (https://www.rubis-project.org).
24. https://worldagroforestry.org/output/wanulcas-model-water-nutrient-and-light-capture-agroforestry-systems
25. LiDAR: light detection and ranging or laser imaging detection and ranging, is a remote senting tool using laser.

Breeding for traits related to smallholder practices

Setting up efficient rubber-based agroforestry systems can be a way to cope with socio-economic issues. Low rubber prices combined with low land productivity drastically affects farmers' incomes. Most farmers use high tapping frequency, which leads to high bark consumption and reduces the rubber production cycle. Bark damage is also a serious problem resulting from combined use of seedlings with variable bark thickness and limited tapping skills. These factors are also behind the high rate of occurrence of TPD in smallholdings.

In 2024, developing high-yielding rubber clones with specific characteristics for smallholders is possible by combining several traits including a short immature period, a good yield, resistance to TPD, to leaf diseases and bark damage. Subsequently, these clones need to be disseminated with specific training for farmers.

Planting clones that are specifically adapted to low-intensity tapping is also a major challenge given the need to improve labour productivity and to give farmers time to diversify their activity and income, particularly with the implementation of RAS. The low-intensity tapping systems require ethephon stimulation. Designing and implementing training dedicated to this system will be necessary to ensure the development of efficient RAS.

The Indonesian case

When rubber is planted using standard single-row spacing, other crops can only be planted for the first 2/3 years because closure of the rubber canopy can reduce light intensity by 55% and crop yields by 60%. At this conventional planting density, RAS are planted with seedlings (still the case in Jambi, Indonesia, in 2017 for instance by migrant farmers from North Sumatra) and with locally available rubber clones (PB 206 in Indonesia). Most of remaining jungle rubber in Indonesia is planted using seedlings. Recommended clones in RAS are PB 260 in Indonesia and RRIM in Thailand. At normal density, clone RRIM 600 has a weak canopy (< 60% shade). This clone is planted in more than 95% of all the plantations in Thailand and hence also in RAS.

Interestingly, double-row spacing enables a light penetration area reaching 3-4 m from the row of rubber trees, which is still more than 80% when the rubbers trees are 8-9 years old. Analysis showed that double-row spacing with upland rice, corn, and soybean is feasible with 1.98 of a marginal benefit cost ratio. In other words, the double-row system was technically suitable for long term intercropping, because when the rubber trees reached 8 to 9 years of age, light penetration was > 80% at a distance of about 4 m from the rows of rubber tree.

Sahuri et al. (2021) reported that some rubber clones are better adapted to RAS (Oktavia and Agustina, 2021). The International Rubis Workshop 2021[26] addressed the question of the need for specific clones for RAS. New superior rubber clones have been produced by the Indonesian Rubber Research Institute (IRRI), namely IRR 112, IRR 118, IRR 220 and IRR 230 with a potential latex yield of about 2.5-3 tons/ha/year (recorded on station). These clones were evaluated in large-scale clone trials and are currently recommended in Indonesia. IRRI is also experimenting these clones for RAS

26. https://www.e3s-conferences.org/articles/e3sconf/abs/2021/81/contents/contents.html

at the Sembawa Research Centre and in on-farm trials. Again, according to Sahuri et al., some clones are well-adapted to the double-row system with wide spacing. Clone RRIM 600 is also better suited for RAS with a low percentage shade (60%) than other clones. Interestingly, some Brazilian clones with small leaves may have some advantages such as providing less shade.

Conclusion

Adapting rubber clones and cropping systems to obtain the efficient agroforestry systems needed to overcome socio-economic issues and face climate change is the main challenge for this decade. The aim of research in ecophysiology is to better understand the response of rubber clones to climate change. In addition to water stress and wind damage, obtaining rubber clones adapted to high concentrations of CO_2 and high temperatures, as well as new diseases like circular leaf disease are new challenges for research.

Early selection methods based on latex physiology and ecophysiology have helped speed up breeding programmes. Molecular breeding is already being attempted in some breeding programmes thanks to next generation sequencing (NGS). Molecular-assisted selection should also reduce the time of selection by skipping the SSCT (small scale clone trial) steps and testing the selected clones directly in LSCT (large scale clone trial). NGS should also facilitate the certification of budwood gardens and commercial nurseries. The certification of planting material should help improve planting material.

Finally, genetic improvement requires access to genetic resources. Erosion of genetic resources is already underway due to deforestation of the Amazon basin, to the difficulties involved in establishing new collections and maintaining germplasm collections. Conserving *Hevea* diversity is a further challenge for both researchers and authorities, but jungle rubber may also represent a source of diversity to be characterised.

Availability of planting material to farmers through development schemes: the limits of government action

In the 1970s, the Indonesian government began to support the smallholder rubber sector, as had the Malaysian and Thai governments, as early as the 1950s in the case of Malaysia[27]. This type of policy was inspired by the green revolution for rice and was funded using income from oil after 1973. Table I.1 summarises historical relations between farmers and the government since the 19th century. The technical model promoted by government development projects for smallholders drew directly on the estate model: rubber monoculture with high labour and input requirements and no intercropping during the rubber immature stage (cover crops were promoted, but only 5% of farmers used them). The objective was to develop a simple rubber system that could be used over a vast area without requiring major adaptations to local conditions (adaptation was generally limited to the choice of clone and the fertilisation rate). This model proved to be efficient but costly. So far, 16% of Indonesian farmers have been directly or indirectly affected by projects, and only some of the projects resulted

27. In 1990, around 80% of smallholders in Malaysia (65% in Thailand) had been reached by various rubber schemes and adopted the estate model with clonal rubber.

in full production plantations. Several "partial approach" (ARP and GCC)[28] and "full approach" (NSSDP and WSSDP)[29] projects were implemented between 1973 and 1980.

The "partial approach" consisted in providing farmers with certain components of the cropping system, i.e., planting material, fertilisers, and a small credit with limited extension. The "full approach" was based on a complete technological package provided to farmers, generally under a full credit scheme. In 1979/80, the government decided to launch two types of projects: the NES/PIR projects that targeted transmigration areas with the settlement of migrants in virgin areas, and SRDP/TCSDP projects for existing local farms[30]. As a general rule in "full approach" projects, farmers were provided with a whole credit package, which was supposed to be refunded within 15 years, and included the following components: clonal rubber plants, fertiliser, pesticides, cash to help farmers with terracing, a land certificate and a monthly wage for the first 5 years (in NES/PIR only for transmigrants). Table 1.3 lists the distribution of rubber planting among the various projects.

Table 1.3. Planting of clonal rubber through projects between 1970 and 2000

	TCSDP	TCSSP	SRDP	NES	PRPTE	GCC/ ARP	NSSDP WSSDP	TOTAL
Period	1990-2000	1990-99	1980–90	1978–90	1980–90	1974–80	1973–79	
Surface area	75,000	78,000	110,000	168,571	15,697	112,600	20,019	501,887
% of total	15%	15.5%	21.9%	33.5%	3.1%	22.4%	4%	
Class A and B	80% estimated	80% estimated	89%	60%	39%	< 25%	80% estimated	309,330 estimated

Source: Gouyon (1995) and Penot (2001). Class A and B: plantations are good quality. productiveplantations.

Historical analysis of innovation processes in rubber farming

In this section, we analyse the production of innovation and the process of its adoption in the three following steps:

– *innovations in the jungle rubber system by non-project farmers*: smallholders produced their own innovations mainly though the development of agroforestry practices, resulting in what can be defined as "indigenous knowledge". Between 1900 and the 1980s, the farmers shifted from slash and burn agriculture to enriched fallows, then to a type of complex agroforestry system called jungle rubber;

– *innovations introduced into the "estate-like" rubber monoculture system by former project farmers*. After having adopted rubber monoculture (as an external technical innovation) in the 1980s and 1990s (Table 1.4), in the case of most farmers as a result of development schemes, smallholders used innovations to adapt the system to their own needs and strategies including the reintroduction of agroforestry practices by some of them (20-40% of farmers depending on the project; Chambon, 2001);

28. ARP: Assisted Replanting Project; GCC: Group Coagulating Centre.

29. NSSDP: North Sumatra Smallholder Development project; WSSDP: West Sumatra Smallholder Development project.

30. Former projects, as well as SRDP-like schemes funded directly by the Indonesian government are grouped together under PRPTE.

– *recombination of knowledge*: in the 1990s, the RAS developed by farmers involved in research project combining endogenous innovations with exogenous innovations provided by SRAP/Cirad/ICRAF[31].

Table 1.4. Past relations between the Indonesian government and smallholder commodity producers

Date	Action	Result
1870	Government passes the Agrarian Act claiming all fallow land belongs to the State and granting it to European estates	Swidden cultivators decide to plant more perennial crops in their fallow fields.
1910-1943	Government restricts the collection of forest latex by smallholders to protect European concessions.	Smallholders decide to cultivate rubber instead.
1910-1930	Smallholders out-plant estates and increase their market share.	Government decides to protect the estates.
1935-1994	Government imposes punitive export taxes on smallholders to force them to reduce their production	Smallholders increase the quantity and quality of their production to maintain a stable income
1951-1983	Smallholders increase their market share from 65% to 84% by extending their cultivated area	Government focuses all capital and technical assistance on the estates to minimise their loss of market share and to Increase yields.
1980-1990	Government promotes nucleus estate schemes to provide markets for cloves, oranges, and coffee. Smallholder cultivation brought under estate control	Smallholders resist the loss of autonomy implicit in these schemes.
Present	No more Government support provided	Smallholders abandon each commodity in turn as prices drop

* The Agrarian Act of 1870 classified as state dominion any land not kept under constant cultivation. Source: Dove (1995).
**This gave swidden cultivators in disputed areas a strong incentive to plant perennial crops in their swidden fallows (Potter, 1988).

In the shift from jungle rubber to improved RAS, farmers looked beyond the limits of jungle rubber and integrated external components either through the SRAP project or endogenously with systems called "RAS *sendiri*" or "endogenous RAS". After experimenting with RAS, up to 60% of SRAP farmers developed their own systems between 1997 and 2002. Such systems proved to be economically competitive with alternative crops (rubber or oil palm monoculture). In the three above-mentioned stages, the innovation process resembles an "innovation elaboration process" rather than simply an adoption process consisting of step-by-step integration of different technical components or agricultural practices, or the re-appropriation or adaptation of technologies. The traditional endogenous/exogenous division of innovations does not apply here as

31. SRAP: Smallholder Rubber Agroforestry Project: a research programme based on farm experimentation using a participatory approach with: Cirad (*Centre de coopération Internationale en Recherche Agronomique pour le Developpement*, France), and ICRAF (International Centre for Research in Agroforestry).

innovation processes include technologies, the transfer of techniques, management and the development of specific "know-how". Re-combining knowledge, techniques, and "learning by doing" is the basis for the development of know-how.

The beginning of the agroforestry system and innovation in the jungle rubber system

Farmers initially adapted the "estate model", which then became a complex agroforestry system. Farmers introduced five major technical innovations in the jungle rubber system.

The first innovation concerns the planting material and its use in an agroforestry system. Clonal rubber stumps are currently relatively expensive and are often not available in many rubber-producing areas. Initially, access to planting material was through seeds collected from nearby estate plantations. After the 1930s, estates started the massive use of clonal planting material. Farmers collected these "clonal seedlings" (generally the product of GT 1, which is the most widely planted clone). The innovation lies in the fact that rubber was not used by smallholders in monoculture (a "copy effect"), but as jungle rubber in an agroforestry system for which it proved to be highly suitable.

The increase in productivity in jungle rubber using clonal seedlings is low although yields can reach 700/800 kg/ha in the case of pure GT 1 seedlings (Gouyon, 1995; Dijkman, 1951)[32]. The real proportion of clonal seedlings (like GT 1 seeds) in the "unselected rubber" population after several generations of jungle rubber is not known (the lifespan of the jungle rubber system is between 30 and 40 years). For the first replanting cycle, farmers may use seeds from jungle rubber that are already mixed with clonal seedlings but these seeds do not conserve the parents' characteristics. No jungle rubber system includes clones, as unless they are planted in rows, clones cannot survive competition with secondary forest for light.

The second innovation concerns planting techniques. In the 1970s, farmers began to plant rubber trees in rows in their jungle rubber systems to facilitate tapping and improve the return on labour.

The third innovation concerns weeding. In the 1980s, farmers tended to weed once a year using selective cutting to conserve useful timber and fruit trees along some other species like rattan. Even with such limited weeding (compared to weeding 6-12 times a year in the estate model), the rubber trees can be tapped in the 7th or 8th year after planting, instead of after 10 years in Sumatra (or 10-15 years in Kalimantan) in traditional jungle rubber.

The fourth innovation is intercropping. Many farmers traditionally intercropped for several reasons: (i) the fact there was a market for some products, for instance chilli and pineapple in Palembang in South Sumatra, (ii) the need to grow food crops where land is scarce, which is the case in the transmigration areas, or (iii) some farmers required continuous very intensive upland food cropping, which is the case of Minangkabau farmers in the East Pasaman district in West Sumatra. Before 1993, such practices were very rare in project areas due to a ban by project management authorities. However, research

32. Yields from original unselected seedlings were around 350 kg/ha/year in the 1920s. Yields from jungle rubber are now around 500 kg/ha/year (including an unknown proportion of clonal seedlings).

programmes in several countries (IRRDB[33] annual meeting, Colombo 1996) showed that in fact, intercropping favours rubber growth and has no negative impact on rubber.

The last innovation concerns the control of *Imperata cylindrica* particularly in transmigration areas and in West Kalimantan where this noxious weed is rampant. *Imperata* control is very time and labour consuming. Due to competition from *Imperata*, production can be delayed up to the 8th or the 9th year. As soon as 1997, and still in 2024, farmers very often use Roundup®, a glyphosate-based herbicide, at a rate of 2 to 5 litres/ha to kill *Imperata cylindrica* and enable rice to grow. The cost is largely compensated by savings in the cost of labour (between 50 and 70 man-days[34]) required for rice crops in the 4th to 5th months of cropping.

Farmers are gradually adopting some of the components of the estate model, at least those which seem to be advantageous for jungle rubber such as a reduction in the length of the immature stage (thanks to weeding), an improvement in the return on labour (planting in rows reduces the amount of labour needed for tapping, the use of herbicide reduces the labour needed for weeding of *Imperata*). So far, these innovations have been integrated in the jungle rubber system with no external help (herbicide is an "external" technical innovation but its use is a labour-saving strategy on the part of the farmer). The "production" of these innovations enabled the transition from the one-by-one production/adoption of selected technologies or practices to the building of more complex real agroforestry systems that are more sustainable, in other words, moving from fallow enrichment to a real cropping system.

When questioned about the main reasons they chose agroforestry systems instead of monocropping, smallholders gave the following answers:

– they did not have enough cash to purchase the complete estate rubber package or enough labour for that system;

– for the savings in time and money for weed control. Farmers said they weed only once a year and this had proved to be sufficient in the jungle rubber system;

– the returns to labour per farm plot are far higher during the immature rubber stage;

– land was, and in many areas, still is available, making a reasonably extensive rubber cropping system possible;

– smallholders observed that agroforestry systems offered efficient erosion control, as well as being a sustainable source of biodiversity through timber and fruit species.

These practices cost little and require only a very limited amount of additional labour except for intercropping, which still is an important step towards intensification. Intercropping is used by farmers who are progressively abandoning shifting cultivation. In fact, intercropping may not require cash or inputs, only labour. However, without any inputs, particularly fertilisers, yields may remain very low and intercropping can thus be considered as relatively risky due to the required investment in labour.

The reasons it will be impossible to maintain this system (except in remote and pioneer zones) at the end of the 1990s are the following:

– other perennial crop alternatives emerged in the 1980s and 1990s such as oil palm, cinnamon (in Jambi and West Sumatra) and, more recently, pulp trees and pepper;

33. IRRDB: International Rubber Research and Developemt Board

34. Labour cost is generally around 3,500 Rp/day (2 US $ in 1997) so the weeding cost for 50/70 man-days is 175 000/200 000 Rp

– other off-farm opportunities are becoming available with industrialisation, expanding city markets and the expansion of trade;
– jungle rubber productivity is limited and farmers all know that rubber clones can double or triple yields (one very positive outcome of rubber development schemes), which means that farmers who use jungle rubber will eventually have to use clonal rubber, irrespective of the system they choose.

The first step in the transition was from improved fallow through enrichment with rubber to jungle rubber. The second step will be from jungle rubber to improved rubber-based agroforestry systems with a high rate of productivity and reasonable initial investment costs. In other words, the jungle rubber system has reached its limits and needs to be upgraded as soon as the end of 1990s. The only areas where it still can be considered as a possible alternative are remote or pioneer areas inhabited by poor farmers who have no capital at all.

The future of the jungle rubber system can be secured by planting clonal rubber to boost rubber production while conserving agroforestry practices that not only provide diversified sources of income and are better suited to farmers' limited resources but also benefit the environment and biodiversity. These aspects are discussed in the third stage of innovations based on RAS, and are the subject of the research implemented by ICRAF/Cirad from 1994 to 2007.

Process of innovation of the rubber monoculture system by former project farmers

Some farmers realise that productive complex agroforestry systems are made possible by re-introducing certain agroforestry practices in monoculture plots.

How farmers re-introduce agroforestry practices in monoculture

Rubber development projects are widely described in the literature (Gouyon, Barlow, etc.). For project farmers, one major innovation was the planting and/or the selection of trees that resulted from natural regrowth in what were originally monoculture plots. Personal observations of such trends in North Sumatra, South Sumatra and West Kalimantan Province (Sanggau area) in 1993-1998 were evidence for such practices. B. Chambon[35] investigated the frequency of this practice in the West Kalimantan Province (Table 1.2) and her results showed it was not an isolated phenomenon but a real trend. Although in 1997 the trend is still limited to 18% in NES projects (transmigrants) due to the influence of extension, the proportion rises to 45-50% in SRDP and in the "partial approach" projects concerning local farmers. In the latter case, 24% of the plots are in fact replanted with a sufficient number of associated trees to be able to describe them as complex agroforestry systems. Table 1.5 shows that up to 65% of farmers use clones in 1997 when establishing new plantations in agroforestry systems and Table 1.6 describes the type of replanting.

In this case, the innovation is clearly diversification through planting or through selection of fruit and timber species in the rubber inter-rows, resulting a tree-tree

35. B Chambon, Cirad/University of Montpellier, France, did her PhD field research in 1997-2000 under the supervision of the author.

Table 1.5. Agroforestry practices used in clonal project plots in West Kalimantan (1997)

Practices/type of projects	NES/PIR	SRDP/TCSDP	Partial approach
Re-introduction of agroforestry practices	18%	44.5%	51%
Type of trees:			
Fruit trees	72%	85.7%	54.5%
Fruit trees + cash crop trees	28%	4.7%	18.2%
Cash crop trees	0%	9.5%	27.3%
Number of associated trees per ha			
2 to 10: no RAS	62.5%	56%	36.7%
11 to 100: simple agroforestry system	25%	34%	40%
> 100: complex agroforestry system	12.5%	10%	23.3%
Age of rubber trees when associated trees were introduced:			
< 3 years	0	45.5%	57.5%
4 to 7 years	20%	27.3%	42.5%
> 7 years	80%	27.2%	0

Source: survey by B. Chambon, 2001, SRAP.

Table 1.6. Replanting by project farmers in West Kalimantan Province (1997)

Type of plantation		Percentage	Average area planted	Type of cropping system
No replanting		42%		
Jungle rubber		8.5%	1.3 ha	Traditional system.
Replanting with seedlings		27.5%	1.5 ha	47% with associated trees 53% monoculture
Replanting with clones (22%)	New plantation (project)	7.5%	1.5 ha	45% monoculture
	Purchase of a plantation	6%	2.25 ha	78% monoculture
	Setting up of a new plantation	8.5%	1.5 ha	69% monoculture

Source: survey by B. Chambon, October 1998 to April 1999 and April to June 2000.

association, which was strictly prohibited by both rubber researchers and extension services[36]. Farmers have always been told by extension services that clonal rubber should be cropped in monoculture. In projects, the farmers were generally obliged to maintain clean inter-rows (at least during the rubber immature stage).

The village of Sanjan in the Sanggau area in West Kalimantan Province – Agroforestry innovation in SRDP: the cradle of RAS

In Sanjan, in 1995, 13 years after introduction of monoculture, 15 out of the original 50 farmers (30%) had re-introduced associated trees in what were originally

36. In Thailand at that time, RRIT (Rubber Research Institute of Thailand) had been experimenting with associating fruit and timber trees with rubber for a decade (Sompong, 1996). ORRAF (Rubber Extension Service for Rehabilitation) and RRIT have been promoting such systems since 1991.

monoculture clonal rubber plots (Figure 1.2). The ratio of associated trees was 94-291 trees/ha (average 167) to 500 rubber trees/ha, mainly using the following species (ranked in decreasing order of importance: pekawai and durian (*Durio* spp.), belian (*Euxyderoxylon zwageri*), rambutan (*Nephelium lappaceum*), cacao, assam (*Tamarindus indica*), cempedak (*Artocarpus integer*), petai (*Parkia speciosa*) and nyatoh (*Palaquium* spp.). Pekawai, durian and rambutan were present in all the plots, underlining the farmers' preference for fruit trees (Figure 1.3). Sixty-four percent of the trees were planted, the rest resulting from natural regrowth and selection. In the study area, income diversification and reintroduction of financially profitable plant diversity in former monoculture plots are only two of the strategies applied by Dayak farmers.

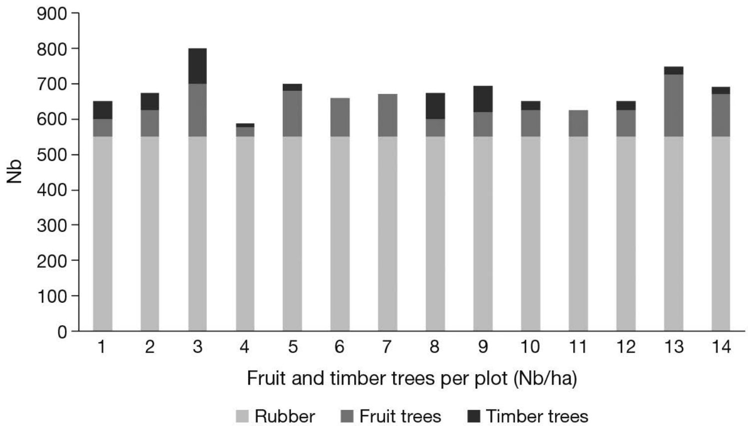

Figure 1.2. Re-introduction of associated trees in former rubber monoculture plots: the case of Sanjan village in West Kalimantan

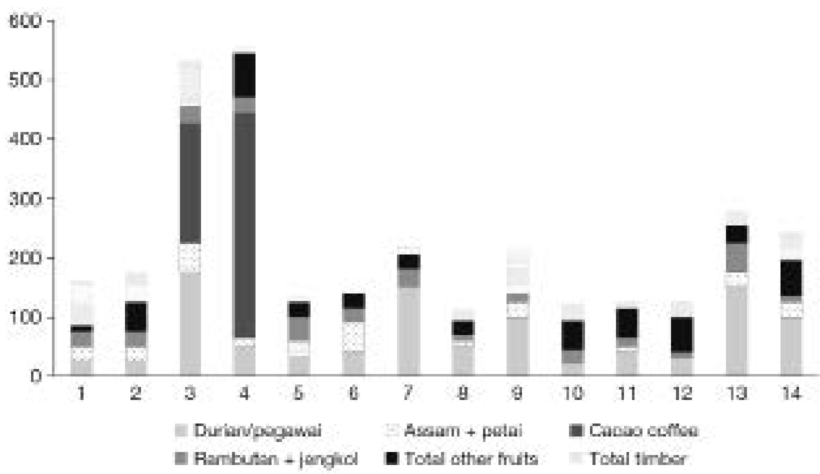

Figure 1.3. Type of associated tree distribution in former TCSDP rubber monoculture

In Sanjan, 35% of project farmers have re-introduced "associated trees". The fruit trees species include meranti (*Shorea* spp.), teak (*Tectonia grandis*), nyatoh (*Ganua* spp.) for timber, durian (*Durio zibethinus*), pegawai (*Durio* spp.), rambutan (*Nephelium* *lappaceum*), duku (*Lansium domesticum*), petai (*Parkia speciosa*), jengkol (*Archidendron pauciflorum*), jackfruit (*Artocarpus heterophyllus*), cempedak (a wild jackfruit, *Artocarpus integer*) (Shueller et al., 2003). In Sanjan, Dayak farmers have also already integrated traditional agroforestry practices in jungle rubber and in their *tembawang* system (a fruit/timber based complex agroforestry system).

This innovation is remarkable for two reasons. Firstly, because farmers always believed it was possible to grow perennial intercrops (trees) with rubber, as is the case in jungle rubber, and consequently decided to proceed. Their problem was knowing what percentage of associated trees can be combined with rubber without causing a serious reduction in latex yield. From the 1920s to the 1950s, unselected rubber seedlings produced the same yield in estates as in jungle rubber, which led researchers to hypothesise that the same was probably true for clonal rubber based on the same density of associated trees. Experiments on RAS were based on this hypothesis, which has been partially confirmed by observations made in the village of Sanjan, where no decrease in yield has been observed (Penot, 2001).

Agroforestry practices increase the sustainability and flexibility of cropping systems

In addition to income diversification and biodiversity, another major advantage of combining rubber with associated trees is that it is possible to change crops when rubber reaches the end of its lifespan (35 years). The plot can then be converted into a fruit and timber agroforest (*tembawang*) with the progressive disappearance of rubber trees. At age 35, clonal rubber wood can also be sold and will give the farmer enough capital to fund replanting.

Rubber trees can also be grown for timber, but in this case no tapping is possible. This is not yet the case in the smallholder sector. In other words, for a short return on investment, the farmer has to choose between latex or wood production. No clones can provide the two products at the same rate, but the economic lifespan of rubber can be considered from two different viewpoints: production of latex or wood, and growing rubber for timber is not economically viable. Apparently, the best economic option in monoculture is to grow clonal rubber at a rate of 550 trees/ha (this is the usual planting density used in Indonesia) first for latex and then to extract the timber as a residual product at the end of a 15-year cycle (Gan Lian Liong et al., 1994). With RAS, farmers have the choice of cutting and extracting all their timber in the 15th year (as mentioned above) or in the 35th year after planting (the end of the rubber lifespan) or of leaving the plot as it is and shifting from a rubber-based to a fruit and timber-based agroforest with a total lifespan of 45 to 50 years. Agroforestry gives farmers a range of options that can be adapted to the market and to their own needs. In other words, agroforestry practices also offer flexibility to change systems.

Farmers' constraints and the slowdown factor in the process of innovation

From an institutional point of view, there are no major constraints to associating fruit and timber trees with rubber as long as project officials no longer have authority over farmers' plots. On the other hand, problems of competition between rubber and associated trees may arise after 10/15 years in the case of fruit trees (such as rambutan) and after 15/20 years in the case of timber trees (meranti or even durian trees) if the planting density of the associated tree is too high, and the density varies with the species. Even in 2014, no scientific data are available on this type of competition, as no trials have been conducted using long-term associations of this type. Some experimental plots do exist (RRIC/Rubber Research Insitute of Cambodia and SOGB/Société des caoutchouc de Grand Bereby in Côte d'Ivoire with timber for instance[37]) but no data are published. The planting density of associated trees observed in Sanjan suggests that farmers are aware of this risk and keep the planting density of the associated trees fairly low, i.e., between 100 and 200 trees/ha vs. an average of 550 rubber trees/ha, while limiting the number of tall trees that have a canopy above that of rubber trees, such as durian. Other important constraints are land and tree tenure. In 1997, planting rubber is, under the traditional "*adat* law", a factor that ensures land acquisition similar to that of ownership. This is still the case in 2024. As far as tree tenure is concerned, it appears that farmers were not officially permitted to cut and sell their timber trees in 1997, but this has changed in 2020. A tax is also collected on rubber wood.

To conclude, in the past, rubber farmers came up with a series of innovations that allowed them to incorporate rubber in their extensive agroforestry practices (i.e. in the jungle rubber system) and later, in the "estate" monoculture model, by associating rubber with annual or perennial crops. But by the end of the 1980s, a point had been reached where further innovation was limited and any additional increase in productivity could only be obtained by including rubber clones and applying other external technologies that required a different management strategy. After passing through two intermediary stages, the first between shifting cultivation and improved fallow, and the second between improved fallow and a complex agroforestry system (jungle rubber), they faced the challenge of how to significantly improve the productivity of their system. Levang recall in 1996 that "*Complex agroforestry systems can no longer compete with other agricultural systems which may be more risky but are more profitable in the short term*". Agroforestry systems based on improved clonal rubber can meet this challenge with reduced risk and an increase in environmental benefits. Farmers have shown their ability to develop remarkable innovations, endogenously or through participatory experimentation in the case of the SRAP projects. In 2002, jungle rubber covered more than 2.5 million ha in Indonesia. The challenge now is to help farmers continue to acquire suitable innovations and to encourage them to adopt RAS.

Indonesia is still going through a stage of "late agricultural transformation". Historically, political instability up to the 1960s and subsequently the priority given to a policy for self-sufficiency in rice production (achieved in 1984) did not allow farmers to acquire improved technologies for rubber on a large scale. In 1997, jungle rubber is still the most widely used system in Indonesia, while sustained economic growth and new crop opportunities, in particular oil palm, invite farmers to increase the productivity of their rubber systems and also diversify. The introduction of external technical innovations (improved availability of good-quality planting material), taking indigenous knowledge (agroforestry practices) into account, providing micro credits and relevant technical information will play key roles in the future of the rubber sector.

37. Current experiments (in Malaysia, Thailand and SRAP in Indonesia) have been underway for less than 15 years on average.

A further important challenge in 1997 is ensuring that all the different types of farmers have access to improved technologies suited to their own particular strategies as well as access to available local resources; in other words, to promote equity as well as sustainability whether through agroforestry or monoculture. In a country that has been able to develop millions of hectares of different types of sustainable complex agroforests, agroforestry still has a great potential as long as environmental concerns are taken into account, and, if necessary, considered as a priority.

The organisation of rubber farmers and the availability of a wide range of rubber cropping systems, from semi-intensive rubber-based agroforests (RAS 1 type as defined later) to intensive monoculture systems, are the main preconditions in terms of policy and technology development that will give environmentally friendly systems a chance to survive and to maintain balanced regional development with other crops. Rubber agroforestry systems may only be options amongst others, but these systems do not entail the risk of crop failure, or uncertainties (in terms of the rubber market and output) that affect other crops, as there is a steady and reliable demand for natural rubber.

Definition of modern RAS

Because of their physiognomic and ecological resemblance to forests, their sustainability, and the well-known environmental attributes of forests, agroforests enjoy a good reputation. The agroforestry literature abounds with favourable judgements such as "*a unique combination of high levels of productivity, stability, sustainability and equitability*" (Soemarwoto and Conway, 1991); "*eminently sustainable agroforestry systems*" (Torquebiau, 1992); "*traditional systems of exceptional merits*" (Nair, 1993); "[…] *agroforestry successfully simulates the forest environment in the form of home gardens and 'analog forests'*" (McAdam, 2000); "[…] *structure of natural forest habitats… imitated*" (Scherr and McNeely, 2012); and *"epitome of sustainability*" (Kumar and Nair, 2004).

Most authors who recognise the quality of agroforests, including recent studies, refer to their ecological attributes, in particular biodiversity conservation and their long-term benefits for soil fertility and water management (Penot, 2001; Gajaseni and Gajaseni, 1999; Kaya et al., 2013), even in somewhat harsh environments (e.g. the Soqotra Island in Yemen; Ceccolini, 2002). Socio-economic variables are taken into account in some studies (e.g. Penot, 2003; Wezel and Bender, 2003) to analyse how agroforests function, but most authors do not describe socio-economic attributes in the same way as they do ecological variables. Some studies that use bio-economic modelling (e.g. with the Beam model) are only performed at cropping system level (e.g. Purnamasari et al., 2002). Labour requirements and return to labour, investments and returns to investment in the medium and long term, product benefits, income generation, are sometimes described, but are seldom presented as arguments for adoption or even taken into account in the innovation process behind the adoption of agroforests. In other words, global advantages as well as positive externalities of agroforests are widely recognised as a whole but are not properly valued. The direct benefits of agroforests are recognised at farm level but not entirely valued either, on the contrary, they are widely under-assessed and sometimes not even taken into account at the community level. To put it in another way: going beyond individual farmers, the impact and use of resources as well as the generation of income and product benefits needs to be considered at the level of what French agronomists call the "territory", i.e., as "anthropic land" and for some components — including biodiversity — at global level.

The only two economic variables which appear to be convincing arguments are: (i) diversification linked with risk spreading, with diverse sources of income and with labour spreading (e.g. Torquebiau, 1992; Penot and Chambon, 2003; Wezel and Bender, 2003), and (ii) income generation as a whole. The large number of products and uses of agroforests make it difficult to go beyond mere description and economic quantification. Similarly, the links between diversification, risk buffering and the long-term economic and ecological sustainability have not been sufficiently taken into account. The role of risk and uncertainty has been studied in the context of agroforestry adoption (Mercer, 2004) but not as an innovation process in its own right.

Deforestation, development of oil palm and other opportunities in Indonesia

Rubber plantations are considered by different authors as a major source of deforestation in tropical areas (Global Witness, 2013; Assembe-Mvondo et al., 2015; Hauser et al., 2015; Roberts, 2016; Vongkhamheng et al., 2016; Fern, 2018; Fritts, 2019; Higonnet et al., 2019). According to Costenbader et al. (2015), rubber expansion is one of the six most important drivers of deforestation in the Greater Mekong Subregion. According to Cowie et al. (2018), forest losses due to the establishment of rubber plantations since 1980 is estimated at 4.5 million ha. However, in 2024, most new rubber trees are no longer planted on forest land, mainly because no such land is available in accessible areas. Forest losses increased after 2000 with the increase in the price of rubber. The total extent of rubber plantations increased by 5 million ha, with major absolute changes in areas in Thailand, where there has been an increase of around 1.6 million ha since 2000, and in China, Vietnam, and Côte d'Ivoire, but not in Indonesia, where the increase has only been 0.3 million ha since 2000 (IRSG, 2018). Is the increase in rubber plantations observed since 2000 only due to deforestation? A field study is needed to answer this question. The example of Côte d'Ivoire where rubber has replaced cocoa is worth thinking about.

In Africa, industrial companies (estates) are responsible for most deforestation undertaken for rubber production (Penot et al., 2020; Fritts, 2019), whereas in Asia, most forest degradation or deforestation, very limited in 2024, takes place to create village rubber plantations, at least in the case of land on which rubber was actually planted (the same is not true for oil palm). The policy of large land concession to oil palm and rubber plantation is over in South-East Asia. It is important to realise that most recent growth of the sector that relies on the increase in area is due to the establishment or extension of village plantations, mostly at the expense of old jungle rubber, but also to a small extent, due to deforestation in remote areas. A major challenge to implementing a "zero deforestation policy" will be including smallholders in the process.