FROM JUNGLE RUBBER TO RUBBER AGROFORESTRY SYSTEMS

History of Rubber Agroforestry Practices in the World

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Conclusion and perspectives for the future

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⏩ Markets trigger agroforestry: the importance of understanding how income is generated in agroforestry

Flexible crop and tree production in agroforests are linked to the mature and immature periods of the crops or trees concerned. It is consequently indispensable to account for the life cycle of plants when conducting a long-term economic analysis. For instance, timber can only be harvested at the end of the agroforest's life span. Therefore, if detailed data are available for a reliable assessment of real income (including self-consumption), comparing systems will be very valuable (Penot, 2001, 2016). A multi-criteria analysis at both farm and community level is far more powerful than simple conventional cost-benefit analysis at cropping system level.

Taking into account externalities is still very difficult due to the lack of accurate dates. Re-internalizing RAS externalities to attribute a value to environmental and sustainability factors is a real challenge.

If the benefits of agroforests can be analysed using the market values of their products and services, then neo-classical environmental economics can be used and externalities can be included (or re-internalised) in the process of income generation. Growth or cost of pollution and delay can be taken into account as negative externalities or constraints to further development. Environmental services (for example, carbon sequestration potential; Albrecht and Kandji, 2003; Montagnini and Nair, 2004) can be valued according to a "system of values" which is perceived locally as being relevant at a higher, community or provincial level. The real problem is therefore understanding whether farmers can potentially or do benefit from the externalities and positive advantages of agroforestry.

Considering "commercially oriented agroforests" or "subsistence-oriented home-gardens" from a long-term perspective must be part of farmers' strategies. However, there is obviously a biased debate between the short term (economics) vs. the long term (ecology). In both cases, farmers have developed long-term farming practices through a long-haul innovation process that in the end, accounts for economics thanks to the risk buffering capacity of agroforests. In most cases, social organisation is closely linked with technical production constraints, reliance on food, securing an income and, possibly land control. There is a strong coherence between technical systems (technical pathways) and social systems (Penot, 2003a).

Economic analysis methods which use farming system modelling and integrates the outputs of mixtures of plants with different life cycles and enables the smoothing of long-term and patrimonial strategies required to accurately explain what farmers do and why they do so. Despite their positive externalities and advantages, agroforests are not a "magic bullet" but rather an ideal compromise between sustainability and risk spreading. Prospective analysis linked with value chains and existing markets make it possible to forecast future scenarios according to new emerging risks, i.e., climate change, market uncertainties, etc.

⏩ Rubber production and sustainability

As a commodity, rubber has a really secure future thanks to the link between natural rubber and the transport industry (road and air). The gradual rise in prices until the price surge in 2011, encouraged a massive increase in new plantations in some countries, particularly in Laos, Cambodia, China, Vietnam, Cambodia, and Côte d'Ivoire. Almost all the recent increase in plantations has been in monoculture, either by smallholders or estates. While global rubber production and consumption are concentrated in Asia, there is also a strong dynamics in West Africa, in particular in Côte d'Ivoire which became the 4th world producer in 2022.

The natural rubber market is influenced by many factors that cause price volatility and are linked to global growth, the oil market, inventories and rubber stocks, public policies, company standards, etc. Adoption of agroforestry systems is still limited and has no real impact on the rubber value chain as a whole, but does have a significant impact for the farmers who have adopted these systems. The low rubber prices since 2013 in fact were a good opportunity to boost agroforestry to both diversify and increase income to improve the sustainability of the rubber value chain, a key issue in the 2020s.

While the focus of "sustainability" issues is often on industrial plantations, it is important to remember that most growth is based on – and will continue to be – based on village plantations (family or employer). Important challenges include climate change, the risk of the spread of *Microcyclus*, environmental issues, the need for diversification to cope with rubber price volatility, optimisation of existing reservoirs of productivity (e.g. low tapping frequency with stimulation, upward tapping), but agroforestry could be one of the solutions if access to markets and diversification alternatives are sufficient where the biophysical conditions are favourable. In the 2020s, various initiatives have been launched and continue to evolve towards certification and different ways of achieving sustainability (IRSG, GPSNR, etc.).

We can present again our feeling expressed in 2004[82]. In the past, rubber farmers in Indonesia and Thailand developed a series of innovations to integrate rubber in their extensive agroforestry practices (jungle rubber) and, later, in the "estate" monoculture model, by associating rubber with annual or perennial crops. But, by the end of the 1980s, they had reached a point where further innovation was limited and any additional increase in productivity could only be obtained by using rubber clones and other external technologies that required a different management strategy. After passing through two intermediary stages, first between shifting cultivation and improved fallow, and second between improved fallow and a complex agroforestry

82. See Penot (2004), *Beyond tropical deforestation* in Babin D (ed), 554 p.

system (jungle rubber), they faced in the 1990s the challenge of how to significantly improve the productivity of their system though rubber clone adoption.

In 1996, Levang wrote: "*Classical Complex Agroforestry Systems such as jungle rubber can no longer compete with other agricultural systems which may be more risky but are more profitable in the short term*" (Levang, 1997). Agroforestry systems based on improved clonal rubber 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, for example, with the SRAP project in the 1990s. Jungle rubber covered more than 2.5 million ha in Indonesia in 2002 and probably less than 1 million ha in 2022. Most of it has been replaced by clonal rubber plantations (1/3 roughly) or oil palm (2/3). The challenge in 2024 is to help rubber farmers continue to acquire suitable innovations and to adopt RAS on a large scale.

Indonesia is still going through a stage of "late agricultural transformation", which began in the 1970s, observed by Barlow (1996) and continues in 20024 in the case of rubber. Political instability up to the 1960s and the subsequent priority given to a policy for self-sufficiency in rice production (achieved in 1984) prevented farmers from acquiring improved technologies for rubber on a large scale as was happening in Thailand and Malaysia. Jungle rubber was the most widely used system in Indonesia in the 1990s and still probably accounted for between 0.5 and 1 million ha in 2024, while sustained economic growth and new crop opportunities, in particular oil palm, invite farmers to increase the productivity of their rubber systems by shifting from jungle rubber to clonal rubber. The move from jungle rubber with unselected rubber seedlings to clonal rubber was a real revolution that was possible due to the increased availability of clonal planting material of different rubber development projects implemented from 1975 to 2000 (SRDP, TCSDP, etc., see chapter 2). By 2024, most producing rubber plots were clonal while jungle rubber was mostly no longer being tapped due to the poor prices since 2013 as well as low productivity. It is considered more as a land reserve for future plantations (oil palm, clonal rubber or any other opportunity that may arise).

The introduction of external technical innovations (low tapping frequency using stimulation, upward tapping, etc.) that take indigenous knowledge on agroforestry practices into account, the availability of micro-credits and relevant technical information on markets and farmers' organisations are key factors for the future of the rubber sector in the coming years.

Another major challenge is ensuring that all the different types of farmers have access to improved technologies suited to their particular strategies as well as to local resources; in other words, promoting equity as well as sustainability whether through agroforestry or monoculture. In a country such as Indonesia that has been able to develop millions of hectares of different types of sustainable complex agroforests, agroforestry still has great potential as long as environmental concerns are considered as a priority. This is also the case in Thailand, Sri Lanka and India.

As early as 1993, Michael Dove asked three important questions that "highlight the challenges of future development of the rubber sector" and are still relevant for Indonesia for agroforestry adoption:
– *Is it possible to promote exploitation of rubber, in the absence of a hierarchical political economic structure*? This raises the question of "producers' organisations" and their ability to control future changes in the commodity system themselves.

Up to now, the answer has been yes, as most farmers started growing rubber without help of any kind. But the use of external components (such as fruit and timber species in agroforestry) and the need for capital (investment) may change this situation. For instance, cooperatives and producers' associations are flourishing in Indonesia these days (Penot et al., 2023). Of course, this situation needs to be secured by appropriate policies on agroforestry.

– I*s it possible to attain goals of both ecological sustainability and socio-economic equity within a hierarchical structure?* The answer is probably yes if improved systems such as RAS, partially based on proven existing systems, are adopted by the farmers; and this seems to be the case, since signs of a move in this direction are becoming apparent. This question was particularly astute in 1993 while most of the world only began to think about it in the 2010s.

– *If both preceding solutions are not possible, what then?* The organisation of rubber farmers, and the availability of a wide range of rubber cropping patterns from semi-intensive rubber-based agroforests (RAS 1) to intensive RAS (RAS 2 and 3, for instance) and monoculture systems, are the main preconditions in terms of policy and technology development that will give environmentally friendly systems a chance to continue and to maintain the equilibrium of regional development with other crops.

The questions raised by Dove in 1993 remain relevant in 2024, as most countries have adopted more environmentally oriented policies since the 2010s. Rubber agroforestry systems as a mean of diversification within one plot may be one option amongst others (diversification at farm level with oil palm for instance), and these systems do not involve risks like crop failure, or uncertainties concerning the rubber market and outputs, as there is a steady and reliable demand for natural rubber.

As Barlow stated as early as 1989, "*It is assuredly appropriate to look seriously at policies which basically aim to help people to transform themselves, in an evolutionary approach where steady improvements are made from within the beginning framework of traditional agriculture*". Indeed, this is exactly what farmers have been doing with their agroforests since the beginning of the last century.

Some countries, including Thailand, Sri Lanka, Malaysia, Vietnam, have had real long-term rubber planting development programmes since the 1960s that continue to produce rubber sectors that perform well. Unfortunately, other countries, including Indonesia, Laos, Cambodia, and Côte d'Ivoire have more or less abandoned all governmental projects or extension services targeting rubber. In Indonesia, as well as in Thailand, the situation in 2023 resembles that in the 1990s except that most farmers already rely on clonal rubber plantations. In Côte d'Ivoire, a real boom linked with the cocoa situation, resulted in a highly performant sector where farmers obtain excellent rubber yields and master techniques like low frequency tapping with stimulation. However, this is a very specific situation based on the fact that planting cocoa after cocoa is problematic due to diseases, soil structure and fertilisation. In Côte d'Ivoire, planting rubber was the best way to break the cocoa/cocoa cycle and to have a forest like plantation (rubber) in which cocoa replanting is far easier.

In countries like Cambodia, Côte d'Ivoire, Cameroon, the sector is developing on its own. In all cases, the very low price of rubber is creating a long-term situation of depreciated prices and a context that is killing any incentive to plant rubber in the future. In some countries including Indonesia, the total area under rubber and rubber production are decreasing to the benefit of oil palm. On the bright side, from the point of view of rubber, such unfavourable conditions also create favourable conditions for income diversification and agroforestry in some countries (Thailand, Sri Lanka, India), but which are not favourable in other countries, for example in Indonesia where oil palm is a serious competitor for rubber.

All rubber producing countries have now adopted – to varying extents – global agricultural development policies that favour the environment, biodiversity conservation and agro-ecological practices including agroforestry in response to international demand. In other words, the political context is very favourable for rubber even if the economic context is not.

New organisations have appeared recently, for example, GPSNR (Global Platform for Sustainable Natural Rubber), which groups producers, cooperatives, processors, traders, tyre companies, civil society (NGOs), and a research institute (Cirad), was created in 2020 to promote sustainable natural rubber and explore ways to globally improve the rubber sector. It was originally initiated by WBCSD's Tire Industry Project members. GPSNR has initiated several activities including tracability feasibility studies, a digital Smallholders Knowledge Sharing Platform, capacity building, and insurance, including agroforestry workshops with champion farmers in Indonesia, Cambodia, Côte d'Ivoire and Liberia.

⏩ A new political environment that accounts for environmental concerns

If an economic perspective with emphasis on local and regional levels is applied to integrate positive externalities such as agrobiodiversity management, improved nutrient cycling, integrated pest management, ecological sustainability and services, decision makers may be convinced that home gardens and agroforests are highly profitable ventures. If an "agroforest rent" approach is applied, policy makers and development agents will see that agroforests are a profitable long-term investment. Hopefully, this will give agroforests a better reputation in research and development programmes worldwide. If agroforests are still a success story for many farmers, it is obviously not for the sake of biodiversity conservation. Other values including social values, security (in terms of risk management and sustainability), diversity (and diversification), land control and land reserve ("rights" as a whole on land and trees with emphasis on tree tenure), are integral parts of the perception of agroforests by most farmers as one cropping pattern among others.

Most farmers who cultivate agroforests also include some monocrops in their farming system, depending on the local situation. If farmers maintain agroforests in some regions, e.g. in India (Kerala), Indonesia (jungle rubber, Pekarangan, Damar systems), Sri Lanka (Kandy agroforests), and West Africa (traditional oil palm based agroforests), it is probably because they have internalised the advantages of agroforests in their systems. A micro-economic analysis at farming system level including all sources of income, cost-benefit per activity and return to labour can explain such long-term strategies, provided it considers the time dynamics of perennial crops in home-gardens and other types of agroforests.

In addition to environmental concerns, rubber sustainability is becoming a real challenge for all the actors involved in the rubber value chain, including governments that have to account for the loss of biodiversity that accompanies the disappearance of forests and the carbon challenge, There is a need to improve the long-term sustainability of cropping systems, which, in the case of rubber, are already in their 3^{rd} or even 4^{th} cycle in some areas.

In 2024, several countries have public policies to support and/or control rubber production and expansion. However, few public policies seem to exist concerning the sustainability of rubber production, whereas at the same time, the biggest companies in the rubber sector are adopting new policies for sustainable supply chain management.

For the benefit of states which wish to be involved in the current process of improving the rubber supply chain, Gitz (2019) identified four possible levers: (i) limiting the negative impacts of land-use change, (ii) regulating land concessions and contract farming, (iii) supporting smallholders and farmers' groups and, (iv) promoting and improving diversified systems.

More generally, as mentioned by Costenbader et al. (2015) in the Mekong subregion of Vietnam, rubber plantation management has to be tackled through inter-sectorial coordination at the landscape, individual country and regional levels. New approaches offer opportunities for such coordination to take place in practice (e.g., landscape level planning, integrated watershed management, integrated and participatory land-use planning, and decentralisation). In order to have a real impact, political will is a prerequisite for the success of these approaches. Governments need to enhance their roles as facilitators in encouraging all sectors and stakeholders to proactively participate in broader natural resources management.

The long period when rubber prices were low not only caused many farmers to temporarily leave their rubber plantation to get work off the farm in another sector, but also in some countries (particularly in Indonesia) to shift to oil palm. In Malaysia and India, rubber trees compete with other crops. Competition is high with oil palm in Malaysia and Indonesia. In India, rubber do compete with high population pressure. Another factor may have contributed to the decline of rubber was the COVID 19 pandemic.

Large rubber estate plantation companies may have converted part of their rubber plantation into oil palm as did many smallholders. On the other hand, some may also have become interested in agroforestry because it is easy to manage like for instance timber based RAS in which timber is harvested at the end of rubber lifespan thereby covering all replanting costs. In Indonesia, mainly in Sumatra and Kalimantan, since the 1990s, rubber has faced fierce competition from oil palm in land allocation and productivity, in terms of both yields and return to labour. “Oil palm/rubber complexes” appeared in many areas in which the two crops competed or complemented each other.

In Vietnam, Cambodia, Côte d'Ivoire and Myanmar, competition with other perennial crops can be far lower, which may increase farmers' interest in agroforestry as a source of income diversification to cope with rubber price volatility, on the condition that there are local markets for associated products in RAS, which is a very important pre-requisite for its further development. In Côte d'Ivoire, there is another explanation for farmers' interest in the cocoa and rubber sectors, because including a rubber cycle makes it possible to interrupt the cacao disease cycles. After the rubber cycle, cacao can be planted again without destroying the naturel forest, which was previously the case.

Local governments need to seriously consider a comprehensive long-term programme for improvement of the rubber industry to support the sector, and to increase its productivity (compared to that of oil palm for instance which is the major challenger in Indonesia) mainly by providing training in tapping practices and RAS as well as ensuring the availability of good quality clonal planting material at an affordable price.

If in a capitalist world, nothing can be done about rubber prices, any and all activities that enable the use of good quality planting material, better tapping practices (including low frequency tapping with stimulation and upward tapping), improved return to labour and the development of RAS as a source of income diversification will significantly improve farmers' incomes and more globally, the long-term resilience of the rubber sector. A balance has to be found that allows all farmers to have balanced farming systems based on both oil palm and clonal rubber (including RAS) in order to be more economically resilient using environmentally friendly practices, in addition to finding a balance between on-farm and off-farm activities.

Agroforestry does have a future but cannot be considered as a "one size fits all" strategy. It needs to be adapted to local socio-economic conditions, to local soil and climate conditions and local markets. RAS offers a real opportunity to strengthen the situation of rubber farmers and to work towards more sustainable rubber production. However, the development of RAS requires both the creation of value chains for associated products, farmers need access to information and probably, for increased efficiency, the establishment of innovation platforms to provide farmers with information about the agroforestry practices that need to be adapted to local conditions, in particular to local climate conditions. The advantage of adopting RAS is to profit from local market opportunities for timber, fruits, gaharu, spices, medicinal plants, etc.

⏩ Some innovative systems for the future

Here we suggest possible innovation pathways during and following the rubber cycle to maintain a certain level of biodiversity while promoting a landscape that is no longer dominated by monoculture.

For more productive adapted RAS, the challenge is to adapt and optimize what already exists

The easiest way to overcome this challenge is to observe and record the types of agroforestry patterns currently being developed by farmers in Indonesia, Thailand, Sri Lanka, China, India, Colombia and Brazil to adapt cropping systems to local conditions. GPSNR recently (2022/2023) boosted this trend by organising agroforestry training and discussion workshops in several countries. The creation of RAS innovation platforms was also suggested to Thai authorities to profit from the considerable reliable know-how of Thai farmers (Penot et al., 2022). There is tremendous scope for valorisation what already exists for the benefit of farmers who are still engaged in monoculture, but such policies require not only organisation, implementation and funding, but most of all, the adaptation of agroforestry patterns to local conditions and markets, including forecasting future climate conditions for the next 30 years. Technical information and know-how is there. Dissemination requires extension services and the willingness of public authorities to develop agroforestry as a possible solution among others.

Towards Indonesian *tembawang*: moving from rubber plantations to productive fruit/timber forests (based on durian, for instance)

The move from rubber plantations to productive fruit/timber forests (based on durian, for instance) is already underway in Sumatra and Kalimantan in Indonesia. After RAS, some farmers decided to change from a rubber-based plot to fruit/trees-based plots called "tembawang" in Kalimantan by Dayak farmers. Once they acquire fruit trees that can produce yields for more than 50 years along with timber species that require up to 60 years before being felled for sale (such as very high quality meranti), these farmers prefer to maintain the fruit/timber-based agroforestry cropping systems without rubber. In this case, rubber is planted on another plot. This system generally prevails where durian trees are growing in the plot as durian produces a good yield and a high-priced fruit.

This trend can also be observed in old jungle rubber plots where rubber is progressively disappearing while fruit/timber trees are preserved. Of the 60 SRAP research project plots dating from the 1990s (see chapter 2), 10% were preserved as *tembawang*, evidence that farmers still have a certain interest in this type of change to their plot. This option remains when farmers have still some land available for future plantation, possibly to replace their old jungle rubber.

Islands of agroforestry in a monoculture dominated landscape

Riparian/rubber corridors: towards the creation of biodiversity corridors using a landscape approach

The idea is to develop a landscape approach based on productive tree-crop plots such as rubber as monoculture or as RAS, and oil palm, with corridors containing local riparian varieties (39 different species), implemented in RAS in order to prepare the future and to have riparian corridors that function as such by the end of the RAS lifespan. The concept was designed and applied to oil palm in a big local private estate located in Sabah province in Malaysia as part of the Trails project. Trails is a Cirad project implemented with University Putra Malaysia, University Malaya, "Hutan" a French NGO and the private estate (Melangking Oil Palm plantations-MOPP). A total of 22 hectares have been planted with 3,000 associated local trees belonging to 15 different species in 3 blocks within the oil palm plantation. In this particular case, the RAS includes not only fruit/timber trees but also local riparian species with no particular productive function aside from biodiversity enrichment. The same system could easily be used for rubber, in particular by local private or government estates with the aim of creating biodiversity corridors and ending the 100% monoculture landscape that currently prevails in mainland Malaysia and in central Kalimantan, Indonesia.

Zemp et al. (2023) described a system based on tree islands located not far away, in Jambi, Indonesia, originally based on oil palm that could also be applied in rubber estates. This project is based on a large-scale, 5-year ecosystem restoration experiment in an oil palm landscape enriched with 52 tree islands, with assessments of 10 biodiversity indicators and 19 indicators of ecosystem functioning in order to compare multi-diversity and ecosystem multifunctionality in tree island systems and conventionally managed oil palm. Enriching oil palm-dominated landscapes with tree islands is a promising ecological restoration strategy, allthough it cannot replace protection of remaining forests.

Such systems are based on the fact that a small part of the plantation will not be replanted with rubber or oil palm, but will instead be devoted to scattered forest-like plots forming corridors or islands within the estate to create a landscape that is more suitable for wildlife.

The double nested cycles system: towards long-term productive forests with a high level of biodiversity

This idea, which was developed by Boulakia (Cirad) in 2002 is a particular type of agroforestry pattern designed to restore the complex and age-old forest cover with “nested” rubber cycles (Boulakia et al., 2010). Rubber plantations are reported to be drivers of deforestation in South East Asia. According to FAOSTAT, between 2000 and 2021, productive rubber area soared from 2.2 to 5.5 million ha in Cambodia, China, Myanmar, Thailand and Vietnam combined. In many regions, rubber expansion is being carried out to the detriment of the forest (To and Tran, 2014; Grogan et al., 2019; Sarathchandra et al., 2021; Bhagwat et al., 2017) with negative consequences for biodiversity and for the carbon balance (Min et al., 2019). In some of these regions, changes in the rubber-driven land use and land cover (LULC) are underway with contrasted types of beneficiaries, with a high percentage of smallholders in Thailand, while in Cambodia and Myanmar, estates drive the dynamics (Fox and Castella, 2013).

Considering these changes in LULC, Warren-Thomas et al. (2018) assessed the threshold value of tCO_2 to reduce the incentive to convert forests into rubber plantations, considering the type of forest that existed previously and the state of degradation. The resulting estimated US$30-51 per ton of CO_2 are far above contemporary market price (US$5-13 per tCO_2). Commenting on the payment for ecosystem services (PES) approach, Dove (2018) pointed out that to be able to reverse or at least limit current forest conversion processes, an economic valuation of PES would have to deal with diverse, complex and often conflictual contexts in terms of resources and land use rights. Based on the analysis of a nation-wide Chinese reforestation programme, Hua et al. (2016) call for a shift from mono or oligo-cultures to more complex planting designs to have a chance to restore biodiversity on similar levels to those of native forests.

Here, we propose some innovative and disruptive planting patterns to reforest or afforest with multi species, using rubber as a relay product in at least two successive rounds of production. The basic principles, presented in figure C.1, are quite simple:

– First, it consists of associating rubber trees planted in hedgerows, e.g. (13 m + 3 m) × 2.25 m, at a normal density of +/- 550 trees/ha, with various ligneous forest species, planted in the double inter-hedgerow space, for multiple production goals like high quality timber in the long term, or non-timber forest products (NTFPs) and ecosystem services as sources of income in the shorter term;

– Second, to escape from the usual around 30-year plantation cycle (a 6-year immature stage followed by 24 years of tapping), 20-25% of the rubber trees would not be opened at 5-6 years old, i.e., when they reach 50 cm-girth, but instead reserved for a second and relay tapping round; this round would exploit 100 to 120 trees/ha opened at a minimum of 31 years old.

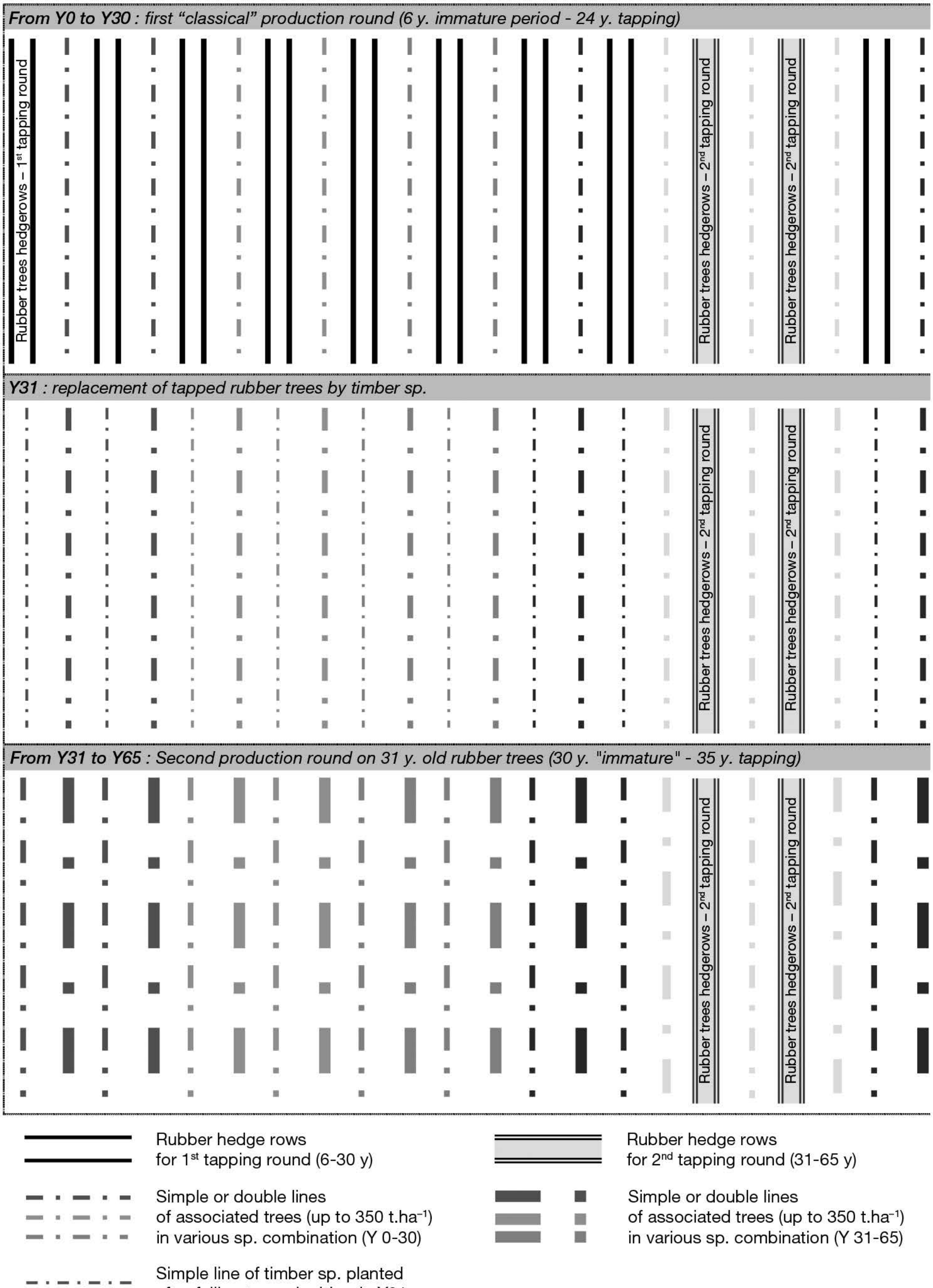

Figure C.1. Sketch of the first two stages of a nested cycle-based rubber agroforestry plantation

This stage makes it possible to imagine a third tapping round involving some of the trees that were tapped during the first round, then reopened about 30 years later (after the second round), thereby enabling regeneration of the bark and of the trees as a whole. This plantation design would produce less rubber per hectare than monocropping, even if the 6 year-long immature period is followed by almost 60 years of continuous tapping but such agroforests would supply complementary products and provide ecosystems services that should be acknowledged and paid for.

Labour is the main production cost of natural rubber and the cost of labour will continue to rise in the future. The design proposed above could be paired with improved labour productivity; after the first, *a priori* standard tapping round (1 tapping every 3 or 4 days, 6 days out of 7 with stimulation adapted to the physiology of the clone concerned), the second period will exploit very large rubber trees, prone to very low tapping frequency (D7 or every 7 days, or D14 or 1 tapping every 14 days) with a high level of stimulation. Rubber trees to be used in the 2nd tapping round should be concentrated in productive patches located on the margins of the planted area in order to limit the need for labour in the innermost part, which was tapped during the first round.

Complementary types of production can be set up in parallel with the progressive and long-term regeneration of complex ecosystems. The different kinds of associated products including NTFPs like fruit, leaves, bark and seeds used for multiple purposes, e.g., food, spices, medicinal plants, gene banks and tree nurseries, are possible sources of income. The most threatened species listed by UICN should be planted in patterns inspired by the structure and kinetics of natural ecosystems. In the long to very long term, timber trees that produce luxury wood with a zero-deforestation certificate will produce high incomes and before being felled, this "growing capital" might also enable access to long term credit secured by the high-quality wood "warrantee".

Throughout their life span, such plantations provide multiple ecosystems services through carbon sequestration and biodiversity recovery.

Carbon will accumulate in plant biomass, notably in the heartwood of luxury and first-class timber species. The sequestration in the biomass of future harvestable wood products (HWP) present two major advantages for the PES: first, it is relatively easy to monitor and report growth of the trees, and second, the sequestered carbon is highly unlikely to revert to CO_2 once the trees reach marketable size due to the extremely high value of their wood. Chayaporn et al. (2021) estimated that teak trees capture between 20 to 30 kg of carbon per year in their aerial biomass between 17 and 35 years old; in the absence of any references, we consider the lowest growth rate of high value timber species, the carbon biomass increment in the sole HWP of about 100 associated timbers could average 1.5 to 2 Mg CO_2e/year/ha, a significant source of income if carbon reaches the expected EU corridor price of between US$60 and US$120 per tCO_2e by 2030. Compared with a monocropping system based on a 30-year cycle from planting to logging and wood export, this long-term regenerative approach should lead to more intense and diversified inputs of fresh organic matter both above and below ground; this continuous supply of litter combined with reduced soil disturbance, should encourage soil organic carbon storage, enhance topsoil diversity and restore function (Panklang et al., 2022a,b), thereby allowing restauration of soil degraded by successive cycles of monocropping in traditional rubber producing areas.

This agroforestry design could also play a role in the conservation of endangered plant species. Beyond these possible conservation functions, Warren-Thomas et al. (2020) reported limited benefits for biodiversity at plot level, of rubber agroforestry systems compared to monoculture. Nevertheless, these authors underlined the positive influence of plant richness, multi-storey arrangements and the presence of neighbouring forest fragments on animal biodiversity assessed through birds, fruit-feeding butterflies and reptiles. Induced and emerging effects on biodiversity enhancement will depend on the scale of application and on connectivity with natural ecosystems. This regenerative agroforestry sequence could be conceived and established at different scales ranging from individual plots to community-managed agroforests; it can serve in conservation programmes designed to restore connections between forest patches or to develop long-term activities with communities in buffer zone programmes. Industrial estates could also use this type of pattern in marginal areas (unsuitable soil type, slope, remoteness, etc.) or to interrupt monocropping schemes after one or two cycles. Public policies could enforce such designs on allocated public land in anticipation of the development of amenities, offering local climate regulation through reforestation or afforestation as outlined by IPCC (2019), in rural zones that are planned to become urban or sub-urban areas in the coming century.

⏩ The final word

Agroforestry systems have been widely applied during the immature period of the rubber trees using different combinations of intercrops, mainly food crops. These temporary agroforestry practices can be found almost everywhere in the world. But agroforestry practices during the rubber mature period combined with fruit and timber trees, resins, spices, food crops and other plants depend on local environmental conditions and on the planting design.

The appropriate degree of shade

Some plants can grow in deep shade but only a few species. According to farmers' experience and our own observations, to enable correct growth of fruit and timber trees or any other plants, the shade provided by rubber trees in a normal planting design should not exceed 70%.

In Indonesia, with a classical planting design, the development of leaf diseases (*Colletotrichum, Corynespora* and *Oidium)* to varying extents limited the rubber canopy. More recently the spread of *Pestalotiopsis* sp. has dramatically reduced the rubber canopy and hence the shade it provides. In Thailand, the widespread use of the clone RRIM 600, which naturally has a limited canopy (i.e. approximate 70% shade) created excellent conditions for agroforestry.

This is not the case in countries like Cambodia, Vietnam, Côte d'Ivoire where deep shade (around 90%) linked with the well-developed rubber canopy prevents any plants from growing with rubber. In such cases, the only option is to change to a different planting design with double or triple rubber rows and wide spacing between the rows of rubber trees.

In designs with double spacing and sufficiently large inter-rows (12 m up to maximum 25 m), it is possible to associate other tree species and plants as, depending on the spacing, they will be in full sun for 10 to 20 years. The shade provided by the rubber trees will only play a role in a limited part of the inter-row. In this example, it is important to design the plot with a minimum of 400 rubber trees to ensure a sufficient yield of rubber. Trials have shown that with 400 trees/ha, the reduction in the yield of rubber is usually limited to 10%, which is considered reasonable and can be largely offset by the value of the associated crops.

Market Opportunity

Agroforestry has expanded in countries where there is a local market, e.g. for fruits in Thailand, Indonesia and Columbia, and more recently for timber as a result of significant deforestation in Southeast Asia, for spices in India, medicinal plants in China, for tea in China and Sri Lanka, for coffee and sugar palm in North Sumatra, etc. Market opportunities clearly drive the development of agroforestry and are a pre-requisite for any further development.

The challenge posed by other crop opportunities

In some countries where rubber is the most widely grown local perennial crop, except for improving rubber growing practices, there are no other ways to obtain the highest possible yield and the best quality, the case in 2024 in Thailand and Côte d'Ivoire. But in other countries, associating another crop may be complementary but is more often competition. Côte d'Ivoire is a good example of complementarity between cocoa and rubber as rubber enables cocoa to be replanted after a rubber cycle of 25/35 years in good conditions close to those of traditional forests which have now almost completely disappeared.

Indonesia, on the other hand, is an example of extreme competition between rubber and oil palm. Other examples of competing crops are coffee and sugar palm (North Sumatra), cassava in Northeast Thailand, and tea in China.

The long periods with uninterrupted low rubber prices (the 12 years since rubber prices fell in 2012) created very unfavourable conditions for most rubber smallholders, resulting in the choice of other crops, particularly, oil palm, which provides double the gross margin/ha and a fourfold return to labour of rubber, and has led to rubber being replaced by oil palm almost everywhere in Indonesia. This long period of depreciated rubber price is the worst enemy of rubber and of any potential improvement in farmers' income from agroforestry practices. Planting oil palm in old rubber plots to eliminate the "no income effect" of immature impact is now very common.

In 2024, North Sumatra is characterised by the expansion of agroforestry practices based on sugar palm, coffee and lemon grass as a transition from a rubber-based system to a system in which the canopy is limited to 30/40% due to significant impact of leaf diseases.

New opportunities

Following the disappearance of local forests in many places in Africa and Southeast Asia, the market for good quality timber is focussed in teak, mahogany, *Dipterocarpaces* and local good value timber such as nyatoh and tembesu in Indonesia, and *cedro odorata* in Central America. Even if income from timber species generally only becomes available at the end of rubber lifespan, timber is already a valuable potential associated crop as it produces sufficient capital to renew a rubber plantation in good conditions with appropriate high quality planting material and the appropriate level of fertilisation. In 2024, tree tenure in Côte d'Ivoire and Indonesia is now favourable in that farmers are owners of their timber trees, meaning they can accumulate patrimonial capital that can be passed on to future generations.

Evolution of rubber systems

Under agroforestry, rubber plantations can also evolve into another system, for example, from rubber to a durian agroforestry system, to the Dayak people's *tembawang* system in West Kalimantan or to enriched forests. This kind of development can help create a new more balanced landscape with a mosaic of different perennial crops and a variety of forests and agroforests.

Rubber Agroforestry Systems remain an interesting alternative

Aside from the adoption of appropriate cultivation practices to improve rubber production and reach a yield of 1,700 kg/ha/year of rubber, the only possible way to increase the gross margin/ha of rubber plots is to adopt agroforestry practices to diversify both production and sources of income. For instance in Thailand, income can be increased by an average of 40% in this way, enabling a better economic result from the plot and helping farmers resist other opportunities.

Agroforestry would probably be more economically effective using double spacing to increase the profitability of associated crops and timber. Double spacing is a new paradigm for the majority of rubber smallholders and continues to represent a real challenge to the adoption of agroforestry. However, such a transition and the adoption of agroforestry is possible with help and support from local estates, as has been the case in Côte d'Ivoire, or from the government like in Thailand or Sri Lanka. Double spacing systems are probably the main challenge for smallholders as well as for countries which intend to maintain their current rubber production despite the presence of newcomers who own very large rubber plantations in Côte d'Ivoire, Vietnam, China, and Cambodia.

The multiplication of sources of income in the medium to very long term, either in the form of products or multiple ecosystem services, opens the way for a vast range of possible agreements between stakeholders, while simultaneously strengthening the resilience of the system. This nested cycle approach offers solutions to some of the limits of rubber monocropping including soil degradation, labour productivity and attractivity or social acceptability of the model. It also makes it possible to couple a response to the growing demand for natural rubber with large scale and self-financed reforestation/afforestation programmes. It creates pathways to establish rubber agroforests that enable the emergence of complex forested ecosystems with large rubber trees; it is a flexible approach that can be fairly adapted to the multiple social contexts encountered under the wet tropical regions of Asia, Africa and Latin America.

To conclude, in addition to the valorisation of existing agroforestry systems and practices, which are already well adapted to local contexts and offer a real economic advantage at plot level, we also perceive the potential for the creation of innovative, more sustainable landscape systems in the long term, landscapes that are more suitable for wildlife and biodiversity conservation. Many farmers who are involved in RAS have knowledge and know-how that could be promoted and disseminated through innovation platforms and at larger scales. Policies on both RAS dissemination and landscape approaches finally depend on governmental willingness to efficiently tackle with environmental concerns and economic sustainability of the rubber sector in the very near future.