

RUBBER AGROFORESTRY

FEASIBILITY AT SCALE



MIGHTY EARTH



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Rubber Agroforestry: Feasibility at Scale

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Agroforestry system with coffee.

Credit: World Agroforestry Centre/ S.K. Dalal



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EXECUTIVE SUMMARY

Background

In this report, we assess the evidence for whether agroforestry practices in rubber production systems could support sustainability in the sector.

Specifically, we: use existing definitions of rubber agroforestry to propose a typology of rubber agroforestry systems (Section 2); synthesise evidence of benefits from existing agroforestry production systems for farmer livelihoods, social issues, and the environment, including biodiversity, climate change and climate resilience (Section 3); discuss best practices, challenges, and barriers to wider adoption of rubber agroforestry (Section 4); and make recommendations for achieving wider adoption of agroforestry practices, both in the context of smallholder farms and larger-scale plantations (Section 4).

Natural rubber production continues to increase in area and tonnage, with almost 90% produced in Asia. In addition to expansion of large-scale plantations, about 90% of natural rubber is produced by smallholder farmers, who are often strongly dependent on rubber tapping for their livelihoods. Despite

A worker on a rubber plantation, Indonesia.

Credit: CC BY-NC-ND 2.0 Tri Saputro/CIFOR

“Smallholder farmers growing rubber in monocultures are exposed to financial risk... because they have few alternative sources of income when global rubber prices are low.”

livelihood and economic benefits from growing natural rubber, research shows **there are social, economic and environmental risks and harms associated with natural rubber production in monocultures.** Specifically, smallholder farmers growing rubber in monocultures are exposed to financial risk through fluctuations in the global rubber price, because they have few alternative sources of income when prices are low.

The degradation of soils and water in monocultures, as well as risks to rubber tree health from disease, drought and frost, are serious concerns. The clearance of natural forests contributes to climate change, and exposes the rubber supply chain, and broader society, to a multitude of risks and harm associated with the loss of biodiversity and natural capital.

In addition to these existing challenges, the COVID-19 pandemic is impacting global supply and demand dynamics that in turn affect the rubber supply chain down to the producer level.

There is a **clear need to improve the sustainability of natural rubber production.** This report facilitates sustainability initiatives for the rubber sector (for example, the Global Platform for Sustainable Natural Rubber, or GPSNR) by providing state-of-the-art information about the **opportunities and benefits offered by rubber agroforestry systems.**



Definition of Rubber Agroforestry

There is currently no standard definition of the term ‘rubber agroforestry’. Multiple and interchangeable terms are used to describe different agroforestry systems such as: jungle rubber, intercropping, or simple versus complex rubber agroforests. Definitions of “agroforestry” and “rubber agroforestry” contain two common themes: 1) a production system from which utility can be derived; and 2) the mixing of rubber trees with other plants/animals (i.e. not a monoculture). In this report, the various forms of agroforestry practices and systems associated with rubber are defined and classified based on management intensity, complexity and planting design, and the terms in this classification are

used throughout the report (Table ES1).

This report uses the terms “smallholder” and “smallholdings” to refer to rubber growers who own or manage smaller plots of land with some degree of autonomy, in contrast to plantation models of rubber growing where larger areas of land are owned or managed centrally by a company with the use of hired labor. Strict definitions of smallholdings often use a 2-hectare threshold, but the relevance of size thresholds varies among countries and other contextual factors. Individual cited studies should be checked if further information about land holding size is needed.

An agroforestry system intercropping rubber with cassava, Cambodia.

Credit: CC BY-NC-ND 2.0 Neil Palmer / CIAT



E.S. TABLE 1

RUBBER AGROFORESTRY PRACTICES AND SYSTEMS

TYPE	DESCRIPTION
Wild rubber (system)	Naturally occurring rubber trees in the Amazon. May not fit the definition of “agroforestry”. At present, wild rubber extraction continues in some communities in the Amazon (including in Brazil, Peru and Bolivia) but is not a major source of latex production.
Traditional jungle rubber (system)	Rubber trees introduced into forests as part of swidden (i.e. slash and burn) agriculture, or via planting in thinned forest. Very extensive system with very limited management and chemical inputs. Typically uses unselected (low yielding) non-clonal rubber seedlings.
Modern jungle rubber (system) / Natural regrowth (practice)	Can be the result of an abandoned or unmanaged monoculture, or a choice by farmers to adopt low intensity of management. Harbors spontaneous/naturally regenerating wild species, which may be selected for their economic, medicinal, or cultural values.
Permanent intercropping (system)	Rubber trees inter-planted during or throughout the plantation cycle with one or more species with harvestable products, including food and non-food crops. A wide range of species can be used, including annuals (maize, pineapple), perennials (cocoa, coffee), fruit trees (mangosteen, orange), timber trees (teak, mahogany), palms, vegetables (<i>Gnetum</i> spp), spices (ginger, cardamom), and mushrooms.
Temporary/short-term intercropping and cover cropping (practice)	Light-demanding annuals/biannuals and leguminous cover crops (e.g. <i>Flemingia macrophylla</i> , <i>Mucuna</i> spp, <i>Senna</i> spp.) can be planted in the rubber plantation in the first few years of rubber establishment. Temporary intercropping with food crops is widely practiced in many countries. Cover cropping with nitrogen-fixing leguminous plants has long been promoted in plantation settings but scholars do not know the prevalence of adoption of this type of agroforestry, particularly regarding its use amongst smallholders.
Animal husbandry (practice)	Animal husbandry in a rubber plot, temporary or permanent, including larger livestock (e.g. cattle, sheep – less recommended), mini livestock (bees, rabbits), poultry and aquaculture.



Agroforestry: livelihood, social, environmental, and climate resilience effects

LIVELIHOOD OUTCOMES

INCOME DIVERSIFICATION, ECONOMIC ANALYSIS AND LIVELIHOOD RESILIENCE

Temporary and permanent intercropping systems in rubber, as well as livestock farming, **significantly contribute to smallholder income** - especially in very poor households - in Asia (Thailand, Sri Lanka, China, Philippines) and Africa (Cote d'Ivoire, Liberia, Nigeria and Gabon). Intercropping provides income to **both smallholders and contract farm workers**

when rubber trees are still immature, and studies from Indonesia found that incorporating intercropping was a crucial **financial strategy** for smallholders to support investment in replanting of rubber trees. A **limitation** for agroforestry is the **unavailability of local or regional markets** for secondary crops, for example, in rubber-lemon systems in Cote d'Ivoire

or jungle rubber-rattan systems in Kalimantan, Indonesia.

Wild rubber extraction in Latin America can contribute to income of rubber tappers, but overall latex yields are much lower than the global average, and the wild rubber tapping industry is not economically viable without subsidies.

LAND AND LABOR AVAILABILITY

Agroforestry systems can provide insurance and flexibility during periods of low rubber price if they produce alternative cash crop products or food resources. However, **constraints on land and labour availability** strongly affect

the profitability of agroforestry practices and systems for smallholder farmers. Smallholders with small plots of land may find intercropping a viable strategy, particularly if additional labour is available but land is constrained. In contrast,

farmers with larger holdings may prefer to **diversify their income at the farm level** by planting single crops separately, which may be simpler to manage than intercropping systems. Agroforestry strategies that require intensive



labour are unlikely to be adopted when labour is scarce. However, some agroforestry practices may actually reduce labour requirements over time, such as reducing intensity of weed removal or the use of long-term cover crops to suppress weeds, while providing additional benefits for soil and water management. Strategies such as **the selection of species that require little extra labour** until the option to harvest becomes preferable over a focus on rubber (e.g. due to market price changes, such as in Southern Thailand), and which provide benefits for soil and water management in the interim (such as in experimental systems in China), could be attractive. Labour availability

varies among regions: for example, **labour constraints are not reported in African case studies**. Smallholders also often **diversify income with off-farm activities** that further constrains their labour availability.

In the case of jungle rubber in Jambi, Indonesia, jungle rubber gave **lower returns on land** compared to monoculture meant that many smallholders opt for the rubber or oil palm monoculture as land is considered scarce. While jungle rubber gave **comparable returns on labour** to rubber monoculture, neither could compete with the returns on labour for oil palm. In Southern Thailand, various rubber

Rubber agroforestry systems can increase livelihood resilience for farmers, tappers, and rural communities.

agroforestry systems gave **the same or greater returns to labour** compared to monoculture, but some agroforestry systems gave **lower returns to land**. Rubber intercropping with fruit and timber trees gave the greatest returns to both land and labour in this case.

RUBBER AND INTERCROP YIELDS

Improving rubber yields - the bulk of cash income even in agroforestry systems - is considered key for improving farmer livelihoods. Using high yielding clones, optimising tapping strategies (e.g. ethylene gas stimulation), and to a lesser extent fertiliser and nutrient management, are important factors to improve latex yields, and continue to be vital to maintain rubber productivity in agroforestry systems. Shading of rubber (i.e. by taller trees) seems to be

the primary factor for latex yield reductions in agroforestry systems, while lower rubber planting densities result in lower total latex yield (i.e. due to there being fewer rubber trees per hectare). However, **latex yields per rubber tree appear to be unaffected by intercropping practises**. Intercropping can also affect rubber tree growth (which affects commencement of tapping time), both positively and negatively depending on the intercrop/country. The shade

from mature rubber, in turn, typically reduces intercrop yields but banana in particular seems to **benefit from being intercropped with rubber**. Yield trade-offs may be balanced out by an overall gain when the yields from rubber and intercrops are combined, or by increasing the planting density of intercrops (e.g. cinnamon, banana).



Agroforestry systems can increase food security by integrating food crops.
Credit: CC BY 2.0 Maren Barbee

PESTS, DISEASE AND INVASIVE SPECIES

Rubber agroforestry can be effective for **regulating various harmful pests and diseases but can also amplify** their occurrence. Jungle rubber and intercropping help to **control invasive *Imperata* grass** in Indonesia. Anecdotaly, intercropping may mitigate build-up of soil diseases in rubber plantations, but evidence from China indicates that cassava intercropping can increase **white root disease** (*Rigidoporus*

lignosus) occurrence. In Brazil, **leaf-eating pest mites** that damage rubber trees can be controlled with natural biocontrol agents such as fungi (e.g. *Hirsutella thompsonii*), which are more prevalent in rubber agroforests. Intercropping coffee with rubber may help reduce pest and disease damage in coffee by increasing shade, compared to coffee monocultures under full sun.

FOOD SECURITY AND NUTRITION

Food insecurity and malnutrition is still a major problem across the globe. While food security and nutrition issues are strongly region and context dependent, and require substantial improvements across the entire food supply chain, **agroforestry can be part of the multi-stranded strategy to improve food security and nutrition**. This may be by directly increasing the availability and dietary diversity of food by intercropping and/or integration of animal husbandry, or by increasing the cash income of farmers such that they can purchase the food they need from market.

Very few studies examined the relationship between rubber agroforestry and food security – **one study (from Liberia) found that agroforestry (including rubber agroforestry) improves household food security**, while other studies (mostly from Asia, one from Nigeria) found that food crops and livestock from rubber agroforestry were used to supplement household food consumption, but also indirectly as a **source of cash income for purchasing food** (sometimes to mitigate the loss of the community's access to forest resources for food and income).



SOCIAL OUTCOMES

GENDER

Gender issues in agroforestry systems are important to consider, because in many societies women and men have distinct roles and preferences, for instance in land-use decision making, divisions in domestic, farm and off-farm labour, tree planting, and participation in rural value chains. However, **information on gender equity and labour burdens specifically in rubber agroforestry systems is still limited.** Overall, **both men and women are involved in rubber farming and tapping** (both monoculture and agroforestry) in Southern China, Thailand, Malaysia, and Indonesia. However, rubber agroforestry could create more opportunities for female participation, because it

requires more family labour, although in some cases (such as Southern Thailand) women may already be strongly involved in rubber tapping alongside other responsibilities and as such would be burdened by additional demands for family labour. Rubber agroforestry strategies can be tailored to local gender roles and cultural preferences to increase female interest and participation in agroforestry, such as women-led trainings and intercropping with medicinal plants (which may be associated with women's roles in some cultures) that could offer additional benefits, including cash income, for underrepresented groups.

Woman tapping a rubber tree.

Credit: CC BY-NC-ND Tri Saputro/CIFOR



LAND TENURE

In some countries, **agroforestry involving permanent or long-lived crops, like rubber trees, can improve land tenure security** compared to annual crops alone for smallholder farmers, because tree planting facilitated claims of ownership and longer tenure durations by farmers. In countries where rubber is classified as an agricultural crop and not timber, **intercropping rubber with timber can increase duration of land tenure**, because

some national policies grant longer leases of land for forestry than for agriculture. However, some smallholders may want to leave farming and, prefer **shorter term or annual crops** over timber trees that **will not tie them to the land**. There is also a risk that without suitable tenure and forest protection policies in place, agroforestry may incentivize forest conversion into agroforestry plots.

OTHER SOCIOCULTURAL BENEFITS

Farmers in Southern Thailand reported social benefits from rubber agroforestry practices, including **knowledge transfer, feelings of autonomy**, and social benefits from harvesting edible species to e.g. provide fruits as gifts to others. These networks have also **increased farmer knowledge** about rubber

processing and assessment, enabling them to cut out middlemen in the supply chain and receive a **price premium**, in addition to enabling farmers to **share knowledge and participate in research** by universities about intercropping practises.

A farmer describes his agroforestry system in Hat Yai, Thailand.

Credit: Mighty Earth



ENVIRONMENTAL OUTCOMES

CLIMATE RESILIENCE OF AGROFORESTRY

Climate change is **exacerbating existing risks facing rubber production, particularly in marginal areas**. As evidence on climate resilience on rubber agroforestry is limited, drawing a simple conclusion is difficult. It is known, however, that water use of rubber cultivation systems is of considerable concern, because rubber is planted often in locations with long dry seasons, increasing the

risk of climate-related drought events. Rubber trees have been shown to adapt their roots and water use patterns to minimise competition with other plants in intercropping systems, while **intercrops can improve soil water retention across the whole system**, although outcomes for wider-scale hydrology are unclear. Smallholder rubber farmers from Thailand and the Philippines report concerns

around climate change and **consider agroforestry as an adaptation or mitigation strategy**. There is some evidence that rubber agroforestry can buffer the effects of normal fluctuations in microclimate, but there is currently little evidence that they could do so during climate change-induced extreme weather events.

CLIMATE MITIGATION THROUGH CARBON SEQUESTRATION

The **carbon stock of a rubber plantation, or agroforest, is more difficult to measure than it may appear**, because the long-term destiny of the carbon stored in trees in any system must be considered. Specifically, it is important to understand the fate of trees at the end of a plantation cycle, and the importance of continuous latex extraction. For rubber monocultures in Southeast Asia, a robust time-averaged carbon stock estimate for rubber is 52.5

tonnes of carbon per hectare, lower than that of natural forests of any type (including dry deciduous forest in Cambodia) but greater than that of annual crops.

Incorporation of additional plant species into rubber systems will **increase above-ground biomass**, and therefore **increase carbon storage in agroforestry systems**. Following evidence from cocoa and coffee systems, agro-

forestry can increase carbon storage, reduce greenhouse gas emissions and therefore mitigate climate change effects.

The **net carbon outcomes of rubber plantation or agroforestry establishment, from the perspective of land cover change, strongly depend on the former land cover**. While strongly context and tree density dependent, rubber carbon balances showed that



when considering monoculture rubber plantations, net carbon sequestration (draw-down) occurs after conversion of arable land to rubber plantations, but carbon emissions (losses) occur if natural forest is converted to rubber.

Therefore, **clearance of natural forest, or permanent jungle rubber agroforestry systems** (that are not felled on a cyclical basis) **will always have a net negative impact on carbon emissions** and climate change.

SOIL HEALTH AND WATER MANAGEMENT

There is evidence from China (Xishuangbanna and Hainan Island) for long-term declines in soil fertility with repeated cultivation of rubber monocultures. Soil nutrient reserves can become depleted in monocultures due to soil erosion, mineralization of soil organic matter (SOM), and nutrient export with rubber tapping. There is, hence, a need for better soil and nutrient management in rubber plantations. A **substantial body of evidence shows the benefits of permanent intercropping and jungle rubber agroforestry** for enhanced **soil carbon, soil nutrients, reduced water runoff and soil erosion, improved soil structure, increased water infiltration into**

soils, complementary water use between rubber and intercrops, **reduced soil acidity and enhanced soil microbial biodiversity**. However, much of this evidence needs further strengthening with repeated larger-scale studies that also capture the strong variation in soil properties between individual farms. There is no evidence for **nutrient competition** between rubber trees and intercrops, and mixed evidence with legume cover crops. Unrelated to agroforestry, terracing protects some organic carbon from losses during rubber development. Minimising herbicide application to once per year could substantially reduce soil loss relative to more regular weeding.

Clearcut and plantation area, Bangladesh.

Credit: CC BY 2.0 Magalee D'Abbee



ECOSYSTEM RESILIENCE AND BIODIVERSITY

Ecosystem resilience and biodiversity benefits of rubber agroforestry depend strongly on the type of agroforestry. Wild tapped rubber from trees growing naturally in the Amazon is unique in that it is sourced from a natural rainforest ecosystem, and like cocoa-rubber agroforestry, these systems provided wildlife habitat for e.g. endangered golden lion-headed tamarins. **Jungle rubber is the most structurally diverse agroforestry system** that contains multiple tree species and supports greater biodiversity than a monoculture plantation. Permanent intercropping systems of fruit, palms, timber or vegetables contain **more species of fruit-feeding butterflies**, but had similar numbers of reptile and bird species than monocultures. **Fruit**

agroforests in Indonesia can support orangutans (but at a cost to farmers who lose fruit crops, which may require compensation). Bird species richness was greater in rubber plots that had more understory vegetation independent of any intercrops. Conservation priority and forest-dependent birds were not supported within rubber agroforests. Agroforests contained similar numbers of ant species (which provide a variety of ecosystem services such as pest control), but crucially they **contained fewer invasive ant species than monocultures**. In general, diversified systems such as rubber agroforestry benefit biodiversity and can maintain biodiversity by connecting natural habitat patches.

Orangutans are among the threatened and endangered species impacted by rubber cultivation.

Credit: CC BY-NC-ND 2.0 Mark Dumon



Discussion

BARRIERS TO ADOPTION OF RUBBER AGROFORESTRY

Implementation of agroforestry production is hindered by various factors. **Outgrower contracts** for smallholders provided by rubber companies guide production methods and **can limit the option to implement agroforestry practices**. Government **policies** favouring monocultures can strongly influence the adoption of rubber agroforestry practices. **Lack of land or tree tenure security** also determines whether smallholders are willing to invest in longer-term agroforestry systems. If smallholders receive sufficient income from rubber monoculture or alternative sources of income, especially when rubber prices are high, they do not see a need to practice agroforestry, which would require an increase in management complexity, including additional knowledge/expertise

and labour. However, **labour shortages** are a common barrier to implementing agroforestry, as in many rural areas of rubber-producing regions economic development and urban immigration have reduced rural labour availability. **Lack of access to markets for intercroops** was also cited as a barrier to agroforestry. As the rubber agroforestry model is still rare in most countries (although a rough estimate suggests 60% of rubber cultivation in Indonesia comes from jungle rubber systems), smallholders and industrial plantations accustomed to the monoculture model are likely to be risk averse and stick to existing strategies. The **lack of technical knowledge** and theft of intercroops was also perceived to be a problem for smallholders.

Children play under sheets of rubber on their parents' plantation.

Credit: CC BY-NC-ND 2.0 IFPRI



Recommendations for Wider Adoption of Rubber Agroforestry

GENERAL RECOMMENDATIONS

In general, it is essential to understand the needs, constraints, and interests of smallholders and plantation managers to effectively implement rubber agroforestry. Recommendations for agroforestry models and best practices will **need to be tailored to the diverse contexts in the producer countries and regions** to produce the best outcomes for livelihoods, food security and nutrition, gender equity, and the environment. There is also a need for better dissemination of information about the benefits of agroforestry to local audiences — in particular, that there are **no yield declines compared to monoculture systems**.

Specifically, **government policies** are needed to promote agroforestry practices that have demonstrated environmental and climate benefits and to discourage unsustainable farm management (e.g. unnecessary herbicide spray-

ing on large areas of rubber plantations). These policies need to be consistent and persistent, account for land-use planning, land tenure policies, avoid detrimental environmental impacts, and support smallholders' investments. In **new rubber development frontiers**, rubber agroforestry models should be encouraged and subsidised as an alternative to monoculture plantations. Farmer-to-farmer **communication networks** should be actively supported and developed, so that Indigenous and smallholder farmer **knowledge and traditions are sustained, food security and nutrition is ensured**, and male and female farmers have **flexibility to meet their own needs**. We also discuss the need for several support systems including the dissemination of technical recommendations via extension services and demonstration plots or model farms.

“There is a need for collaboration between multiple stakeholders to make cultural shifts to agroforestry”

Industrial and large-estate plantations should embrace additional indicators of sustainability around livelihoods, soils, biodiversity and climate resilience, and recognise that agroforestry practices and systems can be a financially viable strategy towards sustainable production. Plantation companies should invest in research and development to **identify cost-effective agroforestry practices** to be published in their sustainability reports. Agroforestry practices to be considered include



reduced herbicide application; cover cropping; intercropping with crops that require little maintenance; planting of riparian areas with diverse native species; and temporary intercropping between rubber rows during the first three years of rubber establishment. Plantation companies can trial rubber agroforestry practices on a portion of their estates, support rubber agroforestry among smallholders via outgrower schemes, provide access to parts of the plantation for rubber workers or their families to intercrop, and facilitate knowledge exchange. **Rubber buyers**, such as tyre companies, should facilitate the adoption of agroforestry rubber by **creating a demand for agroforestry rubber** through procurement policies, and/or by facilitating the adoption of rubber eco-certification that grant a price premium for smallholders and industrial growers who implement agroforestry and other sustainable practices.

Researchers can support smallholder farmers with well-evidenced agroforestry knowledge, by co-developing best practices and help to identify farmers' challenges. Researchers should aim to **co-develop research** where possible, and share their research findings with rubber research institutes, civil society organisations

(CSOs), and the farmer networks and co-operatives they work with, to ensure knowledge is available to those who can apply it. Researchers can help **uplift farmer produced knowledge and personal experiences** by highlighting those in their work, and particularly in situations and cultures where published or accredited research is perceived as having high value and credibility. Our literature review has also highlighted a major research gap in regards to published studies on rubber agroforestry and food security and nutrition, gender equity and labour burdens, land tenure, and other social dimensions (e.g. farmer empowerment, food sovereignty).

Farmer-to-farmer networks and associations facilitate the spread of agroforestry practices and knowledge in farming communities. Farmer networks and co-operatives provide mutual support and more opportunities for men and women to access knowledge, skills and resources via collective action. However, the effectiveness of collaborative networks between stakeholders to address environmental problems is often hindered by individuals fearing that their hard-earned knowledge will be exploited and they do not stand to gain from the networks, differences in knowledge gaps

between participants, and whether such issues can be overcome in a foreseeable time period. In Southern Thailand, rubber agroforest smallholder farmers have formed groups around common interests, which have facilitated the spread of agroforestry among peers as well as collaboration with researchers and industry.

In summary, there is a need for collaboration between multiple stakeholders to make **cultural shifts** to agroforestry, from smallholders and estate companies to **government policies**. There should be a multi-way **exchange of information** regarding agroforestry best practices among and between smallholder **farmer networks, researchers, CSOs and industry**. Agroforestry researchers should **consolidate the global and local knowledge base of agroforestry** and **promote best practices**. Input from industry, in terms of both agroforestry best practices and agroforestry value chain development is another piece of the puzzle. Input from real farmers are necessary to ensure effective implementation. An agroforestry-oriented innovation platform was suggested to facilitate such collaboration and information exchange. Funding or support from the UN, key climate change agencies and rubber buyers could help to facilitate this.



BEST PRACTICES AND PITFALLS FOR RUBBER AGROFORESTRY

There are **no universal best practices** for agroforestry, and experts found it challenging to summarise best practices for rubber agroforestry because they are highly context dependent. Similarly, pitfalls occur when these **context-dependent factors** are not considered implementing rubber agroforestry practices. Effective agroforestry practices or systems

should account for **constraints**, including the **local biophysical environment, market availability, male and female smallholder needs and constraints**, and the **objectives** of implementing agroforestry.

While this report does not provide a list of technical recommendations because of the diversity

of factors and situations, some **strategies for avoiding reduction in rubber yields and increasing productivity in intercropping systems have been established by prior research**. These include: double-row alley cropping with wider interspacing for intercrops, not planting trees that would shade out rubber, and not planting intercrops in the rubber line.

Conclusions

Rubber agroforestry systems are dynamic and versatile, consisting of multiple components that make contributions to smallholder livelihoods, food security and nutrition, provide social advantages, and improvements for soils, water and other environmental and climate outcomes. Research gaps still exist around the ‘best’ practices for agroforestry such as appropriate intercrops, optimal tree spacing, and water usage; as well as the social outcomes of agroforestry such as gender, food security and sovereignty, and nutrition. Better information

sharing is needed, for example through farmer-to-farmer exchanges, the opening up of rubber research institute reports and knowledge into the public domain, and better translation of scientific studies into user-friendly materials for use by government agencies and businesses.

Multiple projects have trialled rubber agroforestry practices with modern rubber varieties and techniques but have found it not to be widely adopted. This may not indicate that rubber agroforestry itself is untenable, because

ample evidence suggests that rubber yields in intercropping systems are no lower than monocultures, while income risk is more diversified in agroforestry systems. Instead, this shows that farmers may not have had access to the information, capital or physical inputs (e.g. seedlings) needed to diversify in the first place, that policy or market conditions were not right for agroforestry to work more widely, or that farmers’ preferences and motivations were not well understood. Rubber is a long-term investment but has short term price volatility. Lessons must

be learned from places where rubber cultivation has generated long-term benefits for farmers and where agroforestry practices are reaping rewards for farmers, such as in Southern Thailand or China, as well as places where existing agroforestry practices are being lost, such as Indonesia, to inform rubber sustainability efforts now. Similarly, there is much potential for plantation companies to benefit from implementing agroforestry practices on estates, and rubber buyers play a crucial role in facilitating demand and developing value chains for agroforestry rubber.

Overall, **creating an environment where farmers have access to knowledge, information, capital, markets** and importantly, **the autonomy to choose which components of agroforestry best suit their needs and constraints would allow them to exercise creativity and sovereignty in their farms and livelihoods.** In the UN Decade of Restoration, learning from existing and taking on the challenge to establish new agroforestry systems has the potential to make a substantial contribution to bring sustainable improvements to the environment and farming livelihoods, if all stakeholders unite to build a better tomorrow. 🌿 MAY, 2021

A rubber forest garden.

Credit: Kittitornkool, J et al (2019)





1 Introduction

1.1 THE CURRENT STATE OF THE RUBBER INDUSTRY

Natural rubber production continues to increase in area and tonnage. In 2019, 12.3 million hectares of rubber were grown globally, an increase of 3 million since 2009, while production increased by 4.3 million tonnes over the same 10-year period (FAO, 2021). Eighty-nine percent of this rubber area, and 88% of tonnage, was produced in Asia. About 90% of natural rubber is produced by smallholder farmers ((IRSG, 2019) as cited in (Gitz *et al.*, 2020)), who are often strongly dependent on rubber tapping for their livelihoods. Large-scale plantations are also continuing to be productive and to expand in area.

Increasing attention is being paid to the social, economic and environmental sustainability of natural rubber production, particularly focussed on the risks associated with monoculture plantations (Warren-Thomas, Dolman and Edwards, 2015). Smallholder farmers dependent on rubber are exposed to fi-

**Rubber systems in Dawei,
Myanmar.**

Credit: CC BY-NC 4.0 TCW



nancial risk through fluctuations in the global rubber price, threatening their livelihoods and the social and economic sustainability of production. The degradation of soils and water in monocultures, particularly those grown on steeper slopes, is a serious concern (e.g. Ziegler, Fox and Xu, 2009; Jiang *et al.*, 2017), while newer plantations in more marginal areas are increasingly exposed to risks of disease, drought and cold (Ahrends *et al.*, 2015). Meanwhile, the clearance of natural forests that store more carbon than plantations contributes to climate change, and exposes the rubber supply chain, and broader society, to a multitude of risks associated with the loss of biodiversity, habitats and natural capital (Warren-Thomas, Dolman and Edwards, 2015; Warren-Thomas *et al.*, 2018). Increasing attention is therefore being paid to multiple aspects of sustainability in the rubber sector, which is made complicated by the long and complex supply chains connecting smallholder farmers to buyers (Kennedy, Leimona and Yi, 2017). Meanwhile, some large-scale plantations and supportive outgrower contracts offer opportunities to rapidly scale-up sustainable cultivation practices to large areas of production.

Given these concerns, sustainability initiatives are now underway for the rubber sector, including the Global Platform for Sustainable Natural Rubber (GPSNR), the International Rubber Study Group's Sustainable Natural Rubber Initiative (which recently signed an MOU with the GPSNR (GPSNR, 2019)), Fair Rubber eV certification, and many other “eco-certification” measures (Kennedy, Leimona and Yi, 2017). These initiatives set out criteria or visions for multiple aspects of sustainability.

The effect of fluctuating rubber prices is of fundamental importance to the sustainability of rubber production. Fluctuations in rubber prices are of serious and direct consequence for smallholder farmers, particularly those who grow rubber in monocultures, and those who have few alternative sources of income or access to adequate food and nutrition. Price variation strongly impacts livelihoods and drives farmer choices about management and production. Prices are influenced by seasonal fluctuations, supply and demand (which is difficult to predict due to time lags from planting to production, the possibility of storage and stockpiling, and because small-

holders who rely on rubber tapping will not necessarily cease production even if prices fall), and crude oil prices (Miller, 2020).

In addition to these existing challenges, the Covid-19 pandemic is affecting many aspects of the rubber supply chain, and the people who produce natural rubber. In early 2020, the Association of Natural Rubber Produc-

“The clearance of natural forests that store more carbon than plantations contributes to climate change, and exposes the rubber supply chain...to a multitude of risks.”

ing Countries (ANRPC) forecast increases in production and demand of 3.8% and 2.7% respectively, but later suggested an overall contraction in production for 2020 (reductions of 4.7% and 6% respectively) (Zengkun, 2021). Demand from auto and tire industries has reduced, while increases in demand for



Rubber plantation, Thailand.
Credit: cc BY SA 2.0 Eleanor WT

other rubber products, such as personal protective equipment (PPE), have not been large enough to offset reductions (Miller, 2020). Future forecasts are likely to be very uncertain (Gitz *et al.*, 2020). **The pandemic has also affected supply chains, the operations of plantations, and the roll-out of sustainability initiatives and farmer support, mak-**

ing rubber smallholders more vulnerable than ever (Zengkun, 2021). Despite the challenges, and especially because of the climate emergency, there is therefore a clear need to push ahead with efforts to improve the sustainability of natural rubber production, and particularly to support smallholder rubber producer livelihoods.

1.2 SCOPE OF THE REPORT

In this report, we assess the evidence for how agroforestry practices in rubber production systems could support sustainability in the sector, as broadly-defined above.

- First, we examine the definition of rubber agroforestry and propose a typology of rubber agroforestry systems;
- Second, we synthesize evidence of benefits from existing agroforestry production systems for smallholder farmer livelihoods, social issues and the wider environment, including climate change and climate resilient production;
- Last, we discuss best practices, challenges and barriers to wider adoption of rubber agroforestry, and make recommendations how wider adoption could be achieved, both in the context of smallholder farms and larger-scale plantations.

“In this report, we would like to emphasize agroforestry for livelihoods which unites agronomic, environmental as well as sociocultural concerns”

2 Definition of rubber agroforestry

2.1 DEFINITION AND PROPOSED TYPOLOGY FOR RUBBER AGROFORESTRY

Agroforestry has been defined as “a collective name for land-use systems and technologies in which woody perennials are deliberately grown on the same piece of land as agricultural crops and/or animals, either in some form of spatial arrangement or in sequence. In agroforestry systems, the woody component interacts ecologically and economically with the crop and/or animal components” (Lundgren, 1982). Agroforestry can be agronomically oriented (e.g. with the goal of maximising crop production on the same land), environmentally oriented (e.g. with the goal of making agricultural landscapes closer to natural forest ecosystems), and/or livelihoods oriented (e.g. with the goal of diversifying smallholder production for better social, economic and environmental outcomes) (Somarriba, 1992; Leakey, 1996).



In this report, we would like to emphasise agroforestry for livelihoods which unites agronomic, environmental as well as sociocultural concerns.¹

There is currently no standard definition for ‘rubber agroforestry’ in the sector, which is also the case for cocoa agroforestry (Sanial *et al.*, 2020). In the literature, the term “rubber agroforest” has been used to describe widely different systems, from extensively-managed complex assemblages of rubber trees in secondary forest fallows, to production-driven simple inter-plantings of timber species with clonal rubber trees. Moreover, there are multiple, interchangeable terms used to describe different agroforestry systems, including jungle rubber, rubber gardens, intercropping, mixed cropping, and simple vs. complex rubber agroforests.

Harvesting cinnamon, Indonesia.

Credit: CC BY-NC 4.0 Tri Saputro/CIFOR

¹ A livelihoods-oriented definition is currently used by ICRAF: “Agroforestry is a dynamic, ecologically based, natural resource management system that, through the integration of trees on farms and in the agricultural landscape, diversifies and sustains smallholder production for increased social, economic and environmental benefits” (Leakey, 1996).

**BOX 1****SOME EXAMPLES OF DEFINITIONS OF RUBBER AGROFORESTRY,
FROM INTERVIEWS AND EMAIL CONSULTATIONS**

“Permanent crops mixed with rubber; not annuals.”

“An agriculture system, where you manage rubber trees within the forest.”

“The mixing of rubber with long-lived plants and animals. Rubber is the main trees in the farm.”

“Modern rubber agroforestry is planting rubber as key crop in a more intensive pattern, intercropping with other plants and maybe livestock.”

“In general, rubber agroforestry refers to rubber grown with other species, but it can vary depending on how much planning is involved.”

“Agroforestry refers to tree culture that incorporates other crops, whether trees, shrubs and/or annuals, and animal husbandry/aquaculture in order to have resemblance of a typical forest. The crops (trees, shrubs and annuals) and the animal components of agroforestry have economic value for food, fiber and the industry. Types of agroforestry depend on the objective of the agroforestry practice.”

“Agroforestry is a forest created by man (people), mixing different small crops for the local producer to have some profit.”

“Diversified production system in which rubber trees are among other crops and timber and non-timber forest products.”

“The definition of rubber agroforestry should not include diversified farms including rubber trees grown separately to other crops or livestock (but that are technically part of the same farm), nor be used to describe rubber farms that have no secondary crops but that contain substantial understory vegetation. These could be termed “wildlife-friendly” or similar, instead. Rubber farms with short term inter-cropping during the immature rubber phase, but which revert to monoculture once trees are mature, should also be considered distinct from mature rubber agroforests.”²

² Eleanor Warren-Thomas, based on (Warren-Thomas *et al.*, 2020)



The interchangeability and ambiguity of rubber agroforestry terms, the context-dependence of agroforestry studies, as well as confusion over the different types of agroforestry systems and practices, has made it challenging to assess the evidence for the potential benefits of scaling up rubber agroforestry practices, as well as recommendations for best practices. In addition, rubber productivity, or latex yields, are strongly influenced by multiple factors unrelated to agroforestry practices (e.g. quality of rubber planting material, planting density, tapping frequency), making comparisons among different studies challenging.

Definitions of “agroforestry” and “rubber agroforestry” varied among experts and stakeholders interviewed for this report (Main report), but two common themes were: (1) it is a production system from which utility can be derived; and involves (2) the mixing of rubber trees with other plants/animals (i.e. not a monoculture). However, opinions varied

on whether practices such as cover cropping, temporary intercropping with annuals during the first few years of rubber establishment, or simply allowing natural regrowth in rubber monoculture plantations could or should be considered “rubber agroforestry”. While incorporating these agroforestry practices into a rubber monoculture can bring environmental, social and economic benefits, doing so does not necessarily turn a monoculture into an ‘agroforest’ (Table 1).

As a step towards clarifying and defining rubber agroforestry, we have attempted to define and classify the various forms of agroforestry practices and systems associated with rubber, as compiled from the literature and expert consultations (Table 1: Rubber agroforestry practices and systems). We have only considered systems involving the Pará rubber tree (*Hevea brasiliensis* Müll.Arg.), but there may be agroforestry systems associated with other latex-producing trees/plants. Rubber agrofor-

estry systems vary by:

- **Management intensity**, including the choice of rubber planting material
- **Complexity**, including the number of species; structural complexity of the vegetation; and temporal scales
- **Planting design**, including spacing of rubber rows and planting density

Given the ambiguity and fluidity of the term ‘agroforest’, we have deliberately avoided using this term in our classification scheme, but in the rest of the report we use it as a general term to refer to any of the categories specified below. We acknowledge that no typology is perfect, but we hope that this will provide a useful and comprehensive guide towards a better understanding of rubber agroforestry practices and systems.



TABLE 1

RUBBER AGROFORESTRY PRACTICES AND SYSTEMS

A proposed typology of rubber agroforestry systems (wild rubber, jungle rubber, permanent intercropping), and agroforestry practices (temporary intercropping, allowing natural regrowth, animal husbandry) that can be implemented in rubber plantations, synthesised from the literature and expert consultations. These practices can be combined with each other and with agroforestry systems (e.g. cover cropping + animal husbandry; temporary intercropping + permanent intercropping + animal husbandry). We have drawn heavily from previously published classification schemes, including Langenberger *et al.* (2017) and Stroesser *et al.* (2018). A more detailed discussion of systems follows in the text.



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CC BY-NC 2.0 Tri Saputro/CIFOR



CC BY-NC 4.0 MWMH – Malaysia

WILD RUBBER (System)

Naturally occurring rubber trees in forest settings. May not fit the definition of “agroforestry”. At present, wild rubber extraction continues in some communities in the Amazon (including in Brazil, Peru and Bolivia) but is not a major source of latex production.

TRADITIONAL JUNGLE RUBBER (System)

Rubber trees introduced into forests as part of swidden agriculture, or via planting in thinned forest. Very extensive system with very limited management and inputs. Typically uses unselected (low-yielding) non-clonal rubber seedlings. Rubber trees of different ages in permanent/sisipan systems in Indonesia.

MODERN JUNGLE RUBBER (System) / NATURAL REGROWTH (Practice)

Starts off as a monoculture using clonal rubber, but spontaneous/natural regrowth of wild shrubs and trees make it resemble a “traditional” jungle rubber. Usually a result of being abandoned or left unmanaged for some time, or can be a deliberate choice by farmers, particularly the most experienced. Limited management, but naturally regenerating species may be selected for their economic, medicinal or cultural values.

TABLE 1 (CONTINUED)



PERMANENT INTERCROPPING (System)

Rubber trees inter-planted during or throughout the plantation cycle with one or more species with harvestable products, including food and non-food crops. A wide range of species can be used, including annuals (cassava, maize, pineapple, soy bean), perennials (cocoa, coffee), fruit trees (mangosteen, orange), timber trees (teak, mahogany), palms, spices (ginger, cardamom), and mushrooms.



TEMPORARY/SHORT-TERM INTERCROPPING AND COVER CROPPING (Practice, but can be considered agroforestry system if permanently integrated)

Light-demanding annuals/biannuals and leguminous cover crops (e.g. *Mucuna* spp, *Senna* spp.) can be planted in the rubber plantation in the first few years of rubber establishment, usually up to three years (“light phase” in the classification of Langenberger *et al* (2017)). Temporary intercropping with food crops widely practiced by smallholders in many countries, and even in industrial plantations under contract farming systems, e.g. in Laos (Hicks *et al.*, 2009). Cover cropping with leguminous plants (nitrogen-fixing) has long been promoted in plantation settings but unsure how widely adopted in rubber, especially among smallholders (Langenberger *et al.*, 2017). Used to reduce erosion, increase soil nutrients, for weed control (e.g. *Imperata* dominated systems in Indonesia), and provide fodder (Langenberger *et al.*, 2017). The use of cover crops that do not produce a secondary product that can be consumed/sold would not usually be termed an agroforestry practice, unless combined with other crops.



ANIMAL HUSBANDRY (Practice, but can be considered agroforestry system if permanently integrated)

In Thailand, stingless beekeeping was highlighted as a successful example,³ and some farmers kept cows, poultry, swine, goat and sheep in immature and mature plantations (Somboonsuke *et al.*, 2011). In Malaysia, some research on sheep and other animal husbandry in rubber plantations has been conducted by research institutes (Tajuddin, 1986; Jusoff, 1988; Chong *et al.*, 1997). In Vietnam, rubber trees are incorporated into local integrated agroforestry systems (“garden-pond-cage-forest”), consisting of forest trees + fruits + annuals + aquaculture + animal husbandry (Sen, 2015). In Nigeria, mini-livestock (bees, stingless bees, rabbits, snails) and aquaculture are used on rubber farms (Mesike, Esekhide and Idoko, 2019). In Cameroon, chickens, pigs and fish were kept in years 4-7 of rubber plantation cycle.⁴ Larger livestock such as cattle typically not recommended (cattle can damage trees or latex collection cups), but smaller species such as bees were noted as successful cases.

3 Interviews, Sara Bumrungsri, Uraivan Tongkaemkaew, and Michael B. Commons.

4 Corrie-Maccoll, 2020. Overview: The Cameroon Outgrower Programme. Website: <https://www.corrie-maccoll.com/cameroon-outgrower-programme-overview/>



2.2 WILD RUBBER

One special case of a rubber system that could be termed “agroforestry” is wild or native rubber in South America. The rubber tree (*Hevea brasiliensis*) and related *Hevea* species are native to the forests of South America. Native rubber was used traditionally by Indigenous communities in the Amazon. Wild rubber extraction in the Amazon became an important industry during the late 1800s and early 1900s, and again during WWII; serious social impacts and human rights violations, for indigenous communities as well as for migrant labor brought in to tap rubber trees, were widespread (Brown and Rosendo, 2000; Stoian, 2000; Gomes, Vadjunec and Perz, 2012; Fitts, Cruz-Burga and La Torre-Cuadros, 2020). In the 1970s-1980s, the Brazilian “rubber tappers” social movement from Acre, Brazil, gained international prominence and became intertwined with environmentalism, leading to the creation of “extractive reserves” in Brazil (Keck, 1995). These ex-

tractive reserves were conceived to provide land tenure rights for forest-based communities while also conserving livelihoods based on sustainable forest use (Wallace, Gomes and Cooper, 2018). In northern Bolivia, wild rubber tapping, linked to a debt-patronage system, was a significant part of economic activity up until its decline the early 1990s (Romanoff, 1992; Stoian, 2000).

At present, wild rubber extraction continues in some communities in the Amazon (including in Brazil, Peru and Bolivia) but is not a major source of latex production (WWF-UK, 2014; WWF Brasil, 2015; Fitts, Cruz-Burga and La Torre-Cuadros, 2020). Some individuals still identify with their traditional cultural identity as a “rubber tapper”, but it does not necessarily reflect their economic activity, nor do they always see themselves as “environmental defenders”⁵ (Gomes, Vadjunec and Perz, 2012).

Associated terms: wild rubber; native rubber; extractivism; rubber tapper.

Management intensity: Little management, wild rubber trees are allowed to grow naturally in the rainforest.

Complexity: Highly complex in structure and species, as wild rubber trees grow naturally in the rainforest.

Planting design: Wild rubber trees are randomly dispersed (as opposed to clustered), and tree density ranges from 0 to 4 trees/ha (average = 1.67 trees/ha) (Jaramillo-Giraldo *et al.*, 2017).

Example locations: Brazil (particularly the states of Acre and Rondonia); Peru; Bolivia.

⁵ Interview, anonymous researcher



2.3 TRADITIONAL JUNGLE RUBBER

“Jungle rubber” is a term used in the literature to refer to traditional rubber agroforestry systems found in Indonesia, where rubber trees were introduced into forests as part of swidden agriculture cycles (slash and burn systems), or via permanent gap-planting in secondary forest (“*sisipan*” system) (Wibawa, Hendratno and van Noordwijk, 2005; Vincent *et al.*, 2011). This type of rubber agroforestry system arose from people introducing rubber trees into their traditional swidden-based shifting cultivation practices (Feintrenie and Levang, 2009), and are characterized by being **extensive systems with very limited management and inputs, which typically use unselected (i.e. low yielding) non-clonal rubber seedlings. These systems are species rich and structurally complex as a result of natural regeneration of native plants** (Gouyon, de Foresta and Levang, 1993). In the permanent *sisipan* systems, jungle rubber plots consist of **rubber trees of different ages as smallholders maintain a number of productive trees by interplant-**

ing rubber seedlings in forest gaps, or allowing spontaneous regeneration from rubber seeds (Wibawa, Hendratno and van Noordwijk, 2005).

Traditional jungle rubber was historically a widespread practice in Southeast Asia,⁶ but is now mostly confined to the Indonesian islands of Sumatra and Kalimantan (Joshi *et al.*, 2003). Even here, traditional jungle rubber systems are increasingly being converted to intensively managed rubber and oil palm monocultures, which provide greater income (Ekadinata and Vincent, 2011; Clough *et al.*, 2016). This type of rubber agroforestry system has received considerable research attention due to its potential for conserving biodiversity, and maintaining forest connectivity between isolated remaining patches of lowland rainforest, while providing cash income to farmers (Joshi *et al.*, 2003). In particular, the Indonesian branch of ICRAF and the Indonesian Rubber Research Institute set up a network of demonstration and research plots

in Jambi, West Sumatra and West Kalimantan, to try and encourage maintenance of jungle rubber systems (Penot and Ari, 2019). They tested the potential for enrichment planting of seedlings or grafted-clonal rubber plants in jungle rubber to improve latex yields and income, as well as different spatial arrangements of intercropping and species (Williams *et al.*, 2001; Wibawa *et al.*, 2006; Vincent *et al.*, 2011; Penot and Ari, 2019). However, switching to clonal rubber plants led farmers to intensify management, making it closer to a typical plantation than a traditional jungle rubber system (Williams *et al.*, 2001). These cases of clonal rubber planted in forest plots

“Traditional jungle rubber systems are increasingly being converted to intensively managed rubber and oil palm monocultures.”

⁶ Interviews, Sara Bumrungsri and Uraiwan Tongkaemkaew.



“may therefore be closer to the “modern” jungle rubber systems detailed below, but the variety of rubber agroforest systems in practice defy neat categorisations into any strict typology.

Associated terms: old jungle rubber; complex rubber agroforests; rubber enriched secondary forests.

Management intensity: Variable, much lower than systems using clonal rubber.

Complexity: High structural, functional, and species diversity, similar to a secondary forest. May be defined by a closed canopy and a dense undergrowth layer dominated by many shrubs, small trees, and seedlings of canopy species (Gouyon, de Foresta and Levang, 1993).

Planting design: Highly variable, likely unplanned – e.g. Gouyon (1993) found rubber tree densities ranging from 200 trees/ha (40-45 year old plot in Jambi) to 490 trees/ha (35-40 year old plot in South Sumatra).

Example locations: Indonesia (Kalimantan, Jambi, North Sumatra, West Sumatra); historically existed in Thailand and Malaysia but few remaining.

2.4 NATURAL REGROWTH / MODERN JUNGLE RUBBER

The term “jungle rubber” is also used by farmers, practitioners, and researchers⁷ to refer to rubber agroforests that start off as a typical monoculture, but are left unmanaged for some time, and the resulting natural regrowth of shrubs and trees make it resemble traditional jungle rubber or a secondary forest. Reasons for such rubber areas

sometimes economic – when rubber prices are low, smallholders may find that it is not worth tapping/maintaining rubber trees and switch to other more profitable livelihood sources. Alternatively, in some cases more experienced rubber growers prefer to leave inter-row vegetation to develop naturally, understanding that this does not affect rub-

ber yields. These systems have limited management (i.e. receiving little or no fertilization or weeding), but naturally regenerating species may be selected for their economic value, as some smallholders have done in Thailand.⁸ Allowing natural regeneration in rubber monoculture plantations may have environmental, livelihoods and sociocultural

⁷ Interviews, Gerhard Langenberger and Sara Bumrungsri.

⁸ Interview, Michael B. Commons. The interviewee described how a smallholder farmer allowed natural regrowth in one of her rubber plots near a forest preserve, selecting for useful species such as wild *Garcinia* (related to mangosteen fruit), and it now “looks like a forest” with thick vegetation.



Natural regeneration rubber in Malaysia.

Credit: CC BY-NC 4.0 MWMH

benefits, as native plants help support biodiversity⁹ and provide additional sources of income and culturally important products such as medicinal herbs and flowers.¹⁰ Allowing natural regeneration also reduces input costs and labor, as fertilisers, herbicides and time taken to clear vegetation are no longer needed. However, this practice may also be culturally stigmatised, i.e. a fear of increased snakes, mosquitoes, or ghosts in an overgrown plantation,¹¹ or smallholders being seen as “lazy” for having an “untidy” farm.¹²

There is grey area between “traditional” and “modern” jungle rubber, as there is a continuous scale of management intensity, complexity, and planning/design between the systems.

Associated terms: (improved) jungle rubber; (simple/complex) rubber agroforests.

Management intensity: Typically uses clonal rubber (but not necessarily); limited management and inputs.

Complexity: The longer the plantation is left unmanaged and natural succession allowed to proceed, the more complex it is likely to be (in structure, function and species diversity) and the more it will resemble a secondary forest.

Planting design: Usually standard planting densities as used in monoculture, but can vary depending on how much planning was involved.

Example locations: The best examples are known from Southern Thailand, but modern jungle rubber systems likely exist in every country with abandoned rubber plantations.

9 Researchers noted that rubber agroforests, particularly jungle rubber, supports higher biodiversity including birds, bats, insects, and earthworms (Interviews, Sara Bumrungsri and Uraiwan Tongkaemkaew).

10 Local native flowers, normally found in forests, spontaneously grow in rubber plantations and can be sold at higher prices. The flowers attract native birds, enhancing agro-eco-tourism potential, which is also a source of livelihoods (Interview, Uraiwan Tongkaemkaew).

11 Interviews, Uraiwan Tongkaemkaew; Linda Preil.

12 Interviews, Linda Preil, and anonymous.



2.5 PERMANENT INTERCROPPING

Rubber trees can be interplanted with harvestable non-timber and timber species, including food and non-food crops (e.g. timber, bamboo). A wide range of species have been intercropped with rubber, including annuals (e.g. cassava, maize), perennials (e.g. cocoa, coffee), fruit trees (e.g. mangosteen, orange), timber trees (e.g. teak, mahogany), palms, vegetables (e.g. *gnetum*), spices (e.g. ginger, cardamom), and mushrooms or various combinations of these. Permanent rubber intercropping systems differ from temporary intercropping (where annuals are planted only in the first few years of rubber establishment) as intercrops are grown throughout the plantation cycle i.e. after rubber trees mature and their leaves create a shaded environment in the plantation (canopy closure). Permanent intercrops can be planted before, at the same time, or after planting of rubber trees, depending on the light requirements of the intercrops. There have been field studies evaluating different planting densities and spatial arrangements for permanent intercropping with rubber (Rodrigo, Silva and Munasinghe,

2004; Zeng Xianhai, 2012; Sahuri, Rosyid and Agustina, 2016). Permanent intercropping systems are also commonly combined with temporary intercropping of annuals (e.g. cassava, maize, pineapple) and can also be combined with livestock or aquaculture.

Rubber-timber systems are a distinct subcategory of permanent intercropping systems, due to different requirements of timber crops (e.g. higher upfront costs, establishment needs, harvesting needs, timber regulations). Langenberger *et al.* (2017) states that studies of rubber-timber systems are scarce and sometimes unreliable. However, several researchers noted the potential for rubber-timber systems, especially in industrial plantation settings, due to high economic returns and low maintenance requirements. Native timber trees can also become a source for seeds and saplings. Species may include teak, mahogany, or native tropical hardwoods (e.g. *Shorea spp.*). Difficulties may arise around matching the planting/felling cycles of rubber with other timber species, and of canopy competition

between timber and rubber trees.

Aside from research on jungle rubber systems, the existing literature around social, economic and environmental outcomes of rubber agroforestry is dominated by studies of rubber intercropping practices and systems as described here, and agroforestry researchers also typically define rubber agroforestry in these terms (Box 1). For a comprehensive review of the history and agronomic challenges of rubber intercropping, including a classification scheme and a list of species that have been evaluated in rubber intercropping systems, please see Langenberger *et al.* (2017). This study notes that despite considerable field trials by rubber research institutes around the world and its commonly cited benefits, there seems to be limited adoption, or limited evidence of adoption of permanent rubber intercropping systems. We discuss reasons for this in a later section of this report.

Associated terms: intercropping, inter-planting, mixed cropping, intercalary cropping, al-



ley cropping, relay cropping.

Management intensity: Typically uses clonal rubber. Requires planning of which crops to plant and when/where. Weeding and fertilizer regimes vary widely by country/individuals/system.

Complexity: Ranges from simple to complex. Simple intercropping would involve rubber +

one other intercrop (e.g. rubber + tea, rubber + *gnetum*). Complex intercropping would involve multiple intercrops (e.g. rubber + fruit trees + vegetables). Structural and temporal complexity will depend on choice of intercrops (annual/perennial, shrub vs tree, timings of establishment).

Planting design: Possible under typical rubber monoculture planting design and densi-

ties, but may affect intercrop yields. Alternative rubber planting designs have been studied, the most commonly recommended being the double-row avenue planting design with wider interspacing between rubber rows.

Example locations: Diverse examples in many countries in Southeast Asia, Africa and South America.

2.6 RUBBER AS A TOOL FOR FOREST RESTORATION

A few researchers discussed the potential of rubber agroforestry as a tool for **reforestation/afforestation**,¹³ by planting rubber alongside native tree species on degraded or low-yielding soils.¹⁴ These native tree species can provide high value timber, non-timber forest products (NTFPs), or be ecologically important (e.g. rare and threatened species, such as shade-tolerant *Dipterocarpus* spp or

Shorea spp, both tropical hardwoods). The rubber trees can be tapped for latex up until their productivity drops, e.g. after 25-30 years, and then harvested for timber, leaving native tree species to continue growing. In this way, the plot undergoes (assisted) natural succession and resembles a native secondary forest, promoting biodiversity, ecosystem services and carbon sequestra-

tion, while also providing income to cover the costs of forest restoration, or for resource-poor communities (Omokhafa, Imoren and Samuel, 2019). An economic modelling analysis demonstrated that a rubber-native timber plot for ecosystem restoration is financially viable and even profitable for ecosystem restoration concession license holders (Harrison *et al.*, 2020). In addition,

¹³ Reforestation is the process of replanting a previously forested area with trees, while afforestation is planting trees in an area that had not been previously forested tree cover.

¹⁴ Interviews, Gerhard Langenberger; Rhett Harrison; Kenneth Omokhafa.

“It’s a theoretical concept – but if everyone plants a single native tree on every hectare, it could contribute to genetic maintenance of native trees.”

Gerhard Langenberger



rubber trees are being explored as a way to facilitate afforestation and to ameliorate desertification in the humid savannah, and restore forest status of the derived savannahs of Nigeria (Omokhafa, Imoren and Samuel, 2019; Omokhafa 2020). It can also be used to restore soil and remove cocoa-related diseases in Cote d’Ivoire.¹⁵ In addition, although this idea is closer to forest restoration than rubber agroforestry, a researcher suggested

that old rubber or cocoa plantations contaminated by white root rot can be restored by using native forest trees, and the old rubber stands can be a nursing stand for the new forest.

“It’s a theoretical concept – but if everyone plants a single native tree on every hectare, it could contribute to genetic maintenance of native trees.”¹⁶

2.7 DEFINITION OF SMALLHOLDINGS AND PLANTATIONS

This report uses the terms “smallholder” and “smallholdings” to refer to rubber growers who own or manage smaller plots of land with some degree of autonomy, in contrast to plantation models of rubber growing where larger areas of land are owned or managed centrally by a company with the use of hired labour.

Strict definitions of smallholdings often use a 2-hectare threshold (for example as used by the FAO (Rapsomanikis, 2015)), but the relevance of size thresholds varies among countries and other contextual factors. Individual cited studies should be checked if further information about land holding size is needed.

¹⁵ Interview, Eric Penot.

¹⁶ Interview, Gerhard Langenberger.



3 Agroforestry: effects on livelihood, social, environmental and climate resilience outcomes

This section of the report is based on a detailed literature review and interview responses from experts on the effects of rubber agroforestry, compared to monoculture where possible, on livelihood, social and economic outcomes. Almost all literature relates to smallholder farmers, but descriptions of systems are given in all cases to relate them large-scale plantations.

Food markets with local products in Thailand.

Credit: CC BY-NC 4.0 EWT



3.1 LIVELIHOOD OUTCOMES

This section summarises the effects of agroforestry practices on smallholder farmer livelihoods, including plantation-based agroforestry systems, broadly grouped under specific themes.

A comparative study of four agroforestry production systems in Lao PDR is shown in Box 2 **to demonstrate how land tenure affects food security and farmer autonomy. Outcomes of**

large-scale rubber plantation expansion onto lands previously used by smallholder farmers are not covered here, because it is not related directly to agroforestry.

BOX 2

CASE STUDY OF SMALLHOLDER LIVELIHOODS IN LAOS: LAND TENURE, FOOD SECURITY AND AGROFORESTRY CONSTRAINTS

A study on effects of tree plantation establishment for smallholder farmer livelihoods conducted four experiments in Lao PDR, for both rubber and eucalyptus: plantations established under concessions, contract farming arrangements, smallholder led agroforestry systems and plantations, and village land lease schemes (Haberecht, 2010). This study concluded that constraints imposed on farmers by rubber companies, which prevented them from diversifying their rubber systems, had negative impacts for farmers.

In Laos, intercropping is strongly dissuaded by rubber companies (who hold contracts with smallholders to plant and grow rubber) except in the case of rice in year 1, and in some cases maize on an ongoing basis. In some villages farmers stated that they were allowed to intercrop with chilli, galangal, sesame or beans, but the farmers either did not have enough time, or the soil was considered unsuitable for these specific crops. Companies stated that intercrops would compete with rubber and reduce yields, but meanwhile few incentives were offered for farmers to obtain income during the immature rubber phase. Despite this, ag-

ricultural experts throughout Laos widely promote intercropping. Rubber companies also prevented integration of livestock into rubber plantations, requiring farmers to pay compensation for any rubber trees damaged by livestock; this led to conflict between rubber and buffalo due to a lack of grazing land, and which were central to village life. At a district level, there was a strong effort to move from subsistence farming to market-oriented farming, but this was challenging in the transition phase while farmers waited for rubber to become productive.



The concession model has been dominant in Lao PDR so far, and much plantation expansion under this model has resulted in negative outcomes for customary land rights, livelihoods, and environmental values. However, some plantation companies have allowed local households to intercrop within plantation boundaries, while also providing wage labor opportunities. These companies were also reportedly “more participatory, transparent, and locally responsive” during the land acquisition process.

Land sharing models, where villages mapped land to be included in the plantation in a participatory process in exchange for village development funds for infrastructure, could either result in labor being brought in by the company to directly manage the plantation, or by contracting local people to clear land themselves and assume responsibility for planting and maintaining plantation trees.

Contract models involve companies providing capital investment to establish rubber, market access and technical expertise, while farmers provide land and/or labor; benefits may be shared via latex-sharing or land-sharing. In two villages with land-sharing models, households could farm crops (primarily rice) between rows of planted eucalypt trees (presumably the same

would be possible for a rubber system).

Independent establishment of agroforestry by smallholders was not reported to be widespread for rubber, but systems of incense-bark trees (*Persea kurzii*) on seven-year rotations with intercropped banana and rice, had been established by smallholders independently.

In most cases, in the contract and independent smallholder models, households did not have formal land titles, but decisions were made instead based on locally-recognised customary land rights following forest clearance for shifting agriculture.

Net present values (the total predicted economic returns for a plot of land over a future period of time, discounted to account for inflation) or eucalyptus plantations under the four systems were compared (based on interviews and questionnaires in four villages), including input costs (zero for villagers in most cases as the company covered costs), benefits packages made to the villages, and crops including intercrops. Some contract farmers were unable to sell their trees at the end of the plantation cycle, meaning some received no return for their investment at the end of the plantation cycle. Returns for independent smallholders practis-

ing agroforestry (incense-bark trees, banana and rice) were at least double the returns from other systems, even plantations with intercropped rice. Many farmers expressed a desire for autonomy, e.g. preferring to plant at ‘their own’ tree spacing and selling ‘their own’ wood to companies independently of other farmers i.e. not being tied into contracts. It was noted that the lucrative banana intercrops under the incense-bark trees would not be as possible under eucalyptus due their high light requirements; the same problem may apply to rubber.

All systems involving companies resulted in households receiving less income than the companies predicted, due to theft of payments, lower yields/failure to plant intercrops, and inability to sell plantation trees at the end of the cycle as expected. Overall, the study emphasised the importance of intercrops in tree plantations for household benefits, that Lao farmers and rural communities prefer diversified livelihood strategies to being reliant on single crops, and recognises farmers’ desire to maintain a level of livelihood autonomy and agency, reinforcing earlier studies that show the importance of agroforestry systems in Lao PDR (Simo, Kanowski and Barney, 2020).



3.1.1 INCOME DIVERSIFICATION, ECONOMIC ANALYSIS AND LIVELIHOOD RESILIENCE

To what extent can income and livelihoods diversification through the adoption of agroforestry systems help maintain income and livelihoods during the rubber immature period, and during periods of rubber price volatility?

3.1.1.1 WILD RUBBER

Most examples of wild rubber production effects on livelihood to date come from Latin America and specifically Brazil. In Brazil, rubber tapper communities associated with extractive reserves have been diversifying livelihood sources, including cattle ranching which has been associated with forest clearing (Brown and Rosendo, 2000; Wallace, Gomes and Cooper, 2018) as well as moving away from forests to urban centers (Gomes, Vadjunec and Perz, 2012; Wallace, Gomes and Cooper, 2018). In both Brazil and Peru, there have been community-based management (CBM) initiatives, from both state governments as well as

external organizations (international CSOs, private companies, development agencies) to promote non-timber forest product (NTFP) extraction such as brazil nuts and other means of sustainable livelihoods (WWF-UK, 2014; Wallace, Gomes and Cooper, 2018; Fitts, Cruz-Burga and La Torre-Cuadros, 2020). An agroforestry researcher based in Peru noted that “there was a little revival of wild rubber with a rubber producer association [in Madre de Dios], but this did not last due to many circumstances (market players, organization structure, capacities etc).”

Studies in Acre, Brazil found that **wild rubber extraction can contribute to house-**

hold income especially for the poorest households, but long-term economic sustainability of this industry is not guaranteed (Jaramillo-Giraldo *et al.*, 2017; Wallace, Gomes and Cooper, 2018). Harvesting wild rubber in the Brazilian Amazon provides extremely low yields on a per-area basis. Specifically, with an average tree density of 1.67 trees/ha, and each tree producing 1-3 litres/tree/year (compared to a global average of 2.26 litres/tree/year), 890 tons/year of dry rubber could potentially be extracted from the large expanse of forests of Southern Acre (average = 0.36 kg/ha/year, i.e. 0.00036 tonne/ha/year). While rubber extraction in native forests therefore is not economically viable without government subsidies, the maintenance of the rubber tapper identity is an important cultural value (Jaramillo-Giraldo *et al.*, 2017). Partnerships with CSOs in Rondonia, Brazil have improved the political empowerment of rubber tappers, but many households remain poor suggesting that income security from wild rubber is questionable (Brown and Rosendo (2000)).



Old rubber tree with weeds in Myanmar.

Credit: CC BY-NC 4.0 TCW

3.1.1.2 PERMANENT AND TEMPORARY INTERCROPPING

Intercropping strategies increase financial viability of rubber replanting for smallholders in Indonesia, as shown by two reports. A USAID report assessed the structure of loans for smallholder replanting in Jambi, South Sumatra, and West Kalimantan in Indonesia, including monoculture and agroforestry (rubber + two or more intercrops) models (USAID Green Invest Asia, 2020). They compared an adjusted Internal Rate of Return (IRR, a metric used to estimate the profitability of potential investments) between the two systems, assuming either a single clearance and replanting event, or a two-phase staggered clearance and replanting event (where half the land is replanted in one year, and the other half is replanted in the following year). Intercrops considered included banana and pepper during the immature phase, turmeric during the mature phase, and timber planted alongside rubber at establishment. Only the agroforestry models produced an IRR greater than 30% per annum, and **only the agroforestry model with staggered replanting was a viable option for a commercial rate loan**, with a total repayment of \$7,855 over seven

years. This demonstrates the improved financial returns from simple high rubber yielding agroforestry systems relative to monoculture rubber in the Indonesian context (USAID Green Invest Asia, 2020). Another study of rubber smallholders in Jambi and South Sumatra, Indonesia, investigated the feasibility of selling the wood of old rubber trees to finance replanting of rubber trees (WWF, 2020). The study found that rubberwood sales alone were insufficient to provide a convincing investment case for replanting, and **needed to incorporate agroforestry to be a viable financing scheme**. The agroforestry (intercrops during immature rubber phase) model, coupled with staggered clearance and replanting, **decreased the cash shortfall** of smallholder farmers and directly reduced their financing (loan) requirements.

In **Thailand**, several studies have shown the benefits of temporary and permanent intercropping in rubber production for smallholder incomes. In Northeast Thailand, rubber-cassava intercropping systems **lowered management costs** by nearly 60% during six years of rubber mature immature phase, compared to a monoculture rubber planta-



tion (Hougni *et al.*, 2018). The cash income from intercropping varied from 0 to **26.8% of the household's total annual income**, which can be of considerable importance for low-income farmers (Hougni *et al.*, 2018). In Northeast Thailand, where rainfall is a major constraint on crops during the dry season, cassava is favoured as a second ('insurance') crop in other systems as the tuber requires minimal care, little investment, and provides greater flexibility in planting and harvesting than longer term crops (Polthanee, 2018). Another economic modelling study in Thailand compared rubber monoculture with various agroforestry systems (fruit, timber, vegetable, livestock) to characterise multiple sources of livelihoods and incomes of smallholder farmers (Stroesser *et al.*, 2018). Most agroforestry farms were **more robust to rubber price volatility** (defined as systems where secondary agroforestry products mitigated the effect of lower rubber prices, leading to a system that remain profitable even when prices are

low) compared to monoculture farmers, who had an over-reliance on rubber trees for their income. The price volatility of other agricultural products also has an obvious impact on net outcomes. Farmers who planted fruits primarily did so for self-consumption, while the social role of edible species was also emphasised. Livestock was thought to reduce fertilization costs for rubber trees, while farmers also expected higher economic returns from agroforestry systems (Stroesser *et al.*, 2018). Moreover, agroforestry systems provide farmers with **different sources of income over different timescales**. For example, timber trees can be harvested and sold in 30-50 years, fruit trees like *long kong*, durian and mangosteen provide seasonal income annually, while vegetables provide weekly income (Stroesser *et al.*, 2018).¹⁷ **Timber trees and native forest species also provide seed and flowers with direct and indirect economic value**. For example, farmers in Southern Thailand collect seeds of timber trees and

“Agroforestry systems provide farmers with different sources of income over different timescales.”

grow seedlings that can then be sold.¹⁸ The flowers attract native birds and enhance agro-eco-tourism potential.¹⁹ Anecdotally, based on interviews with farmers in Southern Thailand, **stingless beekeeping** in rubber plots can even make the same amount of profit as income from rubber itself.²⁰ Moreover, agroforestry practices can reduce fertilization and weeding costs due to healthier soils, the use of organic animal manure, or the presence of cover crops,²¹ and indeed fertilizer use in agroforestry systems is lower than in monocultures in Southern Thailand.²² However, there is also evidence from Southern Thailand that **there is not necessarily a difference in in-**

17 Interview, Uraivan Tongkaemkaew.

18 Interview, Uraivan Tongkaemkaew.

19 Interview, Uraivan Tongkaemkaew.

20 Interview, Michael B. Commons.

21 Interviews, Rhett Harrison, Sara Bumrungsri.

22 Interviews, Sara Bumrungsri and Uraivan Tongkaemkaew.



Chilli paste rural enterprise in rubber-dominated landscapes, Thailand.

Credit: CC BY-NC 4.0 EWT

come, costs, or yield between monoculture and agroforestry systems, but the study is unclear about what types of income are included in these values (all crops, solely rubber, secondary crops sold vs consumed) (Kittitornkool *et al.*, 2019).

Further evidence from Asia and Africa, covering a broad range of intercrop species, show that intercrops can contribute a **significant proportion of total farm or household income**, which is especially important for the poorest households, and sometimes even **more profitable** than monocultures.

Smallholders in **Sri Lanka** have diverse strategies for intercropping, incorporating a wide variety of cash crops, food crops, or timber trees based on knowledge of soil and microclimate conditions on the plot as well as their needs, and this knowledge comes from the local farming community, personal experience, and extension services (Rodrigo, Thenakoon and Stirling, 2001). While rubber provided the main source of income, intercropping during immature rubber phase allow smallholders to intensify their small landholdings to

grow other crops for income, medicinal use, or for food. The study also pointed out that rubber estates should allow estate workers to intercrop on immature rubber land alongside maintaining the immature rubber trees (Rodrigo, Thenakoon and Stirling, 2001). A financial assessment of rubber-banana intercropping, based on agronomic experiments by the Rubber Research Institute of Sri Lanka, concluded that **intercropping rubber with banana at high densities can generate substantial income during the immature rubber phase**, and that the profitability was driven by banana yield, cost of inorganic fertilizers, labour costs, and banana prices (Rodrigo, Stirling, Naranpanawa, *et al.*, 2001). A study from Moneragala district in Sri Lanka found that **88% of farmers depended on rubber-based agroforestry income during the 6-7 years of rubber immature phase**, with an average net return of ~LKR 247,157 per year (US\$ 1,621), with rubber-cocoa generating the highest annual returns (Sankalpa, Wijesuriya and Ishani, 2020). In this case, it was concluded that **intercropping rubber with high-value crops and livestock** (such as groundnut, cocoa, pepper, and raising dairy cattle) **could**



reduce poverty, but intercropping with banana and maize could not. Education, other agricultural income, and non-farm income were significantly correlated with lower poverty, while larger household sizes was linked to higher poverty (Sankalpa, Wijesuriya and Ishani, 2020). In an older case study of a Sri Lankan village, changes in forest policy in the 1990s led to a new reliance on agroforestry strategies (Caron, 1995). When the adjacent forest was established as a protected area, restrictions on forest use meant that the villagers could no longer rely on swidden agriculture in forest and foraging of non-forest timber products (NFTP) for their livelihoods. In the face of land scarcity to grow their own food, homegardens incorporating cash crops (rubber and tea were the largest sources) and subsistence crops became a common livelihood strategy for villagers. Rubber and tea could provide **cash income** to buy food, and families interplanted flowering and fruit trees, tubers, and vines in between rubber rows for food. Rubber tapping was particularly done by women, alongside other activities in homegardens (Caron, 1995).

In **Xishuangbanna, China**, data from ~600 rubber farmers showed that only 28% of rubber farmers have adopted intercropping, accounting for 14% of land area managed by the surveyed farmers. Tea was the most frequently adopted intercrop (47% of farmers) followed by coffee (14%) and maize (25%). Intercropping was an important source of income for households in the lower income category. Intercrops contributed 16.5% on average to total household income but could go as high as 89% for low income farmers and, hence, a critical source of income for the poorest farmers (Min *et al.*, 2017). Similarly, in **Hainan, China**, the net present value after 30 years of rubber-tea intercropping was greater than a monoculture of either crop after 30 years based on measurements taken at a state farm (Guo *et al.*, 2006). State rubber farm workers in Xishuangbanna also practiced temporary intercropping during immature rubber phase (with pineapple, rice, and vegetables) as a livelihood diversification strategy (Xu, 2006).

In two regions of Mindanao, **Philippines**, intercropping between rubber trees yielded 18 - 32% of total farm income (Furoc-Paelmo *et al.*, 2018).

“The net present value after 30 years of rubber-tea intercropping was greater than a monoculture of either crop after 30 years.”

An experimental study in **Cote d’Ivoire** compared standard rubber monocultures with rubber intercropped with coffee, cacao, lemon or cola nut tree (all of which were already cultivated in the study area), in a field trial recording yields and inputs for each crop over 17 years. In the intercrop systems, rubber trees were planted in a double row with wide inter-rows (16m) to allow shorter tree crops to thrive. The yield of individual rubber trees was unaffected by intercropping. **Rubber-coffee and rubber-cacao were significantly more profitable than other intercrops and monoculture up to year 12**, with positive gross margins from year 3 for coffee, and year 4 for cocoa. Rubber monocultures only reached breakeven profitability in year 8. However, beyond year 13, the difference in profitability between monocultures and



coffee/cocoa intercrops was no longer significant. The low price of lemons made rubber-lemon unprofitable. Rubber-cola was also unprofitable because cola nut trees only become productive at year 7. Rubber remained the most important cash crop, accounting for 88% of total revenues, with intercrops contributing 4% (**cola**) to 25% (**coffee**) (Snoeck *et al.*, 2013).

A survey of 80 households in **Liberia**, assessing the socio-cultural feasibility of increasing agroforestry practices and tree cropping more widely (including rubber intercropped with rice, cassava and a bitterball vegetable), found that **increased income was the main motivator** (Fouladbash and Currie, 2015). The survey also found that households practising tree cropping had **diversified incomes**, and those using agroforestry had **better food security and nutrition** (Fouladbash and Currie, 2015) (see also section 3.1.5).

A study by the Rubber Research Institute of **Nigeria** surveyed 33 smallholder farmers across five states who practiced rubber inter-

cropping. Intercrops included cassava, yam, maize, plantain, watermelon, cocoyam, rice, pepper and millet in various combinations, and **all intercrop systems had positive gross margins** (i.e. made profit after accounting for costs). Cassava had the highest return per hectare in Edo, Delta and Ogun states, but coco yam and maize had the highest return per hectare in Akwa, Ibom and Kaduna states. Results depend on local market prices (T. U. Esekade *et al.*, 2014). Another study in **Nigeria** found that all 20 rubber farmers surveyed practiced temporary intercropping during years 1-3 of rubber establishment, increasing farm incomes. Intercrops included melon, maize, cassava, yam, pineapple, plantain, banana, melon, groundnut, cowpea and soybean. Cash income from rubber provided \$670-720 per year (mean per village, n = 10 per village), and secondary crops provided \$500-550; total income was \$1,234-\$1,340, but after input costs, net income was \$324-\$420 per year. These earnings were considered relatively low compared to other rubber-arable crop systems in Nigeria (Esekade, Ogeh and Akpaja, 2006).

“Households practising tree cropping had diversified incomes, and those using agroforestry had better food security and nutrition.”

Experimental work done since 1987 in northern **Gabon** by the CATH (Centre d’Appui Technique à l’Heveaculture, Technical Support Centre for Rubber Growing) has resulted in a range of crop management sequences for improving the productivity of traditional holdings. Intercropping with food crops has a positive effect on rubber tree growth. This work found that rice/ground-nut rotation gave satisfactory results, but that plantain generated the highest income (Enjalric *et al.*, 1999).



3.1.1.3 MARKETS FOR SECONDARY AGROFORESTRY PRODUCTS

Conceptually, rubber agroforestry systems provide a higher yield from the same amount of land area compared to monocultures, as any of the products from intercropping would provide additional value on top of the rubber harvest. However, income benefits from secondary crops in rubber agroforests are only possible if markets and market access exist.²³ This is the key limitation for agroforestry: for example, in rubber-lemon intercropping in Cote d'Ivoire (Snoeck *et al.*, 2013) or rubber-rattan agroforests in Kalimantan due to domestic policies that depress raw rattan prices (van Noordwijk *et al.*, 2014). Economic modelling work in Indonesia has shown that in Sumatran jungle rubber agroforest products were quite well valued, but despite this, returns to land remained low; the authors identified *Parkia speciosa* as a tree species that could potentially improve jungle rubber productivity, and help farmers cope with

economic crises (Lehébel-Péron, Feintrenie and Levang, 2011). Modelling of rubber-tengkawang (a *Shorea sp.* tree that produces fatty fruits, that can be processed for use as a cocoa butter substitute) agroforestry in West Kalimantan suggests that this could be more profitable than tengkawang monoculture. This analysis was based on field measures and interviews with farmers about input costs and local market prices. This tree species was traditionally cultivated, but low fruit prices and increasing demand for timber (*Shorea* are hardwood trees) mean many trees have been felled, rather than retained for fruit harvest (Winarni *et al.*, 2017). Promisingly, recent surveys of a rubber agroforestry experiment have shown that robust markets are emerging for some agroforestry crops, particularly fruits (Penot and Ari, 2019). Hence, the development of regional markets for raw and value-added secondary agroforestry products (e.g. via strengthening farmer networks, co-ops and associations) should be a key consideration for initiatives promoting agroforestry.

Food markets for intercrops from rubber intercropping systems in Thailand.

Credit: © both images EWT

²³ Interviews, Eric Penot and Bénédicte Chambon.



Experimental plots of high-yielding (clonal) rubber agroforestry systems were set up by ICRAF in Kalimantan in 1994. A review of evidence and outcomes from these experiments in 2019 showed that: income diversification from fruits and timber led to better economic resilience. However, poor markets for fruits and timber are currently real constraints for further development of these systems. People in the landscape where the experiments took place were experiencing land scarcity, due to conversion of much land to oil palm by companies. Control of the damaging and fire-prone *Imperata* grass was successful using cover crops in rubber systems, with benefits for farmers due to reduced fire risk. Overall, initial interest in rubber agroforestry and improved rubber growing practices in 1994, that led to this experiment, has fallen away in favour of oil palm cultivation - however, many farmers had kept rubber on to diversify their farming, and valued agroforestry. However, knowledge of good tapping practices to maintain yields, and availability of high-quality clonal planting material, are still in short supply (thanks to abandonment of initiatives since 1994 in favour of oil palm development) (Penot and Ari, 2019).

3.1.1.4 PAYMENTS FOR ECOSYSTEM SERVICES AND ECO-CERTIFICATION FOR AGROFORESTRY

Environment-economic trade-offs are common in agricultural systems and payments for ecosystem services (PES) schemes are one mechanism to offset the economic cost of e.g. wildlife-friendly agroforestry by providing a price premium or other financial incentive. In Indonesia, PES have been suggested to support very low-yielding but biodiverse jungle rubber systems. In Xishuangbanna, China, a contingent valuation survey of 2,500 people living in the city of Jinghong revealed a willingness to contribute financially to a reduction of existing rubber plantations for the sake of a partial restoration of the local rain forest. Interestingly, 58% of respondents did not think it was actually acceptable to put an economic price on nature, but 65% disagreed that they have a right to a sound environment without having to pay for it (Ahlheim, Börger and Frör, 2015). However, PES approaches must be carefully planned and monitored to lead to the intended and not counterintuitive outcomes. For example, agent based model-

ling and subsequent surveys in Xishuangbanna showed that only effectively planned PES schemes can successfully aid transfer of rubber monocultures into agroforestry systems (Smajgl *et al.*, 2015).

“Eco-certification is a multi-stakeholder approach that can incentivise agroforestry production practices with a price premium for both industry and small-holder producer.”

Eco-certification is a multi-stakeholder approach that can incentivise agroforestry production practices with a price premium for both industry and small-holder producer. Such certification systems have successfully been introduced for coffee and cocoa production (Tschardt *et al.*, 2015a) and have been suggested for other natural resource use issues (Wanger *et al.*, 2017). The clear benefit of eco-certification is that it is a customer and demand-driven, rather than government-de-



pendent. However, in comparison to coffee and cocoa, where the awareness of certified products is around 50% in Europe and North America (Tschardt *et al.*, 2015b), certified product market share of rubber is limited, partly due to the non-consumer facing attributes of most rubber end products (e.g. tires). Several eco-certification schemes do

exist for rubber plantations (e.g. FSC; Fair Rubber e.V; Rainforest Alliance; Global Organic Latex Standard) but uptake is currently very limited. Moreover, the lack of definition for agroforestry systems make certification of rubber agroforestry a challenge. Nevertheless, options for agroforestry eco-certification should continue to be explored to create

more market-based incentives for uptake of agroforestry practices and increase awareness of the multiple values (both market-based and non-market based values) of agroforestry among both consumers and producers/manufacturers.

3.1.2 LAND AND LABOR AVAILABILITY AFFECT AGROFORESTRY PROFITABILITY

Do rubber agroforestry systems provide improved returns on land and labor?

In general, **constraints on land and labor availability strongly affect the profitability of agroforestry practices** and systems for farmers. Agroforestry or intercropping could be a viable diversification strategy for farmers with small plots of land, where land is a key constraint but additional labour is available, although off-farm livelihood diversification options may also tie up labour availability.

For larger holdings, or industrial plantations, maximising yields from a single crop may be a preferred strategy, particularly for large-scale business operations. In addition, where land constraints are less of a concern, income or portfolio diversification can be done at the farm level (e.g. monocultures of different crops), which is simpler to manage than intercropping systems.²⁴ In these cases, it should

be noted that **some agroforestry practises may actually reduce labor requirements over time**, such as reducing intensity of weed removal or the use of long-term cover crops to suppress weeds, while providing additional benefits for soil and water management. **Strategies such as the selection of species that require little extra labor** until the option to harvest becomes preferable over a focus on rubber (e.g. due to market price changes, such as in Southern Thailand), and which **provide benefits for soil and water management in the interim** (such as in experi-

²⁴ Interview, Gerhard Langenberger.



mental systems in China), could be attractive.

Labour availability is repeatedly reported to be limited in case studies from Asia, where most rubber is produced, but is not reported to be a problem in case studies from Africa. Constraints on labour availability mean that the integration of additional plants into rubber monocultures either needs to be highly profitable, or must require little additional labour (for example, jungle rubber), for adoption of agroforestry to become widespread (Langenberger *et al.*, 2017). For example, in the Philippines, some areas of rubber plantations in Makilala, North Cotabato, are managed as agroforestry systems, but they do not contain any high value (presumably meaning cash crop) intercrop species, due to the cost of hiring additional labour to maintain additional crops, and the perceived risk of rubber trees contracting diseases from high-value intercrop species (see section 3.1.4 on pest and diseases). Instead, additional plant species are allowed to naturally regenerate (low labour), and are intended for plantation workers' consumption (Agduma *et al.*, 2011). Similarly, rattan harvesting from rubber-rattan agroforests in Kalimantan is labour intensive,

meaning harvesting is not being undertaken (Tata, 2019).

Jungle rubber has lower labor requirements than monoculture (104-115 person days per ha per year vs. 211 in monoculture) (Leimona and Joshi, 2010). Detailed work on mature productive jungle rubber and monocultures in Jambi, Sumatra, Indonesia, has shown that the gross margin per unit of land (ha) is much more variable, but significantly higher, in monocultures (up to ~\$800 USD per ha in 2015) than in jungle rubber, due to latex yields that are 2-4 times higher (Clough *et al.*, 2016). As land is a constrained resource, and jungle rubber is not competitive with monoculture per units of land, many farmers opt for the monoculture system, or even for monoculture oil palm rather than rubber. In contrast, gross margin per unit of labor was not significantly different between the two systems, but was greater in oil palm monocultures, meaning **where labor is a scarce resource, oil palm could be favoured over either jungle rubber or rubber monoculture** (Drescher *et al.*, 2016). The reduced labor inputs for oil palm allow people to undertake additional off-farm livelihood activities, representing another di-

versification strategy aside from agroforestry. This case study particularly demonstrates the importance of land and labor constraints for choice of farming practice. It should be

“Constraints on labor availability mean that the integration of additional plants into rubber monocultures either needs to be highly profitable, or must require little additional labor.”

noted that this study does not take into account longer term costs and benefits (which could be estimated using net present value, discounting costs and returns over time into the future), but compares returns for a productive year of each system. Establishment costs over shorter 25-year planting cycles in monocultures are likely greater than in jungle rubber systems where replacement of rubber trees is done continuously. However, continued conversion of jungle rubber agroforests



to monocultures in this region indicates that farmers perceive that monocultures are more profitable.

Another study compared the livelihoods and incomes of smallholder farmers in Thailand from rubber monoculture versus various rubber agroforestry systems (fruit, timber, vegetable, livestock) (Stroesser *et al.*, 2018). All agroforestry systems had the same or

greater returns to labor relative to monoculture, but some agroforestry systems provided poorer returns per land area relative to monoculture. The best agroforestry systems, both in terms of land and labor, included rubber trees with intercropped fruit and timber trees. Farmers also undertook off-farm activities to complement their family income (Stroesser *et al.*, 2018).

Finally, wild rubber tapping in the Amazon is difficult because wild rubber trees grow far apart in the forest and it takes substantial time to collect sufficient latex to be profitable, and economic returns are meagre (due to low rubber prices and competition with plantation rubber) (Brown and Rosendo, 2000; Gomes, Vadjunec and Perz, 2012; Jaramillo-Giraldo *et al.*, 2017).

3.1.3 YIELDS AND PRODUCTIVITY

Do rubber agroforestry systems affect the yield and productivity of rubber trees and intercrops?

Evidence for differences in rubber yields between agroforest and monoculture systems, and for yields of intercrops, is summarised here. The effects of agroforestry practices on soil health, water availability and microclimate on rubber tree stress, growth and yields are also mentioned (see sections 3.3.1 and 3.3.3).

3.1.3.1 RUBBER YIELDS

Rubber yields vary greatly among the biggest producing countries in Asia, with average yields in Indonesia being particularly low compared to neighbouring countries. Average yields are only 1.04 tonnes/ha (per year, presumed), with smallholders, who manage 83% of the planted area in Indonesia, having

yields of 0.994 tonnes/ha in 2017. However, this average figure masks strong differences in yields between production from jungle rubber (around 0.5 tonnes/ha) compared to monocultures growing clonal planting material (1.4 – 1.8 tonnes/ha). By contrast, Thailand produces 1.8 tonnes/ha, and Vietnam and Malaysia's productivity stands at 1.72 tonnes/ha and 1.51 tonnes/ha respectively, due to a much greater proportion of rubber area being planted with high-yielding clones. It is claimed that around 60% percent of smallholder rubber



cultivation in Indonesia is in rubber agroforests, or jungle rubber (USAID Green Invest Asia, 2020) (although no source was given for this estimate). Improving rubber yields is considered key for improving farmer livelihoods, as rubber provides the bulk of cash income even in agroforestry systems. The evidence summarised here indicates that **permanent and temporary intercropping of rubber trees has either no effect, or a positive effect, on rubber yields**. Studies from Sri Lanka, India, and Nigeria found that **intercropping improved rubber growth**, but rubber-maize and rubber-bamboo intercrops in Thailand **decreased rubber growth**.

Improvements in latex yield have been primarily driven by the development of high-yielding clones and improvement of tapping strategies (which improves long-term, rather than annual, yields by prolonging the number of years for which trees can be tapped) while fertilizer application seems to be only secondary (Vrignon-Brenas *et al.*,

2019). In particular, ethylene (a plant hormone commonly used to stimulate plant growth and fruit ripening) stimulation is often mentioned in discussions around rubber yields, as it allows a reduction in tapping frequency, and therefore increases returns to labour thanks to an increase in yield per tapping day by up to 78%. Fertilizing during the immature period may accelerate tapping commencement, and increase latex yield in the first few years of production, but current recommendations likely lead to over-fertilization (Vrignon-Brenas *et al.*, 2019). Agroforestry strategies (cover crops, intercropping and leaving crop residues on the soil) are widely practiced and can help fulfil nutrient needs of rubber trees (Vrignon-Brenas *et al.*, 2019), e.g. studies from Kerala, India show that the use of farmyard manure can reduce the amount of inorganic fertilizer used by up to 50% without a reduction in growth rates (Abraham, Joseph and Joseph, 2015).

Rubber yield and productivity per tree are

Rubber harvest and drying rubber mats in Dawei, Myanmar

Credit: © both images TCW



not considered to be affected by intercropping,²⁵ if the rubber trees are not shaded by taller trees,²⁶ and there are no other plants or trees in the rubber line,²⁷ as commonly reported by farmers experienced in rubber agroforestry. Multiple studies support this assertion, showing that **intercropping has no effect on rubber yields** (per tree; yields per land area will be altered if planting density of rubber trees is changed). A series of experiments by the Rubber Research Institute of India between 2001 and 2014 showed that **rubber yield was not affected** by a variety of intercropping strategies under typical monoculture planting design and rubber tree density (Jessy, Joseph and George, 2017). These intercrop experiments involved (i) interplanting young rubber with coffee, Garcinia, vanilla and nutmeg, (ii) interplanting mature rubber with shade-tolerant medicinal plants, and (iii) temporary intercropping with annual vegetables during the wintering (leaf-shedding) season of mature rubber, demonstrating that diverse intercropping strategies could work (Jessy, Joseph and George, 2017). Exper-

imental plots of high-yielding (clonal) rubber agroforestry systems set up by ICRAF/CIRAD in **Kalimantan** in 1994 showed no impact of agroforestry practices on rubber production, as long as there were no trees above the rubber canopy (Penot and Ari, 2019). Experiments in **Sri Lanka** intercropping banana during the first four years of rubber establishment also found that intercropping had **no effect on latex yield per tree**, and even enabled **higher yield per hectare** than rubber monoculture plots, as more trees could be tapped earlier in the intercropped plots (Rodrigo *et al.*, 2005). Results of a field trial in **Cote d'Ivoire** showed that the **yield of individual rubber trees was unaffected** by intercropping (with coffee, cocoa, lemon, cola) although spacing between trees was increased relative to the monoculture control (Snoeck *et al.*, 2013). Rubber yields as reported by farmers **did not differ** between agroforestry and monoculture systems in **Southern Thailand** (Kittitornkool *et al.*, 2019; Warren-Thomas *et al.*, 2020). An experimental study in **southeast Brazil** found that intercropping rubber trees with

beans (*Phaseolus vulgaris*) **increased per-tree rubber yields** relative to rubber monocultures (double row planting, with a wider inter-row than typically used in rubber plantations) (Righi *et al.*, 2008).

“Intercropping had no effect on latex yield per tree, and even enabled higher yield per hectare than rubber monoculture plots.”

A 17-year experimental study in **Hainan, China**, asked whether changing the planting arrangement of rubber trees (“double row”) allowed more light to reach the understory, to increase the yields of intercrops, affected rubber yields relative to a normal planting arrangement (“single row”) (Huang *et al.*, 2020). The double row plots had two adjacent lines of rubber trees planted 4m by 2m apart in a

25 Interviews Rhett Harrison, Eric Penot, Sara Bumrungsri, Uraivan Tongkaemkaew, Kenneth Omokhafa.

26 Interviews and email consultations, Rhett Harrison, Eric Penot, and Kenneth Omokhafa.

27 Interviews and email consultations, Eric Penot and Bénédicte Chambon.



'row', with an inter-row spacing of 20 m (420 trees per hectare), while the single-row plots were typical of most rubber plantations with trees planted in rows 7m apart, with trees 3m apart (480 trees per hectare). **Rubber yield per tree did not differ** between the double-row or single-row system, but total yield was lower in the double-row system only due to a lower planting density of rubber trees per hectare. Another field experiment in Sri Lanka used five spatial arrangements of rubber trees (single row, double row, triple row, three plant triangular and four plant square cluster) to test whether increased spacing between rubber trees would affect rubber tree growth and yields. Results over nine years showed that rubber growth and yields were highest in single row alleys and cluster designs than other systems, but **annual rubber yield per hectare did not significantly differ** across planting designs (Rodrigo, Silva and Munasinghe, 2004). Interviewed experts also considered that double-row avenue systems at a standard planting density of 410-420 trees/ha should not result in decrease in

productivity per tree. However, they reported that smallholders tend to plant rubber at much higher densities, which can reduce rubber productivity per tree,²⁸ as well as creating shadier environments which in turn reduce the productivity of intercrops.²⁹

Lastly, four studies, from Sri Lanka, India, Indonesia, and Nigeria, found that intercropping has a **positive effect on rubber tree growth**. A comparison of rubber tree growth and yields in monocultures and rubber-banana intercropping systems in **Sri Lanka** found that intercropping **improved rubber growth** over the six years of the study (Rodrigo *et al.*, 2005). Trees in the intercrop treatment **matured four months earlier** than monocultures, and while tree girth and height were greater in the intercrop system, bark thickness was unaffected. Intercropping also had no effect on latex yield per tree, meaning rubber yields per hectare depended only on rubber tree planting density. A second study, from India, found that intercropping with coffee, vanilla, *Garcinia*, and nutmeg led to

significant higher rubber growth (Jessy, Joseph and George, 2017). A third experimental study in Indonesia found that intercropping with annual crops positively affected rubber tree growth (Penot, 1997). A fourth, from Nigeria, conducted over four years, found rubber intercropped with cassava and plantain had a higher growth rate than monoculture rubber or rubber intercropped with tree crops (Avinger and cherry), allowing earlier commencement of tapping time (T. Esekade *et al.*, 2014). However, the use of nitrogen and potassium fertilizers for sustained growth rates was recommended as continuous intercropping could lead to soil nutrient depletion (T. Esekade *et al.*, 2014). In contrast, modelling of rubber-maize intercropping systems in **northern Thailand** suggests that **rubber tree growth is reduced** in intercropping vs monocultures, and that maize growth during the immature rubber phase needs to be supported by fertilization (Pansak, 2015). A study comparing a mature rubber monoculture (20 years old) with an adjacent agroforest (20 year old rubber + 10-year old bamboo in the

28 Interview, Rhett Harrison.

29 Interview, Gerhard Langenberger.



inter-row) in **southern Thailand** found that **rubber tree girth was reduced** in the agroforest, but this could be attributed to either the lack of fertilization in the agroforest, or the presence of bamboo but there was no evidence for root competition between bamboo and rubber (Andriyana *et al.*, 2020).

3.1.3.2 INTERCROP YIELDS

In general, shading from the rubber canopy are expected to reduce yields of intercrops (see also (Langenberger *et al.*, 2017) for a discussion), and this was confirmed by several studies reviewed below but results varied based on the intercrop used. Shading from the rubber canopy may sometimes even be beneficial, as shown for banana in Sri Lanka, and it has also been suggested that shading may increase the productive lifespan of the intercrops (an avenue for future agroforestry research).³⁰ Increasing the planting density of intercrops could be a way to recoup yield reductions from rubber shading.

Salak intercrop harvest in Thailand

Credit: © both images CC BY-NC 4.0 EWT

In Brazil, work in rubber-coffee agroforests established in 1999 (with rubber tree rows placed a-typically, with large 16m gaps between double rows 4m apart) showed coffee plants had lower biomass when grown under shade (although total biomass and therefore carbon stock was greater in the rubber-coffee system), but **coffee yields were similar** between the two systems, with more **reliable coffee yields in the combined system**, indicating that rubber-coffee agroforestry systems are viable in the Brazilian context, where coffee is the main crop (Zaro *et al.*, 2020). In contrast, in another experiment in Brazil, planting coffee in full sun versus in the shade of rubber trees, showed that air temperatures were reduced and humidity increased, resulting in changes in coffee growth, including a **reduction in coffee crop yield due to shading by rubber** (Araujo *et al.*, 2016). Another study found that **sugarcane growth and yields decreased with proximity to rubber trees**, indicating that rubber-sugarcane intercrop systems may be

³⁰ Interview, Gerhard Langenberger.



most productive for sugarcane yields during the immature rubber tree phase, or may need to be managed for by reducing shading of sugarcane by mature trees (spacing, or tree pruning). Rubber yields were not investigated (Guedes Pinto *et al.*, 2006).

Three experiments conducted by the Rubber Research Institute of India between 2001 and 2014 showed that **some intercrops performed better than others** (Jessy, Joseph and George, 2017). In one experiment, coffee, vanilla on *Glyricidia* standards, *Garcinia* and nutmeg were planted with young rubber without modifying rubber plantation management. The initial yield of all the intercrops was good, but when the rubber canopy began to shade out the intercrops, only vanilla and coffee sustained their yields. In the second experiment, nine shade tolerant medicinal plants were intercropped in mature rubber plantations. All nine plants were established successfully and produced decent yield without affecting rubber yield (*Alpinia calcarata* and *Strobilanthes cuspidata* were highlighted as the most promising species) but the authors noted that market demand was limited for

medicinal plants in India. In the third experiment, annual vegetables were intercropped with mature rubber trees during the rubber leaf-shedding season, again with no impact on rubber yield and decent yields for some vegetables (e.g. *Amaranthus* and cucumber).

In **Hainan, China**, the yields of yam bean, peanut, soybean, common bean and Arabica and Robusta coffee were compared between two rubber planting arrangements (see previous section). The double row system allowed direct sunlight to reach the intercrops. **All crops grown as intercrops yielded less than when grown in their own monocultures, but yield reductions varied among crops:** yam bean produced 75% of its yield in monoculture, while peanut yielded only 38%. Robusta coffee yields were 35% lower than in monoculture, but intercropped Arabica coffee yields were similar to monoculture Robusta. The authors concluded that based on yields alone, rubber-yam bean and rubber-Arabica coffee schemes were the two most promising intercrops (Huang *et al.*, 2020).

In **Sri Lanka**, several studies have found

mixed results for the effects of rubber tree on intercrops. Cinnamon can be intercropped with rubber, but it is most productive during the immature phase, with yields declining by 70% after eight years (when rubber canopy closes). A study of rubber-cinnamon intercropping systems at the Rubber Research Institute of Sri Lanka, where cinnamon was planted under 15-year old mature rubber trees, found that **cinnamon bark yields were unaffected by fertilizer application or cinnamon planting density**. Therefore, although cinnamon is limited by light availability, increasing planting densities under mature rubber can increase yields (Pathiratna and Perera, 2006). Pepper **did not perform well** under mature rubber, neither did tea after six years of rubber growth (even with 30% reduction of rubber planting density) (Rodrigo, 2001 as cited in (Rodrigo, Silva and Munasinghe, 2004)). However, another study found that **banana and rubber growth was improved** in rubber-banana intercropping systems, suggesting that in this case shade could be beneficial for in terms of moderating microclimate and alleviating plant stress (Rodrigo, Stirling, Teklehaimanot, *et al.*, 2001).



3.1.4 PESTS, DISEASE AND INVASIVE SPECIES

Do rubber agroforestry systems affect the occurrence of pests and diseases? Can agroforestry practices improve pest and disease management in rubber?

Agroforestry practices in non-rubber systems have been shown to provide pest control services relative to monoculture production (Maas *et al.*, 2016), although evidence for rubber agroforestry is currently lacking, and there are indications that some diseases could be more prevalent in rubber agroforests.³¹ Climate change also affects the distribution and intensity of pests and diseases of plantation crops and subsequent intensification approaches, meaning agroforestry strategies that reduce these risks will also theoretically improve climate resilience (Tscharrntke *et al.*, 2011a; Wanger *et al.*, 2018a) (also see section 3.3.1). Results from rubber agroforestry are mixed, suggesting that intercropping sys-

tems can, both be effective to regulate various pests and diseases but also amplify their occurrence depending on circumstances.

Interviewees reported that diseases can build up in the soils of monoculture rubber plantations.³² For example in Malaysia, the soil becomes unsuitable for rubber cultivation after two planting cycles, but this may be ameliorated with intercropping if rubber and intercrop rows can be shifted or rearranged within the plot to avoid build-up of diseases in the soil. This is an avenue for future rubber agroforestry research, as there do not appear to be any long term studies on the build-up of soil pathogens or their control

via interventions such as intercropping. In China, the presence of cassava intercrop between rubber trees seems to increase growth of a rubber-tree pathogen, white root disease *Rigidoporus lignosus* (although had no effect on another pathogen, *Corynespora cassiicola*). The authors suggest that cassava intercrops should not be recommended where the *R. lignosus* pathogen is present (Liu *et al.*, 2020).

The fire-prone but invasive Cogon grass (*Imperata* spp.) poses major problems for land management for agriculture in Southeast Asia (Bagnall-Oakeley *et al.*, 1996). Intercropping during the immature rubber phase helped manage *Imperata* re-growth in smallholder rubber farms in Sumatra, Indonesia (Penot and Ari, 2019). Moreover, jungle rubber systems effectively controlled *Imperata* invasion in the long term. However, *Imperata* regrowth occurred once intercropping ceased (unless intensive weed management was undertaken

³¹ Email correspondence, Eric Penot.

³² Interview, Rhett Harrison.



en) (Bagnall-Oakeley *et al.*, 1996). On the other hand, agroforestry practices can harbour more species such as snakes³³ or wild pigs (Vincent *et al.*, 2011) that are considered dangerous pests by rubber farmers.

Pests of rubber crops are more prevalent in South America, where *Hevea brasiliensis* is native. In Brazil, leaf-eating pest mites can severely damage rubber trees in plantations (severe infestation of *Calacarus heveae* mites can cause damages on leaflets, intense defoliation of plants and losses in latex yields of up to 54%). However, these mites can be infected with fungi (*e.g.* *Hirsutella thompsonii*), which can act as a natural pest control of the mites. A study comparing agroforestry with monoculture rubber found greater infection rates with the fungus, implying that agroforestry cultivation practices help support natural pest control of leaf-eating mites (Nuvoloni *et al.*, 2014). Another study asked whether

³³ Interview, Uraiwan Tongkaemkaew.

Rubber agroforest in Thailand.

Credit: E Warren-Thomas

rubber agroforestry species could act as reservoirs for leaf-eating pest mites (Bellini, de Moraes and Feres, 2005) and found that mites in both agroforestry and monoculture systems were similar (numbers of species, genera and families), and there was no evidence that agroforestry species served as a reservoir for pest mites.

Intercropping coffee with rubber may help reduce pest and disease damage in coffee by increasing shade, compared to coffee monocultures with full sun. Studies from Brazil found that coffee plants located $\leq 2\text{m}$ away from rubber trees had the lowest incidence of coffee leaf miner (Androcioni *et al.*, 2018), lowest incidence of disease (*Cercospora* leaf spot) (Androcioni *et al.*, 2015), but damage from leaf miners varied with distance to rubber trees and season (Righi *et al.*, 2013). However, increased shade may result in lower coffee yields.



3.1.5 FOOD SECURITY AND NUTRITION

Does adoption of rubber agroforestry improve household access to food and nutrition?

The latest global assessment of food security and nutrition conducted by the Food and Agricultural Organization (FAO) estimate that 8.9% of the world population are experiencing food insecurity (FAO/IFAD/UNICEF/FFP/WHO, 2020). This translates to 690 million undernourished people, including 64.7 million in Southeast Asia, where most rubber is being produced (although the estimate did not differentiate between urban and rural populations). Food security and nutrition issues are **strongly region and context dependent** but overall, smallholder farmers continue to be the backbone of global food security (Tscharncke *et al.*, 2012). A global meta-analysis of 45 studies found a **small but significantly positive relationship between diversifying smallholder production and nutritional diversity**, but the specifics depend strongly on local conditions (Sibhatu and Qaim, 2018). In Liberia, for example, food security is directly linked to crops that farmers can grow (Fou-

ladbash and Currie, 2015), whereas in many parts of Southeast Asia, it is argued that food security is linked to market-based livelihood strategies rather than local sufficiency of food production (van Noordwijk *et al.*, 2014). However, the FAO recommends that agricultural policies encouraging a move towards integrated methods of food production, including agroforestry, are considered, in order to improve dietary diversity, as well as providing other benefits (FAO/IFAD/UNICEF/FFP/WHO, 2020).

While agroforestry alone cannot solve all the challenges of food insecurity and malnourishment, it can be part of a multi-pronged strategy to improve and diversify food production within the current monoculture cash crop dominated system (thus improving food availability and dietary diversity), alongside other policies targeting other parts of food supply chains. Below, we summarise the

limited information from the literature and interviews directly relevant to rubber agroforestry and food security issues. We have found **only one study** (from Liberia) looking at **whether adoption of rubber agroforestry improves household food security**, and **none specifically looking at nutrition**. The few studies (across several countries) we report here found that food crops and livestock from rubber agroforestry were used to **supplement household food consumption**, but also indirectly as a **source of cash income for purchasing food** (sometimes to mitigate the loss of the community's access to forest resources for food and income). We also note evidence for the very substantial improvements in incomes from rubber cultivation relative to subsistence farming of rice for farmers in Sumatra, Indonesia (Penot, 2004).

A survey of 80 households in Liberia found that agroforestry households (not just rubber agroforestry, also agroforests of coffee, cocoa, palm, fruit trees with secondary crops) reported having better food security than monoculture households (Fouladbash and Currie,



2015). The food security indices measured in the survey found that 22% of agroforestry households ate three meals per adult per day, as compared to none of the monoculture households; while 70% of agroforestry households reported that they always had enough to eat, compared to 31% of monoculture households (Fouladbash and Currie, 2015). A survey of smallholder farmers in Nigeria also found that rubber agroforestry was adopted to meet food and nutrition needs, and to increase household incomes, with intercrops including fruits and vegetables grown for consumption, high-value fruit crops and livestock (including snails and bees) (Mesike, Eskhade and Idoko, 2019).

In Southeast Asia, it has been argued that food security is no longer closely tied to local sufficiency of production, but has transitioned to market-based livelihood strategies, where income security allowing access to markets to purchase food is the primary driver of food security, even in remote places (van Noordwijk *et al.*, 2014). Rubber and other cash crops have been replacing traditional swidden (shifting) agriculture in mainland Southeast Asia; in places with greater market

integration, this process is thought to have improved food security and resulted in fewer health and nutrition problems (van Noordwijk *et al.*, 2014). Indeed, the importance of cash from rubber cultivation for increasing food security in some contexts is very considerable – in Sumatra, Indonesia, the switch from growing rice for subsistence to jungle rubber, or monoculture rubber, increased returns to labour by four and 30 times respectively, offering far higher and more sustainable benefits to farmers than growing rice (Penot, 2004). However, the expansion of land use planning policy and government initiatives to avoid shifting cultivation in Lao PDR, which has included the promotion of rubber plantations, was reported by villagers to have decreased food security (Ramcilovic-Suominen and Kotilainen, 2020). Planting of monoculture rubber was considered to place food security at risk in Laos, particularly during the immature rubber phase before tapping could start to bring in income, as intercropping and integrating livestock into rubber plantations were strongly dissuaded by rubber companies, who hold contracts with smallholders to plant and grow rubber (Haberecht, 2010). There was also concern that the poorest com-

munity members, who are most dependent on non-timber forest products for food and household income, were losing access to resources due to forest conversion to rubber monoculture. (see also Box 2 for full details of the Lao PDR case study in section 3.1).

In Indonesia, it is possible to purchase rice grown elsewhere rather than needing to grow it within mixed systems when rubber prices are relatively higher than rice prices. However, smallholder farmers strongly recognise the role of agroforests in providing food products alongside rubber (for example rubber-rattan agroforests in Kalimantan, Indonesia, contain fruit trees and other food crops that provide food security for farmers (Tata, 2019)). In Sumatra, the conversion of jungle rubber agroforests to rubber monocultures suggests that not only rice, but other components of diets are bought at markets and therefore outsourced to other locations. However, farmers in these landscapes also switch from agroforestry to segregated land uses, e.g. growing vegetables/rice in plots separate from rubber monoculture to maintain some food cultivation (van Noordwijk *et al.*, 2014) (see also section 3.2.1).



In Mindanao, Philippines, rice and mungbean intercropping in rubber has been adopted by some farmers, especially during the immature phase (1-3 year old trees), with both products sold at market and consumed directly (Hon-drade *et al.*, 2017). Agduma *et al* (2011) report that although the plantation company (Platinum Rubber Development Corporation, Inc., Makilala, North Cotabato, Philippines) do not plant high value intercrop species, there is an area of agroforestry where additional plant species are used for food, medicine and sources of construction materials, fodder for livestock, fuel wood, source of fibre and other industrial and household uses, by local communities - so these systems provide additional non-market value, including food resources (Agduma *et al.*, 2011).

In Sri Lanka, there is evidence from a 1995 study for improved food security from agro-

forestry both through direct production, and increased cash income to spend on food at markets. Villagers living just outside the Sinharaja Man and Biosphere reserve planted rows of rubber trees intermixed with a variety of flowering and fruit trees (e.g. mango, papaya, breadfruit, jackfruit), tuberous crops and climbing vines in “homegardens”; fifty-five edible plant species were recorded in a survey. The designation of the adjacent forest as a protected area meant that for villagers, food procurement activities, such as shifting cultivation and collection of non-timber forest products and edible plants from the adjacent forest became illegal. Homegardens therefore became more important as a source of food and cash income. However, families were not food self-sufficient, and the majority of families in the village spent more than half of their monthly income on food (Caron, 1995).

An experiment from the Rubber Research Institute of India found that annual vegetables (*Amaranthus* and cucumber grew well) during the leaf-shedding or wintering season in mature rubber plantations without affecting rubber yield, and these vegetables can contribute to part of household food needs (Jessy, Joseph and George, 2017).

Finally, even in the well-developed market economies in Southern Thailand, old jungle rubber provides access to local and medicinal plants,³⁴ and certain food crops in rubber agroforests are planted for household consumption, especially those that are less productive (e.g. mangosteen). Other food crops have higher commercial value and so are grown as cash crops (e.g. snake fruit, salak, cempedak).³⁵

³⁴ Email consultation, Bénédicte Chambon.

³⁵ Interview, Sara Bumrungsri.



3.2 SOCIAL OUTCOMES

The changing dynamics and practices of rubber cultivation in Southeast Asia, and elsewhere, have a complex history (Warren-Thomas, Dolman and Edwards, 2015; Langenberger *et al.*, 2017). In some regions, such as Southern Thailand and Indonesia, rubber cultivation has been part of smallholder livelihoods for multiple generations. For example, see (Dove, 1993, 1994) for in-depth discussion on the history and political economy of forest-dwelling tribal smallholders in Borneo who have integrated *Hevea* rubber into swidden practices. Agroforestry systems were historically present in these places, but have been replaced with monocultures either in response to gov-

ernment incentives (Stroesser *et al.*, 2018) or changing market pressures (Drescher *et al.*, 2016). Food production has therefore been spatially separated from rubber production in these regions for a long time, while monoculture rubber has improved household incomes for many people in e.g. China, Thailand, and Indonesia. However, concerns around widespread land-grabbing, forced eviction, coercion to produce rubber, and displacement of Indigenous communities and smallholder farmers from lands used to produce food, for foraging, and areas of cultural and spiritual importance, have been raised in areas where rubber has expanded more recently, partic-

ularly mainland Southeast Asia (e.g. see Box 2, (Fox and Castella, 2013)). These histories and contexts influence the social outcomes of agroforestry practices in rubber cultivation.

To date, there have been very few published studies on the impacts of rubber-based agroforestry on social, gender, or land tenure as the literature has focused primarily on the agronomic, economic and environmental aspects of rubber agroforestry. Here, we synthesize the most relevant information on the **social outcomes of rubber agroforestry** from the literature and from the interviews.

3.2.1 GENDER

Do rubber agroforestry systems contribute to gender equity?

Gender issues in agroforestry systems are important to consider, because in many societies women and men have distinct roles and preferences, for instance in land-use decision

making, farm labour and domestic workloads, tree planting, and participation in rural value chains. This topic has been broadly approached across all continents with a focus



on the relevant laws, cultural and religious trends, access to natural resources, norms of behaviour, access to education and funds, daily economic roles, demographic issues, domestic roles and power dynamics, and available economic alternatives (see (Colfer, Catacutan and Naz, 2015) and special issue therein). For example, in Africa, female farmers frequently manage trees in agroforestry systems at the beginning, and also make up half of farm labor. However, women can face many more restrictions than men to access land, labor, education, extension, financial services and technology. Surveys have shown that there are also gender differences in ‘tree tenure’, whereby women may only have rights to use less-valuable by-products such as branches, fodder and indigenous fruits. Moreover, women only receive 5% of extension services. With access to the same resources,

women in African agroforestry systems could increase their yields by 20-30% (FAO, 2011; Kiptot, Franzel and Degrande, 2014).

Specifically on rubber agroforestry systems, very little peer-reviewed research has been published on gender equity and labour burdens. Interviews with researchers suggested that agroforestry could create more opportunities for female participation, because it requires more family labour.³⁶ Both men and women are thought to be involved in rubber farming and tapping (both monoculture and agroforestry) in Southern China, Thailand, Malaysia, and Indonesia.³⁷ Women are more involved in selling intercrop or agroforestry products such as fruits, vegetables, and native wildflowers.³⁸ For example, in Thailand, women form the majority of small-scale fruit and vegetable vendors at markets, and are more

³⁶ Interview, Sara Bumrungsri.

³⁷ Interviews, Rhett Harrison, Sara Bumrungsri, Uraiwan Tongkaemkaew, Michael B. Commons, and anonymous.

³⁸ Interviews, Sara Bumrungsri and Uraiwan Tongkaemkaew.

Woman in Dawei, Myanmar is processing raw latex

Credit: CC BY-NC 4.0 TCW



likely to prepare food for the family, which may be why most perennial vegetables and other basic food plants within agroforestry system are primarily managed by women.³⁹ This is consistent with observations from the literature from Indonesia that men play a larger role in physical tasks, and women contribute more to financial aspects (Villamor *et al.*, 2015). Where rubber trees are primarily managed by men, this may mean that women could manage the intercrops.⁴⁰ Some intercrop options may be culturally or traditionally more attractive to women. However, this depends on the existing demand placed on women's labor, as in some contexts, such as Southern Thailand, women may already be heavily involved in rubber tapping and tree management, alongside holding responsibilities for domestic management and care, and therefore have little additional labor to spare.⁴¹ Rubber agroforestry strategies could thus be tailored to local gender roles and cul-

tural preferences to increase female interest and participation in agroforestry that could offer additional benefits, including cash income. For example, in Nigeria, arable crops like melon, maize and cowpeas were traditionally handled by women.⁴² Another example noted by a practitioner in Thailand was that of medicinal plants, which more closely resonates with traditional roles of women.⁴³ To increase the **interest of women in agroforestry, women-led training in potential use of intercrops such as medicinal plants** was suggested.⁴⁴

In a case study of wild rubber extraction in an indigenous community in Peru, Fitts *et al.* (2020) found that women were more involved in forest management compared to other communities, but men's voices were given more weight in decision making due to traditions, language ability and knowledge of the topic. They surmised that this was a typi-

cal finding in forest management studies and REDD+ projects. Hecht (2007) criticised the lack of attention paid to gender divisions of labor in extractive reserves in rural Amazon, and highlighted a failed development project to promote rubber and brazil nut extraction, where women pulled out of the project because their labor was required (and generated better returns) in agricultural work. The authors also suggest that extractive reserves can be effective for gender equity, but attention needs to be paid to where they are located geographically (e.g. near areas with higher densities of economic trees), and what roles women play in labor.

In Jambi, Indonesia, surveys and role-playing games with farmers found differences in land-use preferences between females and males (Villamor *et al.*, 2014). In this landscape, a matrilineal inheritance system existed for rice paddies, whereas men could claim

39 Interview, Michael B. Commons.

40 Interview, Rhett Harrison.

41 Personal observation, Eleanor Warren-Thomas.

42 Interview, Kenneth Omokhafa.

43 Interview, Michael B. Commons.

44 Interview, Michael B. Commons.



land rights by planting rubber trees. Most men tapped rubber while women grew rice. In the role-playing games, women were more likely than men to choose to convert jungle rubber into other more profitable land uses such as logging or oil palm monoculture. Men preferred to retain blocks of forests and jungle rubber for timber to use in building houses, whereas women preferred to retain only jungle rubber to support water supplies for electricity, irrigation, and drinking, demonstrating different values placed on ecosystem services. Women also preferred a spatial separation between rubber and vegetable gardens, due to the risk of wild boar (that live in forest) damaging vegetable crops (see also section 3.1.4). An exercise in a semi-matrilineal community in Sumatra revealed similar trends, with women more likely to convert jungle rubber to economically profitable rub-

ber and men preferring to retain rice fields and jungle rubber (Villamor and van Noordwijk, 2016). The researchers suggest that it was important to involve women more directly in information dissemination activities regarding the environmental values of forests and jungle rubber, to improve outcomes of projects designed to promote conservation of these systems.

Villamor *et al.* (2015) found that gender roles and perception of gender roles in Sumatra were shifting with land-use changes, as rice-based swiddens and jungle rubber are converted to monoculture oil palm or rubber production. While their findings were detailed and complex, they suggest that in the lowlands, where the largest shifts in land-use systems have occurred, women are increasingly more involved in rubber agroforestry

and other agricultural work which were traditionally men's responsibilities. They also noted that women had relatively more responsibility in managing farm finances compared to the physical work.

Finally, Fouladbash and Currie (2015)'s survey of tree-cropping households in Liberia found no significant differences in gender between household heads that practiced agroforestry (in the case of rubber farms, this refers to temporary intercropping during immature phase) and households that only practiced monoculture. However, they found that female household heads were less likely to practice tree cropping, which they found to be consistent with other studies in Liberia and across Sub-Saharan Africa. This could have implications for uptake of agroforestry practices in the region.

3.2.2 LAND TENURE

Do rubber agroforestry systems improve land tenure security?

Planting and managing trees can help confer some form of tenure to the owner of a farm plot. For example, in Sri Lanka, growing rubber helps confer land tenure because rubber trees provides a permanent and continuous income (Rodrigo, Thenakoon and Stirling, 2001). This means that despite low rubber prices, some farmers still choose to plant rubber, as the trees require little maintenance can help improve land tenure security for the entire farm system. Similarly, in Nigeria, agroforestry involving permanent crops like rubber trees improved land tenure security compared to annual crops alone.⁴⁵

Similarly, intercropping rubber with timber can increase duration of land tenure, because some national policies grant longer leases

of land for forestry than for agriculture (in some countries rubber is classified as an agricultural crop and not timber). In these cases, incorporating timber trees into farms will improve land tenure security. However, some smallholders may want to leave farming and, hence, prefer shorter term or annual crops over timber trees that will not tie them to the land.⁴⁶ In other words, longer leases of land or land tenure is not always the preferred option of the farmers.

Temporary intercropping in rubber plantations allows villagers in Lao PDR to maintain their livelihoods after involuntarily losing land tenure to company investments (IUCN and NERI, 2011). In some locations, rural livelihoods are negatively affected when

large companies transform forest into rubber plantations, as in land-grabbing in Cambodia (Schoenberger and Beban, 2018). Local people are, in some cases, only able to maintain their livelihoods because they are able to intercrop in the plantations and, hence, rubber agroforestry partly mitigates the negative effects of lost land tenure (see also Box 2).

Rubber agroforestry may lead to forest clearing as happens with cacao agroforestry.⁴⁷ For example, in Peru a lack of tenure security, government capacity to enforce encroachment onto forested land, or, simply, because many smallholders have forests on their agricultural land, agroforestry revenues could stimulate forest conversion into agroforestry plots. In these cases, certification mechanisms may help to incentivise forest protection (Tscharntke *et al.*, 2015).

⁴⁵ Interview, Kenneth Omokhafa.

⁴⁶ Interview, Rhett Harrison.

⁴⁷ Email consultation, Julia Quaedvlieg.

3.2.3 OTHER SOCIOCULTURAL BENEFITS

Farmers in Southern Thailand reported strong social benefits from rubber agroforestry practices, including teaching other farmers, sharing seedlings and secondary crop products, and participating in nationwide agroforestry social networks (Theriez *et al.*, 2017, Kittitornkool *et al.*, 2019). People who planted fruits in rubber agroforests primarily did so for self-consumption, while the social role of edible species was also emphasised in the Thai context (e.g. providing fruits to gift to others) (Stroesser *et al.*, 2018). Agroforestry farmers in Thailand have additional opportunities: they have “better opinions and are more creative”, report that agroforestry benefits others, and that additional revenues from agroforestry can be given to their children.⁴⁸ (See Box 3 on farmer autonomy and Box 4 on connecting networks for case studies of agroforestry farmer networks in Southern Thailand).

The indirect role of attention from international researchers interested in agroforestry has also affected farmers in Southern Thailand.⁴⁹ Researchers stated that farmers benefitted from international researcher visits: international students stayed with farmers who practise agroforestry to conduct research, which increases interest from other farmers, bolstering farmer confidence in agroforestry. It should be noted that this is unlikely to be a widespread or sustainable long-term benefit of rubber agroforestry.

Agroforestry has the potential to allow for more flexible tapping schedules, enhancing participation of women and quality of life for rubber tappers.⁵⁰ The reason for tapping at night is that cool temperatures improves latex flow. Theoretically, rubber agroforestry can keep microclimates on farms cooler, which could potentially allow for more

flexible tapping schedules without affecting yields. This could make rubber tapping more amenable to women, as tapping at night can be a safety concern, as well as increase the quality of life for rubber tappers. However, this is so far unsupported by any empirical evidence, and would need a much stronger evidence based before it should be used as a reason for wider adoption. See also section 3.3.1.3 on microclimates.

For wild rubber tapping, Brown and Rosendo (2000) found that while partnerships with CSOs in Rondonia, Brazil, improved the political empowerment of rubber tappers, they did not improve livelihood conditions of the poorest.

48 Interview, Uraivan Tongkaemkaew.

49 Interview, Uraivan Tongkaemkaew.

50 Interview, Michael B. Commons.



BOX 3

FARMER AUTONOMY IN A FARMER NETWORK-INDUSTRY PARTNERSHIP, SONGKHLA PROVINCE, THAILAND ^{51, 52}

The agroforestry farmer network in Songkhla began as a group of farmers who had a **common passion for planting trees** from seedlings that were being given out for free from the Royal Forest Department. A local university researcher became involved when the group invited the researcher to give a lecture on agroforestry. They were subsequently approached by Einhorn, a condom company based in Germany, who were looking to directly source latex produced via fair and sustainable means.

Facilitated by two local consultants, this group of about 35 agroforestry farmers came up with a common vision for how they wanted to work with each other and with Einhorn, which was formalised as a **participatory guarantee system**. The participatory guarantee system is an arrangement where the farmers themselves define their own standards and regulations for being part of the group. For example, they have agreements on the usage of agro-chemicals, or agroforestry criteria such as having at least 30

other species in their rubber plots, including not just timber trees but also bushes and herbs, or integrating bees or other animals.

Members of this farmer group have also learned to measure the dry rubber content in latex and assess latex quality themselves, and so do not have to rely on middlemen. They manage an independent **group latex collection point**, from which their latex is picked up by the processor, and the farmers receive a **premium** for the latex they send.

Additionally, the agroforestry farmers are also **collecting information** on the species in their agroforestry plots and on different intercropping ideas, working closely with researchers from Prince of Songkhla University in Hat Yai, Thailand.

Currently, Einhorn purchases about 30-35% of the agroforestry farmers' latex output for their condom production, but they are work-

ing with their condom manufacturer (Richter Rubber) to market the sustainable latex to other companies.

This farmer network – industry partnership model based on the participatory guarantee system seems to be working well thus far. **Economically**, it has helped by securing a price premium and direct access to processors for their rubber latex. **Socially**, the farmers have increased autonomy, and they show enthusiasm and pride in their work and how their ideas are being spread to others. The Royal Forest Department also supports the farmers' travel to other regions in Thailand for meetings and trips, during which farmers meet other farmers to exchange ideas. Farmer networks will continue to benefit from the latest knowledge in farming practices and support to further develop their business models, especially in terms of managing and marketing agroforestry products other than rubber latex.

51 Interviews, Linda Preil and Sara Bumrungsri.

52 YouTube video about Einhorn's project: <https://www.youtube.com/watch?v=VY1k-1looc4>

BOX 4

CONNECTING AGROFORESTRY FARMER GROUPS IN PHATTALUNG PROVINCE, THAILAND⁵³

In Phattalung province in Thailand, adoption of agroforestry practices originated from individual pioneer initiatives that spread more widely through farmer-to-farmer networks (Thaler *et al.*, 2019). The smallholder farmer network was reportedly initiated around common values (local species preservation, increase of farmers' income) with the objectives of better access to funding and knowledge sharing. Farmers appeared motivated to join collective action by incentives such as access to funding or to activities organised by local government agencies. When farmers were asked about their

reasons for joining a group/network, the most frequent answer was to share knowledge or to learn about agriculture, and the next most frequent was access to government support.

Within the networks farmers shared information, such as the plants they used in their agroforestry systems, and also worked together to market the products. Researchers from CIRAD and Thaksin University worked together with these rubber agroforestry smallholders. With the aim of scaling-up rubber agroforestry systems from a marginal to a widespread system,

the researchers studied the feasibility of mobilising current agroforestry networks to set up an agroforestry innovation platform, which would better connect farmer groups with each other, and with other stakeholders involved in the promotion of agroforestry practices. Researchers also proposed the possible organisation of a regional innovation platform to co-construct and encourage the adoption of innovative agroforestry systems. The challenge now is to convince Thai institutions to take the leadership to initiate such a platform.

See also Theriez, M. *et al* (2017)

⁵³ Interview and email consultations, Uraiwan Tongkaemkaew and Bénédicte Chambon.

3.3 ENVIRONMENTAL OUTCOMES

This section addresses a number of inter-linked issues around the sustainability of rubber cultivation, in terms of climate resilience, climate mitigation, soils, water use, ecosystem resilience and biodiversity. Each of these

topics is strongly integrated with livelihoods, yields and pests and diseases that have been covered earlier in the report, but also relate to the global challenges of global heating and the extinction crisis.



3.3.1 CLIMATE RESILIENCE OF AGROFORESTRY

Do rubber agroforestry systems offer smallholder farmers climate adaptation potential and greater resilience to the effects of climate change?

Concerns have been raised that rubber is being established in increasingly marginal sub-optimal environments, i.e. those where rubber tree stress or death is likely due to drought, cold, wind damage or soil erosion, and that climate change is likely to exacerbate risks to rubber cultivation in future (Ahrends *et al.*, 2015). Although this analysis acknowledges considerable uncertainties, the study estimates that marginality will be exacerbated by climate change for up to 69% of current rubber area in sub-optimal locations (as defined in their study). Meanwhile, within highly suitable areas for rubber cultivation, such as Southern Thai-

land, there are increasing concerns that climate change induced changes to weather patterns may increase risks of disease and drought stress, potentially impacting rubber yields (Neo, 2020).

Although agroforestry systems are touted as win-win solutions for productivity, climate resilience and ecosystem services including climate mitigation (i.e. carbon storage), evidence from cocoa and coffee agroforestry shows that there are trade-offs between these benefits. Both crops grow in the shade of canopy trees, whereas rubber trees form the canopy, so conclusions are not directly transferable, but findings from these systems are informative. Coffee agroforestry systems can limit precipitation and drought impacts on coffee compared to non-shaded

Rubber-cocoa intercropping in Bahia, Brazil

Credit: CC BY-NC 4.0 TCW



plantations and, hence, could avoid income losses (Tscharrntke *et al.*, 2011b). Recent studies from West Africa show that cocoa agroforests with low- to medium shading created multiple benefits, including climate resilience, while maintaining production, but that once shading increased above ~30%, win-win scenarios were less likely, with trade-offs appearing (Blaser *et al.*, 2018). This work showed that while more shaded systems (i.e. more complex agroforests) could buffer some climate extremes (heat, drought, humidity) in some seasons, there were also negative effects, such as decreases in soil moisture in other seasons. Similarly, in smallholder coffee systems in Ethiopia, farmer incomes declined by ~70 – 80% in the 2015/16 El Niño year relative to previous years, and farmers with greater shade cover suffered most due to a combination of biotic and social factors (Morel *et al.*, 2019). A study from Ghana suggesting that cocoa monocultures are advantageous to reduce climate change impacts compared to agroforestry system due to water competition between cocoa and shade trees (Abdulai *et al.*, 2018)

has been rebutted due to major methodological flaws (Wanger *et al.*, 2018b). If cocoa and coffee systems can be considered a surrogate for rubber, agroforestry systems may support climate-resilient rubber production. This is congruent with thinking from Nigeria, where rubber trees are noted for their resilience and low maintenance costs which makes them suitable for agroforestry.⁵⁴ Evidence around rubber-specific climate resilience is summarised in this section.

3.3.1.1 WATER USE AND DROUGHT TOLERANCE

Water use of rubber cultivation systems is of considerable concern because rubber is often planted in locations with long dry seasons (Ahrends *et al.*, 2015), increasing the risk that climate-related drought events could impact production. Rubber is a **drought-avoidant plant with strong water uptake plasticity and it can avoid interspecific competition** by adapting which soil layers it takes water from (Wu, Liu and Chen, 2016b). Larger (older) rubber trees tend to absorb water closer to

the surface in both monocultures and jungle rubber (Hardanto *et al.*, 2017). Several studies assessed whether intercropping can enhance water use efficiency and drought tolerance of rubber. Overall, the literature shows that **intercropping rubber with other plants can improve soil water retention** across the whole system, although outcomes for wider-scale hydrology are unclear.

Rubber trees in jungle rubber adapt by taking up water from deeper soil layers, while rubber trees in monoculture mainly take up water from layers closer to the surface. In Sumatra, this pattern was because native trees would take water from shallower layers (Hardanto *et al.*, 2017). In Xishuangbanna, China, water use efficiency of rubber trees in jungle systems was more stable (i.e. more even water uptake across wet and dry seasons) than in monoculture, and jungle rubber has higher soil water content than monocultures in both wet and dry seasons, demonstrating that rubber trees in jungle rubber would be more tolerant to drought stress (Zeng *et al.*, 2019).

⁵⁴ Interview, Kenneth Omokhafa.



Rubber cover-cropping with legumes in drought-prone areas has been shown to have mixed effects on climate resilience. A study in northeast Thailand examined the effects of two cover crops (a legume *Pueraria phaseoloides* and a grass *Vetiveria zizanoides*) on the roots of young rubber trees, to assess whether they improved drought resilience. In shallow soils, rubber trees cropped with the legume grew faster, had higher leaf nutrients, and more fine roots in deep soil layers than monocultures, but rubber trees cropped with grass had no such effect. Trees with cover crops benefited from increased water extraction in deep soils. The authors suggest intercropping with the legume may increase drought resistance in young rubber trees, but might not reduce drought-induced tree mortality (Clermont-Dauphin *et al.*, 2018). This result came from an earlier study which found that in some plots where soils had low water storage capacity, rubber trees with the legume cover crop were less likely to survive intense drought despite having better nutrient content and growth (Clermont-Dauphin *et al.*, 2016). In China, the legume cover crop (*Flemingia macrophylla*) and rubber used different soil layers, increasing water use efficiency and drought tolerance of rubber (Wu, Liu and Chen, 2016).

In Xishuangbanna, China, water usage was more efficient when rubber trees were intercropped with tea or coffee but not cocoa (Wu, Liu and Chen, 2016b). It has been suggested that crops selected for rubber intercropping should have a “relatively fixed water use pattern, short lateral roots and a moderate amount of fine roots that overlap with the roots of the rubber trees in the shallow soil layer” (Wu, Liu and Chen, 2016b). Tea and coffee showed drought-tolerance strategies enabling them to compete for surface soil water. Tea was the best intercrop in terms of water use because moderate interspecific competition helped the soil retain water (Wu, Liu and Chen, 2016b). But in terms of rooting depths, cocoa, the legume *F. macrophylla* and rosewood (*D. cochinchinensis*) were preferable over coffee because the former intercrops have most of their fine roots in the topsoil (Chen *et al.*, 2017). Other rubber-tea studies confirmed that rubber and tea used water from different soil layers (Wu, Liu and Chen, 2017). Soil around tea rows contained more water than other parts of the plantation, alleviating soil drought on rubber terraces (Wu, Liu and Chen, 2017), while greater soil water infiltration around the tea shrubs may help reduce runoff and soil erosion, redistribute

soil moisture, increase deeper drainage and recharge groundwater (Zhu *et al.*, 2019).

“Rubber did not compete for shallow soil water resources with tea, cocoa and galangal intercrops.”

In contrast, a year-long study showed that rubber did compete for shallow soil water resources with tea, cocoa and galangal intercrops during the dry season, as all species primarily used water from the topsoil (0-20cm) (Yang *et al.*, 2020). However, intercropping also increased the available soil water, such that rubber trees acquired more water from the topsoil than when in monocultures.

Shallow rooted medicinal herbs (*Amomum villosum* and *Clerodendranthus spicatus*) may also help mature rubber trees use deeper soil water during the dry season (Wu, Zeng, Chen and Liu, 2019). Five years after establishing intercrops with these herbs, more water was transported, redistributed and stored in different soil layers (Jiang *et al.*, 2017). However, there



was no improvement in water use efficiency or soil water in these systems relative to monocultures (Wu, Zeng, Chen and Liu, 2019).

Studies of intercropping effects on water use from other locations are harder to find, but a comparison of rubber monocultures with intercrops of coffee, vanilla, *Garcinia* and nutmeg in India showed that soil moisture status during summer was higher in mixed planting systems compared to monocultures, while soil nutrient status was maintained (Jessy, Joseph and George, 2017). Finally, a study comparing a mature rubber monoculture (20 years old) with an adjacent agroforest (20-year-old rubber + 10-year-old bamboo in the inter-row) in southern Thailand found no evidence for root or water competition between rubber and bamboo roots. The authors suggest that although bamboo uses a lot of water, especially from the topsoil, its greater root density in the topsoil may actually increase the water-holding capacity of soils, as found in other studies on bamboo, as well as providing additional organic matter through leaf litter that can improve soil structure (Andriyana *et al.*, 2020).

3.3.1.2 FARMERS' PERCEPTIONS OF CLIMATE RESILIENCE

Rubber farmers in multiple locations **report concerns around climate change and consider agroforestry as an adaptation or mitigation strategy**, although no studies investigated whether these perceptions were based on observations. A structured survey questionnaire survey of 623 farmers in Mindanao, Philippines, found that farmers perceived drought (El Nino), typhoons, strong winds, heavy rains/excessive rainfall, flash floods and landslides to be evidence of climate change, and identified agroforestry and diversified farming systems as effective adaptation strategies (Furoc-Paelmo *et al.*, 2018). In Cote d'Ivoire, 384 people were surveyed about climate change and water impacts using focus groups, interviews and questionnaires. 95% of respondents were aware that climate change was occurring, reporting changes in economic activity (e.g. income losses) and cropping patterns (e.g. crop failures, yield losses, delays in cropping season, new pests and diseases) and food insecurity (Yeo *et al.*, 2016). Agroforestry (55% of people) was among various adaptation strategies to these changes report-

ed by communities (also: crop diversification (64%), crop substitution and calendar redefinition, agroforestry, borrowing from friends and money lenders, and increasing fertilizer application) (Yeo *et al.*, 2016).

In Southern Thailand, droughts and extreme rain are becoming more frequent, resulting in the deaths of rubber trees, and reductions in rubber yields. Trees tapped during droughts are reported to have reduced productive lifespans, while trees tapped during unusually humid conditions raises the risk of fungal diseases (*Phytophthora*), both of which reduce rubber yields and farmer incomes (Neo, 2020). Agroforestry practices may increase humidity and water availability on farms during droughts, potentially mitigating the effects of climate change on rubber yields in this region. It is also argued that reducing soil erosion and improving soil moisture and organic matter through agroforestry practices (evidence for which is provided in section 3.3.3 of this report) can improve rubber tree health and provide secondary agricultural products for consumption or sale and, hence, reduce risks from reduced rubber yields (Neo, 2020), see section 3.1.1).



3.3.1.3 MICROCLIMATE

There is **some evidence that rubber agroforestry can buffer the effects of normal fluctuations in microclimate**, but there is currently **little evidence that they could do so during climate change-induced extreme weather events**. Air temperature was lower (by $\sim 0.5^{\circ}\text{C}$) and relative humidity was higher (by $\sim 5\%$) in jungle rubber than monocultures (Drescher *et al.*, 2016). However, a three-year study of microclimates in forest, jungle rubber and monoculture rubber in Sumatra, which included the strong 2015 ENSO (El Niño) event, found that jungle rubber maintained more stable microclimate (in terms of air temperature, soil temperature, relative humidity and vapour-pressure deficit) than monoculture rubber, although not as stable as forests. This was mostly due to increased canopy cover. The relative effect of the ENSO event (reduced rainfall, increase temperatures) on below-canopy microclimate variability was smaller in monocultures than in forests because they were already more similar to open areas (e.g. already showing strong daily fluctuations in temperature). Changes in microclimate of jungle rubber during the

ENSO event was similar to monoculture, indicating that although jungle rubber had more stable microclimate in normal years, it could not buffer the effect of ENSO in the same way as natural forest. As jungle rubber reached comparable temperatures, humidity and vapour-pressure deficit as in monocultures during the ENSO event, despite having cooler and more humid conditions in normal years, this suggests that jungle rubber systems are still vulnerable to extreme climatic events (Meijide *et al.*, 2018). Overall, climate change related impacts are buffered in agroforestry systems by introducing shade trees. In rubber intercropping, rubber trees provide shade to other crops and, hence, positive effects can be expected for the overall system instead of just for rubber trees.

Nutrient cycling may be affected by climate change, by altering the seasonality of nutrient inputs. The seasonality of leaf litter fall, root litter and above-ground woody biomass production was compared between jungle rubber (where 35% of tree individuals were rubber), monocultures and rubber, to assess whether temporal fluctuations in litter inputs were more intense in species-poor-

er (i.e. monoculture) systems, because this could have knock-on effects for soil nutrient fluxes and nutrient use efficiency. Leaf litter fall was highly seasonal in rubber monocultures in response to rainfall, but was much more even throughout the year in jungle rubber (similar in quantity and temporal

“Diversified agroforestry systems may therefore have benefits for resilience of nutrient cycling the face of climate change.”

pattern to natural forest) where it happened irrespective of rainfall. The results suggest that **nutrient and carbon cycles are more directly affected by climate seasonality in species-poor agricultural systems** than in more species-rich systems, and may be more susceptible to inter-annual climate fluctuations and climate change (Kotowska *et al.*, 2016). Diversified agroforestry systems may therefore have benefits for resilience of nutrient cycling in the face of climate change.



3.3.2 CLIMATE MITIGATION THROUGH CARBON SEQUESTRATION

Do rubber agroforestry systems better sequester carbon? What role can rubber agroforestry play in climate adaptation and mitigation for industrial plantations?

We provide an overview of how carbon stock and sequestration are measured in the context of rubber monoculture plantations and rubber agroforests, which is important for understanding how to compare carbon outcomes between the systems. Differences in former land cover/land uses and the long-term destiny or end-use of the trees (in both systems) complicate such comparisons. In general, incorporation of additional plant species into rubber systems will **increase above-ground biomass**, and therefore **increase carbon storage** in agroforestry sys-

tems. While strongly context and tree density dependent, data on rubber carbon balances showed that when considering monoculture rubber plantations, net carbon sequestration (sinks/draw-down) occurs after conversion of arable land to rubber plantations, but carbon emissions (losses) occur if natural forest is converted to rubber. Therefore, **clearance of natural forest, or permanent jungle rubber agroforestry systems** (that are not felled on a cyclical basis) **will always have a net negative impact on carbon emissions and climate change.**

Vegetation growing in shade in natural regeneration under rubber, Malaysia

Credit: CC BY-NC 4.0 MSHW



“What happens to the trees after felling is critical to whether the carbon stored in trees can be considered a long-term carbon sink.”



3.3.2.1 CARBON ACCOUNTING OF RUBBER SYSTEMS – ESSENTIAL KNOWLEDGE

The carbon stock of a rubber plantation, or agroforest, is more difficult to measure than it may appear. Trees can help mitigate climate change by extracting carbon from the atmosphere as carbon dioxide, and laying it down in a stored form (carbon sequestration); carbon stocks are a measurement of the carbon stored in trees. However, the long-term destiny of the carbon stored in trees in any system (forest or plantation) must be considered, i.e. what happens once trees are felled at the end of a plantation cycle. If felled rubber trees are destined for paper or pulp, the carbon stored in them is likely to be re-emitted when these products break down/decompose over time. Alternatively, if the trees are used as timber, at least a proportion of carbon in the trees can be considered to be in a long-term or permanent stored state, offering benefits for climate change mitigation.

In the case of rubber plantations, estimates of the above-ground carbon stock of trees can be made through tree measurements – these represent the amount of carbon stored by the trees at any one point in time. However,

in a typical rubber plantation cycle, trees are planted, sequester carbon through growth over the plantation cycle, and are then felled after 25-30 years. Carbon stocks not only change throughout the duration of the plantation cycle, but what happens to the trees after felling is critical to whether the carbon stored in trees can be considered a long-term carbon sink, or whether the carbon will just be re-emitted. For example, rubber trees destined for the timber trade may be used for construction or furniture, meaning much of the carbon in the tree remains out of the atmosphere, or they may be used as firewood, or burned in-situ, resulting in re-release of stored carbon back to the atmosphere. A full life-cycle assessment of rubber-based products, including timber products, would be needed to fully quantify net carbon outcomes. However, in the case of converting a system with permanent tree cover (such as a forest, or agroforestry systems that permanently retain tree cover such as jungle rubber) to a cyclical plantation (such as a rubber monoculture or permanent intercropping within a normal 25-year rotation), there is usually a net emission of carbon.

Similarly, across a landscape, rubber planta-



tions (whether monocultures or agroforests) will be of different ages. So, when calculating the potential carbon stock of a whole landscape or region, a measurement of the maximum carbon stock of a mature rubber plantation cannot simply be multiplied across the area of interest. Instead, the different ages of plantations, and the cyclical nature of growing and felling, must be taken into account.

This is why when assessing the carbon outcomes of land use change involving cyclical plantations, the carbon accounting methods recommended in the IPCC Good Practice Guide recommend the use of time-averaged carbon stocks (taCs) which give the mean (average) or median (middle) value for the carbon stock over a plantation cycle, from planting to felling. By doing this, carbon stock estimates can be scaled up from a single plot or farm to the landscape level, accommodate clearance and carbon release at the end of the crop rotation, and better reflect the net carbon outcomes and long term climate impact of a transition from one steady-state land use to another (Warren-Thomas *et al.*, 2018).

There is strong evidence for soil carbon reductions when forest is converted to rubber (Blagodatsky, Xu and Cadisch, 2016) or other tree cash crops (Van Straaten *et al.*, 2015), but the Intergovernmental Panel on Climate Change (IPCC) tier 1 carbon outcome calculation method assumes no SOC change with forest conversion to perennial tree crops, so this is not always taken into account (Warren-Thomas *et al.*, 2018).

For rubber monocultures in Southeast Asia, a robust time-averaged carbon stock estimate for rubber is 52.5 tC per ha; this is based on multiple estimates of taCs calculated either as the carbon stock in the median year of the plantation cycle using logistic or Gompertz models of growth, or 50% of the carbon stock in the final year of the plantation cycle assuming a linear biomass increase (Blagodatsky, Xu and Cadisch, 2016). However, the maximum carbon stock achieved will be greater than this, e.g. 128.4 MgC ha⁻¹ for plantations in Thailand (Petsri *et al.*, 2013).

Lastly, carbon stock calculations are further complicated by continuous latex ex-

traction from the trees. A study from southern Thailand calculated that greenhouse gas emissions of fresh latex were between 56-169g CO₂ kg fresh latex depending on farm size (Usubharatana and Phungrassami, 2018). The same study suggests that the carbon footprint of latex rubber gloves is independent of farm size but is primarily driven by chemical fertiliser inputs in the farms. Hence, rubber agroforestry practices that reduce the use of chemical fertilisers should reduce greenhouse gas emissions in the rubber glove production supply chain. The study also demonstrates that latex extraction should be accounted for carbon stock calculations.

Together, these issues mean that **the benefits that rubber agroforestry can offer from a climate change mitigation perspective require careful thought**. The factors outlined in this section need to be understood, in order to accurately predict the outcome of adopting agroforestry practices on carbon drawdown (sequestration) and storage (stocks) – processes which can deliver benefits for climate change mitigation.



BOX 5

CARBON POOLS AND CARBON DIOXIDE

Natural systems contain a range of carbon pools including:

- Above-ground biomass
- Below-ground biomass
- Soil carbon
- Leaf litter/dead wood
- Rubber latex

Above-ground biomass (AGB) is the mass of the live portion of plants above ground (i.e. excluding roots), which is assumed to contain 50% carbon (above-ground carbon, AGC). This includes rubber trees, understory plants, and any secondary crops or trees.

Below-ground biomass (BGB) is the mass of the live portion of plants below ground (i.e. root structures). This is rarely measured, and is often assumed to be a proportion of above-ground biomass (e.g. 0.24, or 24% of measured AGB (Warren-Thomas *et al.*, 2018)).

Dead wood and leaf litter are assumed to eventually release its stored carbon into the atmosphere as carbon dioxide as it decomposes; these generally form a much smaller part of the total carbon pool.

Soil carbon is held in organic matter in the soil. It has the longest lifetime if it is undisturbed (i.e. it takes a very long time to decompose and release carbon dioxide) and therefore not only reflects current conditions, but also historical land use.

Latex collected from rubber trees should also be accounted for, as this harvest removes biomass from the rubber plantation system, and represents a long-term carbon sink, as rubber goods tend to have long lifespans (although production processes require carbon-emitting technologies and transport, meaning a life-cycle assessment approach may be needed to fully account for this).

Total carbon stocks in plantations depend on three main factors:

- plantation **age**
- plantation **management**, including tree density; latex tapping and fertilization
- **environmental and edaphic** (soil) **conditions** controlled by the local climate and topography

BOX 6

CARBON UNITS AND DEFINITIONS

Carbon stored in living organisms or the soil (C) can be converted to carbon dioxide (CO₂) using a conversion factor of 3.76; therefore, any measure of carbon (C) can be converted to carbon dioxide equivalents (CO₂e) by multiplying by 3.76, and vice versa.

One metric tonne (1 t, 1000 kilograms) of carbon can also be written as a one megagram (1 Mg). Therefore, 1 tC = 1 MgC = 1000 kgC, which approximately equal ≈ 3.76 t CO₂e.



3.3.2.2 RUBBER VS NON-RUBBER LAND USES

The net carbon outcomes of rubber plantation or agroforestry establishment from the perspective of land cover change, strongly depend on the former land cover. A meta-analysis of carbon outcomes of multiple land use transitions in mainland Southeast Asia showed that outcomes are very context dependent, particularly when they involve shifting agriculture (Ziegler *et al.*, 2012). While allowing forest to regenerate on cropland increases net carbon sequestration (positive), and converting forest into cropland leads to net carbon losses (negative), the carbon outcomes are uncertain when converting from swidden (especially long-fallow systems) to cash-crop-oriented systems, such as monoculture rubber. In some cases, lengthening the fallow periods of existing swidden systems may increase carbon sequestration and storage, as would conversion from intensive farming to high-biomass plantations and some types of agroforestry (Ziegler *et al.*, 2012).

A review of rubber carbon balances also showed that when considering monoculture rubber plantations, and using time-averaged carbon stocks, net carbon sequestration occurs after conversion of arable land to rubber plantations, but carbon emissions usually occur if natural forest is converted to rubber (Blagodatsky, Xu and Cadisch, 2016). Local climate conditions, soil properties, and topography all strongly affect carbon outcomes. The carbon sequestration potential of any rubber systems is less at higher elevations (300 – 1000 metres above sea level) and in drier conditions (i.e. anywhere that tree growth is reduced) than at lower elevations with greater precipitation. Planting density of rubber trees strongly determines carbon stocks, and planting density tends to decline over time as trees die due to pests or wind damage, or through thinning of weak trees as reported in Sri Lanka (Blagodatsky, Xu and Cadisch, 2016). Together, this means that when looking towards the future, the **net outcome of rubber agroforestry adoption for carbon sequestration will be affected by**

“Net carbon sequestration occurs after conversion of arable land to rubber plantations, but carbon emissions usually occur if natural forest is converted to rubber.”

the pre-existing land use. If the pre-existing land use has a higher carbon stock than rubber agroforestry (for example, if a rubber-intercrop system replaces natural forest or a permanent jungle rubber agroforest), there may be net emissions of carbon, contributing to climate change. In contrast, if the pre-existing land use has a lower carbon stock (for example, if a rubber-intercrop system replaces annual cassava crops), there may be net sequestration of carbon, helping to mitigate climate change.



3.3.2.3 CARBON SEQUESTRATION AND STORAGE IN DIFFERENT RUBBER SYSTEMS

In general, the addition of more plant biomass to a rubber plot will increase carbon stocks of the mature system. For example, in the Colombian Amazon, rubber monocultures had a greater above-ground biomass carbon stock than rubber-cupuaçu (a fruit tree, related to cocoa) agroforests, due to a higher planting density of rubber trees in monocultures (Orjuela-Chaves, Andrade C and Vargas-Valenzuela, 2014). However, carbon outcomes at wider temporal and spatial scales depend on longer term management decisions, such as clearance versus selective replanting and planting cycle length. We summarise estimates of carbon stocks in different rubber systems in Table 2. Systems with greater carbon stocks mean the system has drawn more carbon dioxide down from the atmosphere, which is beneficial from a climate change mitigation perspective (please also see Section 3.3.2.1 for important caveats to this).

In jungle rubber systems, total carbon stocks

(root, soil, litter, dead wood, and above-ground biomass) in Kalimantan, Indonesia, increased with age, with 50-year-old rubber gardens actually storing more carbon than [logged] secondary forests, but younger rubber gardens contained less carbon, although still more than cocoa-dominated-rubber-banana agroforests (developed from former rubber gardens). Deep soil carbon storage (up to one metre depth) exceeded that of above-ground biomass carbon in all systems, and was stable among all systems i.e. although above ground biomass carbon stock changes over time with land use and tree growth, deep soil carbon remains stable (Borchard *et al.*, 2019).

A study in India outlined strategies to enhance carbon stocks in rubber systems, including increasing cycle length (i.e. delaying felling and replanting), selective replanting instead of clear felling (see also section 3.1.1.2 on economic analysis of selective felling) and retaining tree cover by using agroforestry. The carbon stock of 35-40-year-old rubber trees in North East India was measured via destructive sampling (cutting down the

trees and physically measuring, rather than using allometric equations to measure carbon stocks based on tree diameter) (Brahma *et al.*, 2018). This showed that carbon losses due to clear-felling of mature rubber plantations was estimated at 135 Mg C ha⁻¹. The authors suggest that lengthening the plantation cycle (e.g. to 40 years) could be beneficial by retaining carbon stocks for longer, citing evidence that rubber yields remained high until

“Lengthening the plantation cycle (e.g. to 40 years) could be beneficial by retaining carbon stocks for longer.”

40 years; they also suggest that selective felling of 20% of trees each year from 35 years to 45 years could be an alternative management strategy for maintaining carbon stocks during the replanting phase, or that agroforestry methods to retain tree cover should be promoted to avoid carbon losses at the clear felling stage.



Lastly, evidence from other agroforestry systems is also informative. In general, cocoa agroforestry systems have been shown to increase carbon storage, reduce greenhouse gas (GHG) emissions and mitigate climate change effects. Carbon storage can be increased via enhanced shade cover by standing biomass; while soil organic carbon stocks of cocoa agroforests can be similar to prima-

ry forests. Greenhouse gas emissions can be reduced in cocoa agroforestry systems by reducing chemical fertilizers, from which nitrogen is converted into nitrous oxide, the third most important greenhouse gas after carbon dioxide and methane (Tschardtke *et al.*, 2011b).

In summary, inclusion of additional plant bi-

omass in a rubber plantation will increase the total above- and below-ground biomass and carbon stock of that system relative to a monoculture. However, the net outcome in terms of carbon dioxide depends on the former land use, long-term management of plots, and the eventual destiny of products within the agroforestry system.

TABLE 2

CARBON STOCKS OF DIFFERENT RUBBER SYSTEMS

ADAPTED AND EXTENDED FROM (BLAGODATSKY, XU AND CADISCH, 2016)

Accounting method: Time-averaged stock is a method to account for the cyclical nature of rubber tree planting and felling, recommended by the IPCC (please see Section 3.3.2.1 for a detailed explanation of this); maximum stock is the maximum carbon stock recorded in a mature system towards the end of a plantation cycle, which can be a problematic metric for plantation systems where trees are felled and the destiny of the carbon in the trees is unknown (Section 3.3.2.1), but is useful if trees

are left in perpetuity, such as in permanent jungle rubber agroforestry systems.

Carbon pools: AGB = Aboveground biomass, means carbon content in all parts of living plants that are above the ground, such as wood, leaves, branches, etc.; BGB = Below Ground Biomass means carbon content in all parts of living plants that are below the ground, such as roots.



TABLE 2

CARBON STOCKS OF DIFFERENT RUBBER SYSTEMS

ADAPTED AND EXTENDED FROM (BLAGODATSKY, XU AND CADISCH, 2016)

CARBON STOCK MG C HA ⁻¹	ACCOUNTING METHOD	CARBON POOLS	ROTATION LENGTH (YEARS)	TREE DENSITY PER HA	SYSTEM (see Table 1.1 for complete definitions)	LOCATION	SOURCE
46.2 (57.3)	Time-averaged stock	AGB (+ BGB)	30	NA	Jungle rubber – rotational	Indonesia	(Blagodatsky, Xu and Cadisch, 2016)
23.0	Time-averaged stock	AGB + BGB	15	500	Monoculture	Brazil	(Blagodatsky, Xu and Cadisch, 2016)
38.2	Time-averaged stock	AGB	30	No data	Monoculture	Indonesia	(Blagodatsky, Xu and Cadisch, 2016)
40.4	Time-averaged stock	AGB + BGB	30	variable	Monoculture	Sri Lanka	(Blagodatsky, Xu and Cadisch, 2016)
41.7	Time-averaged stock	AGB + BGB	20	500-680	Monoculture	Thailand	(Blagodatsky, Xu and Cadisch, 2016)
42.0	Time-averaged stock	AGB + BGB	20	500	Monoculture	Indonesia	(Blagodatsky, Xu and Cadisch, 2016)
42.4	Time-averaged stock	AGB + BGB	25	No data	Monoculture	China	(Blagodatsky, Xu and Cadisch, 2016)
43.2	Time-averaged stock	AGB + BGB	30	Variable	Monoculture	Sri Lanka	(Blagodatsky, Xu and Cadisch, 2016)
45.3	Time-averaged stock	AGB + BGB	30	375	Monoculture	China	(Blagodatsky, Xu and Cadisch, 2016)
47.0	Time-averaged stock	AGB + BGB	40	No data	Monoculture	Indonesia	(Guillaume <i>et al.</i> , 2018)
51.2	Time-averaged stock	AGB + BGB	35	469	Monoculture	Brazil	(Blagodatsky, Xu and Cadisch, 2016)
63.7	Time-averaged stock	AGB + BGB	25	419	Monoculture	Thailand	(Blagodatsky, Xu and Cadisch, 2016)
65.1	Time-averaged stock	AGB + BGB	38	450	Monoculture	China	(Blagodatsky, Xu and Cadisch, 2016)
89.0	Maximum stock	AGB + BGB	NA	NA	Jungle rubber - permanent	Indonesia	(Palm <i>et al.</i> , 1999)
75.2	Maximum stock	AGB + BGB	NA	NA*	Jungle rubber – permanent	Indonesia	(Guillaume <i>et al.</i> , 2018)
61.8	Maximum stock	AGB	No data	No data	Rubber – cocoa intercrop	Indonesia	(Santhyami <i>et al.</i> , 2018).
322	Maximum stock	AGB	NA	No data	Wild rubber	Brazil	(Salimon <i>et al.</i> , 2011)
105.7	Maximum stock	AGB + BGB	30-40	No data	Monoculture	India	(Brahma, Nath and Das, 2016)
128.4	Maximum stock	AGB + BGB	25	No data	Monoculture	Thailand	(Petsri <i>et al.</i> , 2013)
143.1	Maximum stock	AGB + BGB	35-40	No data	Monoculture	India	(Brahma <i>et al.</i> , 2018)
214	Maximum stock	AGB	44	No data	Monoculture	Ghana	(Kongsager, Napier and Mertz, 2013)

*Rubber trees comprised 21% of tree biomass.



“Rubber management should aim to maximise rainwater penetration whilst meeting biodiversity conservation and crop diversification goals—objectives that could be achieved using agroforestry methods.”

3.3.3 SOIL HEALTH AND WATER MANAGEMENT

Do rubber agroforestry systems promote better soil health and water management compared with monocultures?

Soil and water management feeds back directly to farmer livelihoods by effects on yields (section 3.1.2), the costs of inputs, and to climate resilience (section 3.3.1). There is evidence (although only from small-scale studies) for long term declines in soil fertility with repeated cultivation of rubber monocultures. For example, in Hainan Island, China, soil fertility was measured in rubber monocultures from soil samples taken in 1954, 1982, 1990 and 1995. These showed that soil organic matter decreased by 48%, total nitrogen by 54%, available potassium by 57%, and available phosphorus by 64%, despite fertilizer application (Cheng, Wang and Jiang, 2007). **Soil nutrient reserves become depleted in monocultures** due to soil erosion, mineralisation (decomposition) of soil organic matter (SOM) and

nutrient export with yield products i.e. rubber tapping; thus there is a need for fertilizer application or agroforestry practices to increase soil organic matter (Maranguit, Guillaume and Kuzyakov, 2017). In Xishuangbanna, China, soils became degraded in structure, moisture, nutrient and severe erosion 30 years after conversion from forest to monoculture (Chen *et al.*, 2019). Similarly, the ability of rubber trees to deplete groundwater resources has been shown at the local scale in the Xishuangbanna (reviewed by (Ma *et al.*, 2019)). Here, the authors suggest that, in order to provide dry season water resources, **rubber management should aim to maximise rainwater penetration** whilst meeting biodiversity conservation and crop diversification goals – objectives that could be achieved using



agroforestry methods (Ma *et al.*, 2019).

This section summarises evidence for soil health and water management outcomes of agroforestry practices in rubber, relative to monoculture practices. Our review found a substantial number of studies showing the **benefits of permanent intercropping (especially cover crops and understory plants) and jungle rubber agroforestry** for various indicators of soil health and water infiltration, and little evidence of **nutrient competition between rubber trees and intercrops**. Terracing and reducing herbicide application to once per year (thus allowing more weeds to cover the soil) were also beneficial for soil health, and can be complementary to agroforestry practices. While we have not closely scrutinised the statistical methods used in each study presented here, we caution that changes in soils in relation to land use change must be replicated across multiple study plots to take into account spatial variability. For example, a study of jungle rubber, mono-

Soil erosion in rubber terrace system in Thailand

Credit: CC BY-NC 4.0 EWT

culture and forest in Indonesia found that 5-7 replicate plots were ideally needed to detect land-use change effects on soil nutrient parameters (Allen *et al.*, 2016). Seasonal variability, soil types, fertilizer application also all affect soil metrics. Hence, it is important to keep these methodological considerations in mind and to understand that not all studies in this section may fulfil these considerations.

3.3.3.1 AGROFORESTRY METHODS (PERMANENT INTERCROPPING; JUNGLE RUBBER)

Intercropping rubber with perennials, annuals, and cover crops in young and mature rubber plantations can improve soil quality by various interlinked mechanisms. Intercrops contribute to soil quality by physically sheltering the soil from erosion and nutrient leaching, by producing root exudates and contributing leaf litter to the soil, or via beneficial fungi associated with roots of cover crops (especially leguminous species). Intercrop plants also affect soil pH or soil acidity, which in turn is related to soil microbial activ-



ity, and also impacts carbon (C) and nitrogen (N) cycling.

Cover cropping has received much research attention. There is **strong evidence of positive benefits for cover cropping in rubber plantations from older literature, including “a long-lasting rubber yield increase” based on long-term trials** ((Broughton, 1977) as reviewed in Langenberger *et al.* (2017)). The long-term benefits are particularly true for leguminous cover crops on poor soils, but natural regrowth of ground-covering plants on fertile soils and recently cleared forest soils also provide similar benefits ((Broughton, 1977; Blencowe, 1989) as reviewed by Langenberger *et al.* (2017)). **Multiple recent studies from China show the soil benefits of cover cropping with *Flemingia macrophylla***, a popularly grown leguminous shrub with medicinal properties, compared to rubber monoculture alone (Table 3).

In monocultures, rubber leaf litter covering >70% of the soil surface helped reduce surface runoff and soil erosion on slopes in southern China (Liu *et al.*, 2017); however, a

study on steep slopes in Northern Thailand found that rubber tree leaf litter was not effective in reducing water and soil runoff at the end of the rainy season when the leaves have partially decomposed (Neyret *et al.*, 2020). **The presence of understory plants further reduces surface runoff and soil erosion, such as tea** (Liu *et al.*, 2017) and maize in young rubber plantations (Neyret *et al.*, 2020). The Northern Thailand study also show that increasing ground cover with low-growing plants (unspecified, but could be spontaneously occurring plants, or cover crops) to ~31% cover would decrease runoff by a third (Neyret *et al.*, 2020).

A common concern of farmers is that intercrops or the presence of other plants may compete with rubber for soil nutrients and water (but see evidence for facilitative water uptake in the presence of intercrops in section 3.3.1.1). A few studies asked whether below-ground competition between intercrops and rubber would affect uptake of nutrients by looking at leaf nutrient content. There were no obvious effects on leaf nutrients in sharp-leaf galangal intercrop systems (Wu, Zeng,

“The presence of understory plants further reduces surface runoff and soil erosion, such as tea and maize in young rubber plantations.”

Chen, Liu, *et al.*, 2019) or legume cover cropping with *Flemingia macrophylla* (Wu, Liu and Chen, 2016a), but leaf nutrient content was higher with the legume cover crop *Pueraria phaseoloides* (Clermont-Dauphin *et al.*, 2018).

This substantial body of evidence – also summarized in Table 3 – clearly shows the benefits of permanent intercropping (and jungle rubber agroforestry) for enhanced soil carbon (important for nutrient retention, water holding capacity and climate change mitigation), soil nutrients (nitrogen, phosphorus, potassium, calcium and magnesium, iron, sulphur and manganese), reduced erosion, improved soil structure, reduced soil acidity and enhanced soil microbial biodiversity.

**BOX 7****THE COMPLEXITIES OF SOIL AND WATER MECHANISMS IN AGROFORESTRY SYSTEMS**

A study from China compared soil nutrient concentrations, water content and soil water residence time between rubber monoculture and four agroforestry systems: two single intercrop (orange, tea), a double intercrop (orange and tea), and a ‘jungle’ system formed from abandonment of an orange/tea system that was allowed to develop natural vegetation, and contained 11 non-rubber species of tree, shrub and herb (Wu *et al.*, 2020). This study offers nuanced insights into how natural regrowth may affect intercropping systems, and how ‘jungle’ rubber weighs up to simple intercropping systems.

Soil carbon and nitrogen were lowest in monoculture, highest in natural forest, and increased relative to monoculture in all four agroforestry systems (no strong differences between the systems). Soil nutrients (P, K, Ca, Mg) varied among the agroforestry systems, with no effects for some nutrients in some systems relative to monoculture, but in most cases, jungle rubber had reduced nutrients relative to all other rubber systems, and less

than natural forest, while simpler intercrop systems showed esoteric responses. However, effects on soil water content, residence time and some soil nutrients (P, K, Ca) were negative with increasing complexity, thought to be caused by below-ground competition between plant species. Soil water content was lower in jungle rubber than in the other agroforestry systems, or in forest. This was considered to be due to water competition from the herbaceous plant layer in the jungle rubber system. Increased soil carbon generally improves the water-holding capacity of soils, due to changes in soil structure, so there were positive correlations between soil carbon, nitrogen and water content. However, the presence of herbaceous plant complexity alongside shrubs and trees in the jungle system may improve drainage to such an extent that soil water content was reduced, combined with the effects of additional plant transpiration which could be offsetting any benefits of soil shading by leaves on soil moisture. Competition between complex vegetation and rubber trees may cause rubber trees to take up water from deeper in

the soil profile, leading to drier deep soil layers in jungle rubber (and natural forest) relative to monoculture and simple agroforests.

The authors conclude that intercropping in rubber plantations is effective at increasing soil organic matter (and thus carbon and nitrogen), and in turn increase soil moisture content. Soil water and nutrients were reduced in the more complex systems (forest and jungle rubber) due to increased competition between plant species (particularly from herbaceous plants), and due to increased drainage and aeration of the soil (which may in turn lead to nutrient leaching). However, as rubber trees are deep-rooted, soil moisture at deeper levels may be unaffected. The authors suggest avoiding dense planting of herbaceous species between rubber trees to avoid negative impacts on soil moisture and nutrients (P, K, Ca). However, the study did not control for application of fertilizers in the simpler systems, which would be expected to affect soil nutrients (Wu *et al.*, 2020).



TABLE 3

EFFECT OF DIFFERENT RUBBER INTERCROPPING SYSTEMS ON SOIL HEALTH, AS COMPARED TO MONOCULTURE RUBBER

EFFECT OF AGROFORESTRY SYSTEM/PRACTICE	SYSTEM	LOCATION	SOURCE
SOIL CARBON (C = CARBON, SOC = SOIL ORGANIC CARBON)			
Lower SOC, labile C, recalcitrant C but higher dissolved organic carbon	Intercrop: Cardamom	China	(Wang <i>et al.</i> , 2020)
Higher SOC, reduced C loss, better C accumulation rates	Intercrop: Cocoa/ Coffee/Rosewood Cover crop: <i>Flemingia macrophylla</i>	China	(Chen <i>et al.</i> , 2017)
Higher SOC in topsoil (0-10cm)	Intercrop: Coffee/Tea	China	(Li <i>et al.</i> , 2020)
Higher soil C	Intercrop: Orange/Tea/ Orange+Tea	China	(Wu <i>et al.</i> , 2020)
Higher soil C (no significant difference to managed intercrops)	“Jungle rubber”- abandoned Orange+Tea	China	(Wu <i>et al.</i> , 2020)
No significant difference in soil C	Intercrop: Coffee/ vanilla/ Garcinia / nutmeg	India	(Jessy, Joseph and George, 2017)
SOC greater in the double and triple plantain-row systems at one of the two study sites	Intercrop (temporary): Plantain	Ghana	(Tetteh <i>et al.</i> , 2019)
Higher soil labile organic carbon and nitrogen	Cover crop: <i>Flemingia macrophylla</i>	China	(C.-A. Liu <i>et al.</i> , 2018)
41% versus 62% loss of SOC in the topsoil (0-30cm) relative to natural forest; likely only lost by mineralisation to CO ₂ and not by erosion	Jungle rubber	Sumatra, Indonesia	(Guillaume, Damris and Kuzyakov, 2015)
Higher annual carbon return to the soil (3.7 Mg C ha ⁻¹ vs only 1.9 Mg C ha yr in monoculture)	Jungle rubber	Sumatra, Indonesia	(Kotowska <i>et al.</i> , 2016).



EFFECT OF AGROFORESTRY SYSTEM/PRACTICE	SYSTEM	LOCATION	SOURCE
SOIL NUTRIENTS (N = NITROGEN, P = PHOSPHOROUS, K = KALIUM, CA = CALCIUM, MG = MAGNESIUM, FE = FERRUM, MN = MANGANESE)			
Higher N (total organic, labile and recalcitrant N)	Intercrop: Cardamom	China	(Wang <i>et al.</i> , 2020)
Higher soil organic N, reduced N loss, better N accumulation rates	Intercrop: Cocoa/Coffee/Rosewood Cover crop: <i>Flemingia macrophylla</i>	China	(Chen <i>et al.</i> , 2017)
Higher total N stock in topsoil (0-10cm)	Intercrop: Coffee/Tea	China	(Li <i>et al.</i> , 2020)
Higher N at all depths	Intercrop: Cocoa	Brazil	(Oliveira <i>et al.</i> , 2019)
Higher P concentrations in all fractions	Intercrop: Cocoa/acai palm/cupuassu fruit	Brazil	(Viana <i>et al.</i> , 2018)
Higher soil N; variable results for soil P, K, Ca, Mg (fertilizer application not accounted for)	Intercrop: Orange/Tea/Orange+Tea	China	(Wu <i>et al.</i> , 2020)
Higher soil N; soil P, K, Ca, Mg generally lower than managed intercrops	“Jungle rubber”– abandoned Orange+Tea	China	(Wu <i>et al.</i> , 2020)
No significant difference in P, K, Ca, Mg; but higher in some cases 10 years after rubber planting.	Intercrop: Coffee/vanilla/ <i>Garcinia</i> /nutmeg	India	(Jessy, Joseph and George, 2017)
No difference (despite monoculture being fertilized annually, and rubber-bamboo not)	Intercrop: Bamboo	Thailand	(Andriyana <i>et al.</i> , 2020)
SON greater in the double and triple plantain-row systems at one of the two study sites (note NPK fertilizer was applied to each plantain plant)	Intercrop (temporary): Plantain	Ghana	(Tetteh <i>et al.</i> , 2019)
Higher soil labile organic nitrogen	Cover crop: <i>Flemingia macrophylla</i>	China	(C.-A. Liu <i>et al.</i> , 2018)
P fractions varied depending on the type and soil depth and stand age. Total P stock, to a certain extent, was reduced in young intercrop (10 years), but increased in mature intercrop (22 years)	Cover crop: <i>Flemingia macrophylla</i>	China	(C. -A. Liu <i>et al.</i> , 2018)
Higher or no difference in soil nitrogen – effect was site dependent	Jungle rubber	Sumatra, Indonesia	(Guillaume, Damris and Kuzyakov, 2015)
Higher annual return rates for soil S, N, P, K, Fe, Mg, Mn	Jungle rubber	Sumatra, Indonesia	(Kotowska <i>et al.</i> , 2016).
Conversion of jungle rubber to monoculture led to overall reduction of P stocks due to a strong decrease of soil organic matter; fertilization did not compensate for the P losses in long term in monoculture.	Jungle rubber	Sumatra, Indonesia	(Maranguit, Guillaume and Kuzyakov, 2017).



EFFECT OF AGROFORESTRY SYSTEM/PRACTICE	SYSTEM	LOCATION	SOURCE
SOIL EROSION			
Better soil physical properties and nutrients	Intercrop: Cocoa Cover crop: <i>Flemingia macrophylla</i>	China	(Chen <i>et al.</i> , 2019)
Improved soil aggregation, reduced soil erosion	Intercrop: Cocoa/ Coffee/Rosewood Cover crop: <i>Flemingia macrophylla</i>	China	(Chen <i>et al.</i> , 2017)
Better infiltration of rainfall into soil, reduced surface runoff and soil erosion	Intercrop: <i>Clerodendranthus spicatus</i> / <i>Amomum villosum</i> (medicinal plants)	China	(Jiang <i>et al.</i> , 2017)
Reduced surface runoff and soil erosion	Intercrop: Tea	China	(Liu <i>et al.</i> , 2017)
Greater rainfall interception; no difference in soil bulk density	Intercrop: Bamboo	Thailand	(Andriyana <i>et al.</i> , 2020)
Increased water infiltration (higher in triple row vs double or single row)	Intercrop (temporary): Plantain	Ghana	(Tetteh <i>et al.</i> , 2019)
Reduced surface runoff and soil erosion	Intercrop (temporary): Maize	Thailand	(Neyret <i>et al.</i> , 2020)
Less soil eroded (over 15 years) from the upper soil layer (measured at one site). Subsoils were not affected.	Jungle rubber	Sumatra, Indonesia	(Guillaume, Damris and Kuzyakov, 2015)
SOIL PH (ACIDITY)			
Less acidic soil	Intercrop: Cocoa/coffee	China	(Li <i>et al.</i> , 2020)
Mitigated soil acidification and nutrient depletion	Cover crop: <i>Flemingia macrophylla</i>	China	(C.-A. Liu <i>et al.</i> , 2019);
No significant difference in soil acidity	Intercrop: Coffee/vanilla/ <i>Garcinia</i> /nutmeg	India	(Jessy, Joseph and George, 2017)
SOIL MICROBES			
Higher soil bacterial biodiversity	Cover crop: <i>Flemingia macrophylla</i>	China	(C.-A. Liu <i>et al.</i> , 2019)
Significantly higher soil microbial population, no difference in fungi or Actinomycetes	Intercrop: Coffee/vanilla/ <i>Garcinia</i> /nutmeg	India	(Jessy, Joseph and George, 2017)
Increased microbial mass (higher in triple row vs double or single row)	Intercrop (temporary): Plantain	Ghana	(Tetteh <i>et al.</i> , 2019)
Higher species richness, abundance and biomass of testate amoebae (soil and leaf litter microbes), including reduced density of species with siliceous (silicon-containing) shells	Jungle rubber	Sumatra, Indonesia	(Krashevskaya <i>et al.</i> , 2016).



3.3.3.2 NON-AGROFORESTRY METHODS (TERRACING, WEED MANAGEMENT)

Terracing helped reduce soil organic carbon loss from converting secondary forest to rubber monoculture in mountainous southern Yunnan province, China (De Blécourt *et al.*, 2014). The study found that terracing enhanced soil organic carbon recovery (down to 1.2 m depth) as compared to non-terraced areas in rubber plantations.

A computer model simulating weed growth impacts on soil erosion in rubber monocultures over 20 years indicates that **minimising herbicide application to once per year, or no weeding at all, could substantially reduce soil loss relative to more regular weeding (twice per year)**. A no-weeding approach would result in dense undergrowth that is unacceptable to local farmers due to their concerns of poisonous caterpillars and inconvenience for tapping; hence, the authors recommended limiting weeding to once a year (H. Liu *et al.*, 2019).

3.3.3.3 RUBBER AS A TOOL FOR RESTORATION OF DEGRADED LAND

An agroforestry system comprising 30 native tree species (used for timber, food or medicinal purposes), intercropped with rubber, wild crape myrtle (*Malpighia glabra*) and Axioté (*Bixa orellana*), was established in Brazil as part of a land restoration scheme following major soil erosion problems. The agroforestry system showed accumulation of soil organic carbon over five years in all plots, but was slowest in plots that included soil ploughing as part of management (Siqueira *et al.*, 2020).

3.3.4 ECOSYSTEM RESILIENCE AND BIODIVERSITY

Do rubber agroforestry systems enhance biodiversity and ecosystem resilience compared with monocultures?

A global extinction crisis is underway, and providing space for nature within cultivated lands is critical for conservation of biodiversity in all its forms. This section summarises the role agroforestry practices and systems can play in supporting ecosystem resilience and biodiversity, relative to monoculture practices.

3.3.4.1 WILD RUBBER AND AGROFORESTS IN BRAZIL

Wild tapped rubber from trees growing naturally in the Amazon is unique in that it is sourced from a natural rainforest ecosystem, which will therefore support rainforest biodiversity (WWF-UK, 2014). Rubber tapping

in the Brazilian Amazon was dependent on subsidies, and when subsidies were available (re-introduced in 2012 and current status unknown) they also supported the planting of rubber agroforests along riverbanks (separate from natural rubber tapping from wild trees), adjoining natural forest. These agroforests additionally provided wildlife habitat, shown by the use of the agroforests as hunting grounds (Schroth *et al.* 2003, in (Schroth and Da Mota, 2013)).



In a plantation context in Brazil, the number of fruit feeding butterfly species was greater in unmanaged rubber plantations that contained substantial plant regrowth between the rubber rows, than in highly managed rubber plantations, and may act as stepping stones for forest-dependent species to move through the landscape (Cambui *et al.*, 2017). Rubber plantations containing additional trees (eg cacao, banana, jackfruit and guava), as well as supporting epiphytic bromeliads (specialised plants that grow on the surface of trees), were also used by endangered golden lion-headed tamarins and Wied's marmosets, as part of their home range; there was no evidence that they used monoculture rubber in the same way. These species eat fruit, and insects (found in bromeliads) (De Vleeschouwer and Oliveira, 2017). Rubber agroforestry therefore provides benefits for biodiversity whether in plantation-dominated landscapes, or in landscapes still containing tracts of rainforest.

Great Hornbill (*Buceros bicornis*) in Thailand.

Credit: CC BY-NC 4.0 TCW

Flying lizard (*Draco spp.*) in Thailand rubber system

Credit: CC BY-NC 4.0 EWT

3.3.4.2 JUNGLE RUBBER

As the most structurally diverse agroforestry system in Southeast Asia, jungle rubber systems in Indonesia have received research attention for their biodiversity benefits. Jungle rubber systems contain multiple tree species (native, wild-grown or introduced/planted) and are minimally managed, meaning multiple species of plant naturally regenerate beneath the tree canopy. This complex physical structure, together with a diversity of plant species, is expected to support much more biodiversity than a monoculture plantation. A review of studies prior to 2015 showed that **natural forest conversion to rubber monoculture inevitably results in biodiversity loss** (reduced numbers of bird, bat, plant and insect species), but that **jungle rubber agroforests can support some forest-dependent species that are never found in monocultures of rubber or oil palm, representing critical forest-like habitats in places where forest is rapidly being lost** (Warren-Thomas, Dolman and Edwards, 2015). Subsequent studies in Sumatra have reiterated these findings.

Data from several studies was brought together to show that for birds, ferns and trees,



species richness in jungle rubber was higher than in rubber monocultures, and for birds and ferns, species diversity in jungle rubber was quite similar to natural forest, including some forest-dependent species (Beukema *et al.*, 2007). Jungle rubber type agroforestry in Central Kalimantan also supports a diversity of rattan (vine) and tree species (Rotinsulu *et al.*, 2013; Tata, 2019).

A more recent comparison of the epiphytic plants (those that grow on another plant e.g. ferns, bromeliads, air plants, orchids) in jungle rubber compared to monocultures in Sumatra, Indonesia, found that jungle rubber had similar species diversity to natural rainforest, which was much higher than rubber monocultures. The authors conclude that jungle rubber is a refuge for epiphytes and

Butterfly (*Hypolimnas bolina*) in rubber agroforestry, Thailand; *Trimeresurus* spp. pit viper in Thailand rubber

Credit: CC BY-NC 4.0 EWT

Young pangolin (*Manis javanica*), captured in rubber plantation in Myanmar by local farmers

Credit: CC BY-NC 4.0 TCW

are important for conserving epiphyte diversity, especially of ferns and orchids (Böhnert *et al.*, 2016).

In a study of all plants in just eight plots found that jungle rubber contained 652 plant species, while rubber monocultures contained only 230 plant species (natural forest contained 963) (Rembold *et al.*, 2017). The genetic and phylogenetic diversity of plants found in jungle rubber agroforests were also much greater than in rubber monocultures, because jungle rubber contains species with different life history traits, and species that are more distantly related to each other (therefore capturing a wider range of functional features) (Breidenbach *et al.*, 2018; Kusuma *et al.*, 2018). Finally, the number of invasive plant species, which can dominate agricultural systems and cause problems for farmers and local biodiversity, was lower in jungle rubber than in monoculture (Wahyuni *et al.*, 2016).

A study that combined extensive sampling of tropical biodiversity (almost 27,000 species, including high diversity and high biomass groups spanning all trophic levels, i.e. from birds to bacteria, above and below ground)



found that strong biodiversity losses from almost all groups occurred when natural forest and jungle rubber agroforests were converted to monocultures (whether of rubber or oil palm); exceptions were e.g. bacteria, although even within these groups, the diversity of species found in natural forest (rather than all possible species) declines (Grass *et al.*, 2020). The only exception to these patterns are soil macroinvertebrates: the total number of spider species, and their functional diversity (the types of functions they provide in the ecosystem), was similar between jungle rubber and monoculture, although the number of forest species was much lower in rubber monocultures than jungle rubber, and the types of species differed between the two systems (Potapov *et al.*, 2020). Similarly, centipede species number, abundance and biomass did not differ between jungle rubber and rubber monoculture (Klarner *et al.*, 2017), and species richness, density and functional group richness of leaf litter macro-invertebrates did not differ between jungle rubber and monoculture rubber (Mumme *et al.*, 2015)

Finally, jungle rubber systems can also support orangutans, which were found to routine-

ly eat cultivated fruits grown in rubber agroforests in northern Sumatra (i.e. crop-raiding, eating fruits grown for human consumption), but were unable to forage in neighbouring oil palm plantations. The authors conclude that retention of rubber agroforests containing fruiting trees, and preventing their conversion to oil palm monocultures (an ongoing pattern in the region) is critical for orangutan conservation in that landscape (Campbell-Smith *et al.*, 2011). Managing conflicts between farmers growing fruit crops for consumption or sale, and protection for orangutans, is likely to be a complex problem in this case.

3.3.4.3 PERMANENT INTERCROPPING

The evidence for biodiversity benefits from permanent intercropping in rubber is scarcer, not least because these systems are less common in the landscape. Permanently intercropped systems will be much less structurally complex than jungle rubber, containing fewer layers of vegetation below the tree canopy, and will contain fewer plant species. However, there is evidence for some benefits

relative to monoculture practices.

Rubber agroforests containing permanent intercrops of fruit, palms, timber or vegetables contained more species of fruit-feeding butterflies than monocultures, and different butterfly species, but had similar numbers of reptile and bird species. Bird species richness was greater in rubber plots that had more understory vegetation, whether or not they contained agroforestry crops. Conservation priority and forest-dependent birds were not supported within monoculture rubber (Warren-Thomas *et al.*, 2020). In contrast, in North Sumatra, bird surveys found that intercropped rubber systems containing tree species such as durian (*Durio zybethinus*), candle nuts (*Aleurites moluccana*), duku (*Lansium domesticum*), jengkol (*Pithecellobium lobatum*), mangosteen (*Garcinia mangostana*) and cacao (*Theobroma cacao*) contained 46 bird species (including one species of conservation concern), compared to 30 in rubber monocultures, and 122 in nearby forest (Ayat and Tata, 2015).

In Hainan, China, leaf-litter ants, including invasive species (that can disrupt native biodiversity and cause ecosystem disruption),



were compared between rubber agroforests containing understory crops and rubber monocultures. Agroforests contained similar numbers of ant species, but crucially they contained fewer invasive ant species than monocultures (thus agroforests were better for native biodiversity). The study showed that invasive ant species were associated with simpler undergrowth structure in monocultures, so the addition of secondary plant species in the agroforest, which increases the vegetation structure, reduced the presence of invasive ants (Lee, Wang and Guenard, 2020).

Finally, in the Philippines, (Agduma *et al.*, 2011) reported 110 plant species growing alongside rubber in an agroforestry system within a plantation, including trees, shrubs, vines, herbs, grasses and ferns. These include eight threatened plant species, including dipterocarp trees, endemic trees and figs that are keystone species for ecosystems. (Achondo *et al.*, 2011) found in a short bird survey that rubber agroforests (containing fruit trees and native tree species (Agduma *et al.*, 2011)) in Mindanao contained 23 bird species (same as nearby oil palm plantations) including eight endemic bird species (restricted to the Philippines), but this is low number compared to bird diversity in natural systems in the area,

and many species are generalists that can live in a range of different habitats, are not species of conservation concern, and are not forest-dependent species.

3.3.4.4 NON-AGROFORESTRY METHODS (WEED MANAGEMENT)

There is some evidence from Thailand that the presence of **understory vegetation** i.e. “weeds” or “undergrowth” **increases bird species richness** slightly compared to rubber monocultures (Warren-Thomas *et al.*, 2020). Similarly, (Aratrakorn, Thunhikorn and Donald, 2006) found that rubber and oil palm plantations supported lower bird diversity (41 species each) than nearby forest (108 species), with different species of birds living in each system (species in plantations were mostly widespread generalists, but that the presence of dense and extensive understory vegetation growing between the rubber trees increased bird diversity from eight species per survey, to 10 species.

3.3.4.5 CONNECTIVITY AND BIODIVERSITY BENEFITS

Agroforestry of any kind cannot replace the role of forest ecosystems in supporting

biodiversity. If agroforests replace forests, this will result in **declines for biodiversity and ecosystem resilience**, as well as **carbon emissions** (see section 3.3.2 on carbon). However, **diversified agricultural systems on the farm and landscape scale support biodiversity and an array of ecosystem services** (Tamburini *et al.*, 2020). Multiple studies report increased diversity of plants and birds in jungle rubber compared to other systems, and the conservation of these forest-like systems in lowland landscapes that contain few forest fragments may be critical to the persistence of forest-dependent species in these landscapes, including orangutans. Meanwhile, simple intercropping systems (i.e. simple agroforests consisting of just two or three crops) do not necessarily benefit birds, but can benefit butterflies, ants and plant species. Crucially, there is also evidence that diversified systems can increase the hospitability of the landscape for species moving between patches of remaining forest habitat, meaning agroforestry may increase habitat connectivity for species, relative to monocultures (Haggar *et al.*, 2019). This will be critical not only for long-term species persistence, but also to allow species respond to climate change and move through landscapes to track changes in their environment.



Discussion

The evidence outlined above shows that agroforestry systems can provide multiple benefits for livelihoods and food security and nutrition, improve soil quality, available nutrients and water use, reduce soil erosion, enhance biodiversity, and offer options for climate resilience. It is clear that agroforestry systems can fail to provide benefits relative to monocultures if they are inappropriately designed, if they do not match local constraints on land and labour, or if markets for secondary products are weak. It is also clear that **farmers in multiple contexts independently choose agroforestry practices, sometimes in the face of direct disincentives from government policies, or through constraints of contract farming.**

In the following sections, barriers and problems associated with adopting rubber agroforestry are explored, and recommendations for scaling-up of rubber agroforestry are made. This section contains information from interviews, supplemented with evidence from the literature, and uses case studies to examine complexities and feedbacks among barriers. This section will largely focus on rubber-based (permanent) intercropping systems, as this system has the most potential for scaling up among smallholders and industrial plantations.

Rubber agroforestry to secure resources for future generations

Credit: CC BY-NC 4.0 TCW

4.1 BARRIERS TO ADOPTION OF RUBBER AGROFORESTRY

4.1.1 GOVERNMENT POLICIES, LAND TENURE, AND CONTRACTS

Government policies have been cited as a major factor influencing adoption of rubber agroforestry practices (Viswanathan and Bhowmik, 2016; Stroesser *et al.*, 2018).⁵⁵ Monoculture was promoted as an agricultural model in countries like Malaysia, Thailand, Laos, Cambodia, China and the Ivory Coast, so policies tended to favour rubber monocultures, and technical recommendations from state institutions were focused on monoculture systems. This resulted in a lack of awareness by smallholders about agroforestry. In other countries with a cultural history of agroforestry, which have not had such strong governmental incentives for monocultures, such as Sri Lanka, Vietnam and Nigeria, rub-

ber-based agroforestry is more widespread (Rodrigo, Stirling, Naranpanawa, *et al.*, 2001; Omokhafa *et al.*, 2014; Sen, 2015; Sankalpa, Wijesuriya and Ishani, 2020).⁵⁶

In the context of Thailand, the world's biggest rubber producer, government initiatives to improve rubber production played a key role: low-yielding complex “jungle rubber” agroforestry systems, comprising a wide diversity of fruit and timber trees, were widely grown until a clonal rubber replanting program by the Office of Rubber Replanting Aid Fund (ORRAF) strongly incentivised monoculture planting in the 1960s, effectively banning agroforestry, while hugely increas-

ing Thailand's rubber production (Stroesser *et al.*, 2018). The remaining practitioners of agroforestry in Thailand are therefore rare, despite the lifting of a ban on multi-cropping by ORRAF in 1992 and policy to promote agroforestry and non-rubber tree crops in 2014 (Delarue and Chambon, 2012). Financial support or subsidies without technical recommendations for setting up rubber agroforestry plots may not be sufficient to convince farmers accustomed to monoculture system to adopt agroforestry.⁵⁷ It should be noted that modern intercropping systems may require different knowledge to that used to maintain traditional jungle rubber systems.

⁵⁵ Interviews, Rhett Harrison, Eric Penot, Michael B. Commons, and anonymous.

⁵⁶ Interview, Kenneth Omokhafa.

⁵⁷ Email consultation, Bénédicte Chambon.



Lack of land or tree tenure security was also cited as a barrier to adoption of rubber agroforestry.⁵⁸ Smallholders are more likely to invest in longer-term agroforestry systems when they have more secure tenure and land-use rights on their farms, and to plant trees when they have sufficient length of tenure and full rights on the trees they plant (FAO and ICRAF, 2019). In addition, the classification of rubber trees by government agencies (as an agricultural crop vs timber crop vs forest cover) can also affect smallholder decisions, in response to land-zoning decisions and policies from the government (e.g. encouraging agricultural intensification or forest restoration on certain lands). Interlinked with that, **policies around timber trees** also discouraged the establishment of rubber-timber intercropping systems. For example, prior to 2019, the Rubber Authority of Thailand (formerly ORRAF, as above) restricted the number and type of species of timber on farms⁵⁹ and smallholders required permits to cut native

hardwoods even if those trees were planted on their own land.⁶⁰ Once this prohibition was lifted, hardwood tree planting greatly increased and many more farmers grew and sold hardwood seedlings.⁶¹ A lack of land titles in Cambodia also makes it difficult for smallholders to access finance (e.g. loans) to invest in rubber farms (Andriessse, 2014). In Liberia, land tenure was the main impediment to adopting agroforestry or tree-cropping, as well as perceptions around competition between tree crops and herbaceous crops (Fouladbash and Currie, 2015).

Contracts for smallholders provided by rubber companies guide production methods and the ability to implement agroforestry practices. A comparison of smallholder farmer livelihoods growing rubber in Cambodia and Laos showed that rubber companies contracting farmers advise smallholders in Laos not to intercrop, in order to maximise rubber yields (Andriessse, 2014). This is despite smallholder interest in adopting agroforestry practices

“Smallholders are more likely to invest in longer-term agroforestry systems when they have more secure tenure and land-use rights on their farms, and to plant trees when they have sufficient length of tenure.”

(see detailed case study Box 2 in section 3.1). Contractual obligations can also change land tenure – deliberately, when smallholders decide to provide labour instead of land for rubber companies or involuntarily, when farmers are illiterate and do not understand the contractual conditions (for more details see section 3.2.2). The lack of support for smallholder associations, networks and co-operatives (which would facilitate community organizing and collective action) likely further limit smallholders’ options and negotiating power.

58 Interviews, Rhett Harrison (land tenure and China example). Email consultation, Eric Penot (unfavourable tree tenure in Vietnam and Cote d’Ivoire).

59 Interview, Sara Bumrungsri.

60 Interviews, Sara Bumrungsri and Michael B. Commons.

61 Interview, Michael B. Commons.

4.1.2 MARKETS, LABOR CONSTRAINTS AND RISK

Low rubber prices may encourage smallholders to switch to intercropping so they can derive income or subsistence from intercrops.⁶² Low prices may also lead to the temporary abandonment of rubber and renewal of tapping once prices recover, or to the conversion of rubber to other plantation crops, such as banana in Xishuangbanna post-2011.⁶³ Although jungle rubber agroforestry can provide environmental benefits, this does not translate to any significant incentives for smallholder farmers in Indonesia (Leimona and Joshi, 2010). Smallholder farmers showed a willingness to participate in a certification program, but expected a 100% price increase in natural rubber (note that the study was written in 2010, before the 2011 price spike and subsequent slump; prices today are roughly similar to 2005-2006). Barriers to eco-certification adoption includ-

ed a lack of local supportive policies, and on the demand side, hesitancy from companies to adopt the eco-certification concept due to concerns about distorting market prices (Leimona and Joshi, 2010).

Labour shortages were a commonly cited barrier, as this was a crucial aspect for practicing most forms of agroforestry.⁶⁴ In general, there is a decline in the rural farming labour force due to economic development and urban migration. The **demands on a smallholder's time** – especially from other more profitable sources of income or off-farm livelihood activities – may mean that they do not have the time to set up or maintain agroforestry plots.⁶⁵ These same factors apply to wild rubber extraction in the Amazon. As rubber tapping provides low returns for how physically and time demanding it is, locals will pre-

fer other more profitable economic activities. In the case of jungle rubber, it is less labour intensive than rubber monoculture but provides lower returns (if high yielding clones are not used), so often the specific decision depends on the financial and labour resources available to the smallholder farmer. Agroforestry strategies with less labour requirements (e.g. allowing natural regeneration in rubber plantations) can be suitable in locations with labour scarcity.

Lack of access to markets for intercrops were also cited as a barrier to agroforestry.⁶⁶ A review of agroforestry in Vietnam also highlighted further **market constraints**, such as the difficulty of scaling for market (the diversity and small volume of products from small scale agroforestry, which exceeds household consumption but insufficient for commercial

62 Interview, Rhett Harrison.

63 Interview, Rhett Harrison.

64 Interviews, G. Langenberger, R. Harrison, S. Bumrungsri. Email consultation, B. Chambon.

65 Interview, Uraivan Tongkaemkaew.

66 Email consultations, Gerhard Langenberger and Julia Quaedvlieg.



purposes), limited or unstable markets (agroforestry products not matching commercial requirements) (Sen, 2015).

As the rubber agroforestry model is still rare in most countries, and farming is already subject to multiple threats (e.g. weather and market volatility), smallholders and industrial plantations accustomed to the monoculture model are likely to be **risk averse**

and stick to existing systems that have been “tried and tested”.⁶⁷ This is, because there is a risk that either rubber, or the associated crop, or even both will not do well.⁶⁸ There is also a perception that intercrops will compete with rubber and reduce rubber productivity, among both smallholders and rubber companies⁶⁹ (Haberecht, 2010). Researchers based in Thailand also mentioned the **social stigma** related to having an “untidy” farm,

including a fear of increased snakes, mosquitoes, and ghosts.⁷⁰ Conversely, in areas where rubber agroforestry is a common practice, risk aversion may mean that farmers would prefer to retain some agroforest area instead of fully converting to monocultures (e.g. a model based study in Indonesia found that risk-averse farmers chose to retain a greater area of jungle rubber (Djanibekov and Villamor, 2017).

4.1.3 FINANCE, CAPITAL AND KNOWLEDGE

Some interviewees suggest that adoption of rubber agroforestry is largely driven by **economics and practical constraints**. If smallholders receive **sufficient income** from rubber monoculture or alternative sources of income, especially when rubber prices are high,

then they do not see a need to practice agroforestry, which would require an **increase in management complexity, including additional knowledge/expertise and labor needs**.⁷¹ Every additional crop or livestock species added to the plot requires knowledge

of best practices and problems, their interactions with the rubber trees and each other, as well as knowledge of how to design the agroforestry plot. Industrial plantations will need to develop whole new systems to manage the different components and outputs of agro-

67 Interviews/email consultation, Bénédicte Chambon, Sara Bumrungsri, Uraiwan Tongkaemkaew, Michael B. Commons, Linda Preil.

68 Email consultation, Bénédicte Chambon.

69 Interviews, Rhett Harrison, Uraiwan Tongkaemkaew, anonymous.

70 Interviews, Sara Bumrungsri, Uraiwan Tongkaemkaew.

71 Interviews, Gerhard Langenberger, Rhett Harrison, Sara Bumrungsri, Uraiwan Tongkaemkaew, Michael B. Commons.

“Some types of agroforestry require financial investments with delayed returns, such as intercropping with timber, whereas smallholders may prefer to invest in shorter term revenue options.”

forestry. In Thailand, there is a decreasing trend in family labor availability, as younger family members have access to improved education and employment prospects in urban areas; rubber tappers are increasingly hired to help run rubber smallholdings, and landowners have reduced capacity for plot management activities which may reduce their interest in increasing management complexity with additional crops, although new benefit-sharing agreements with rubber tappers to include intercrops (for example, in the non-tapping season) may be an option.⁷² In other locations, such as Laos, agroforestry practices have been independently established by farmers who, until recently,

72 Interview, Michael B. Commons.

73 Interview, Rhett Harrison.

74 Interview, U. Tongkaemkew

practised shifting cultivation (see Box 2 in section 3.1). In addition, some types of agroforestry require **financial investments** with **delayed returns**, such as intercropping with timber, whereas smallholders may prefer to invest in shorter term revenue options.⁷³

In Sri Lanka, **lack of technical knowledge** was a constraint for farmers to adopt rubber intercropping (Iqbal, Ireland & Rodrigo, 2006) in (Hondrade *et al.*, 2017) and (Rodrigo, Stirling, Naranpanawa, *et al.*, 2001). **Security**, or theft of intercrops was also perceived to be a problem for smallholders in Sri Lanka (Rodrigo, Stirling, Naranpanawa, *et al.*, 2001), and Thailand.⁷⁴



BOX 8

AGROFORESTRY ADOPTION AND EFFECT OF POLICY REFORMS IN XISHUANGBANNA, CHINA

The adoption of rubber intercropping in Xishuangbanna, China, was influenced by **ethnicity, household wealth, labor capacity, the possession of livestock and altitude** (Min *et al.*, 2017). Farmers with more plots of land were less likely to adopt intercropping, perhaps due to labor constraints. Indigenous minority farmers, who had traditionally practiced a highly diversified farming system in the same area, were less likely to adopt intercropping practices than relative newcomers to the region. Farmers with greater income were more likely to adopt intercropping, but the magnitude of change was very small (10% increase in income led to 0.7% increase in likelihood of adoption). Labor capacity had a strong positive effect on adoption of intercropping, while many intercrops can be a source of livestock feed, explaining increased adoption among farmers with livestock. Farmers with off-farm livelihood activities were less likely to adopt intercropping

(labor constraint), as were farmers with more mature rubber area (also labor constraints, as tapping is labor intensive). Farmers at higher altitudes (above 1000m) and those with more widely spaced rubber trees were more likely to intercrop, but those with steep slopes were less likely to.

Although not directly related to adoption of agroforestry or rubber-based agroforestry, **land tenure reforms** in China have influenced smallholder decisions to integrate rubber into their farming practices. The nationwide Household Responsibility System in 1978, which allocated communal land to household-based tenure, led to an increase in smallholder-based rubber monoculture plots in Xishuangbanna, mostly replacing swidden and rice, but also intercropping immature rubber with rice, pineapple and vegetables, creating a diverse mosaic landscape of rubber and other crops that allow

smallholders to adapt livelihood strategies when rubber prices fluctuate (Xu, 2006). When the government encouraged smallholders to plant trees, smallholders preferred to plant rubber because rubber trees were (1) classified as forest cover by the government, and (2) could provide income from latex without requiring additional logging/harvesting permits (Xu, 2006). Since 2003, China implemented forest tenure reforms which increased tenure security and increased length of tenure to forest land (from 15-30 to 70 years) for farmers. A study by Lin *et al.* (2020) found that tree planting investments were significantly positively linked to smallholders having full logging rights and not significantly affected by whether they had a government-issued land certificate; although other socio-political factors likely come into play into smallholder decisions.⁷⁵

⁷⁵ However, it has still proven difficult to persuade Chinese farmers to invest in native timber, possibly because of the recent history of political upheaval and distrust between the minorities who occupy the rubber growing areas and the Beijing Government (Email consultation, R. Harrison).

**BOX 9****DIFFERENCES IN ADOPTION OF RUBBER AGROFORESTRY
IN NORTHERN AND SOUTHERN INDIA**

Rubber farmers in Southern India and North-east India differ in their adoption of agroforestry practices (Viswanathan and Shivakoti, 2008). In Kerala, Southern India, a traditional rubber-growing region, 1-25% of farmers had adopted intercropping with fruit trees, timber, coconut or pepper vines. Reasons for the dominance of monoculture practices in Kerala included **planting subsidies from the Indian Rubber Board that restrict planting of secondary crops/trees in the holdings**, and **land ownership policies** (sub-division of inherited land into small holdings) that lead farmers to intensify and specialise production on small areas of land (e.g. 0.5 ha holdings) (Viswanathan and Shivakoti, 2008). In addition, increasing household incomes means rubber is increasingly tapped using hired labor, rather than household labor, resulting in **labor con-**

straints and a lack of time for additional cropping; chosen intercrops had relatively low labor requirements, and adoption of intercropping was greatest in households with more family labor availability.

In contrast, in Northeast India, where rubber growing is a new phenomenon since the 1980s, integrating rubber with other farming systems is much more common; **communities in this region formerly practised shifting cultivation and rubber was promoted by the Indian Rubber Board as way to cease shifting cultivation practices. Land tenure** in the Northeast is predominantly through **village commons and communal ownership** (vs land titles in Southern India), and land is allocated for rubber cultivation in barren/marginal areas by village leaders, **where rubber is inte-**

grated with upland paddy rice, fisheries, poultry, pigs and shifting cultivation. Adoption of diversified systems was much greater than in the south. It is not clear whether rubber is intercropped, or whether the ‘diversification’ of rubber-based livelihoods in this region is based on patches of rubber planted among other land uses. Rubber growing has provided financial security for farmers in this region, improved food security by avoiding the need to sell rice in times of distress (selling rubber instead) and providing cash income, allowing livestock-rearing for both cash and consumption. Institutional support for rubber monoculture had a negative effect on diversified rubber systems in Northeast India, as in Southern India. Full-time farmers and those with more experience growing rubber were more likely to have diversified systems.

**BOX 10****WIDESPREAD USE OF INTERCROPPING IN SRI LANKA**

A survey of 587 smallholder rubber farmers in Sri Lanka assessed the prevalence of rubber-intercropping during immature phase of rubber. The percentage of smallholders engaged in intercropping ranged from 23 to 54% depending on location. Banana was the most common companion crop of rubber,

increasing farm income, but high input costs were a potential barrier for increasing the planting density of banana intercrops to further increase profits. The authors noted that the widespread practice of multiple cropping on homesteads in Sri Lanka suggests that local farming systems already have an

understanding of the value of intercropping, and that this knowledge needed to be incorporated into further research, for example through the development of a participatory research process at the Rubber Research Institute of Sri Lanka (Rodrigo, Stirling, Naranpanawa, *et al.*, 2001).

**BOX 11****MULTIPLE FACTORS AT PLAY IN FARMERS' DECISIONS TO KEEP JUNGLE RUBBER OR TO CONVERT TO MONOCULTURE IN INDONESIA**

A participatory on-farm research experiment on the establishment of clonal (high-yielding) rubber planting stock in jungle rubber agroforests in Indonesia involved four farmers who grew clonal rubber trees in 20 plots (Williams *et al.*, 2001). Vertebrate pest damage by monkeys and wild pigs were the most important influence on the establishment of the new rubber trees within jungle rubber agroforests, explaining ~70% of variation in rubber tree growth. The amount of labor invested in weeding was also positively correlated with rubber tree growth: farmers generally decided to completely cut back vegetation between rows of rubber trees, including potentially valuable trees, rather than weeding within the rows and selectively pruning trees in the inter-row, as farmers considered inter-row vegetation to harbour vertebrate pests and compete with the new rubber trees. Instead, farmers accessed fruits, firewood and other non-timber forest products from other land, rather than retaining integration with rub-

ber. Therefore, contrary to expectations, farmers opted to use plantation monoculture methods to protect what they considered a valuable asset (high-yielding rubber trees), rather than maintain the traditional multispecies strategy they use with lower-yielding locally sourced rubber trees (Williams *et al.*, 2001).

In Kalimantan, Indonesia, initial interest in rubber agroforestry and improved rubber growing practices in 1994, that led to the establishment of an ICRAF experiment, has fallen away in favour of oil palm cultivation — however, many farmers had kept rubber on as a means to diversify their farming, and valued agroforestry. However, knowledge of good tapping practices to maintain yields, and availability of high-quality clonal planting material, are still in short supply (thanks to abandonment of initiatives, such as farmer-led nurseries, since 1994 in favour of oil palm development) (Penot and Ari, 2019).

A computer-model-based study of jungle rubber agroforest conversion to monocultures in Indonesia investigated reasoning for conversion, and whether market-based instruments (such as premium prices for eco-certification, carbon payments, taxes on particular conversion processes) could influence farmer choices. Risk-aversion by farmers influenced the decision to convert, with more risk-averse farmers choosing to retain a greater area of agroforestry. However, multiple market-based instruments would still be needed to avoid any agroforest conversion; these would stabilise farmer incomes, and reduce income inequality among farmers (Djanibekov and Villamor, 2017).

Other studies also found that gender roles and preferences affect whether jungle rubber was converted to monocultures (Grace B Villamor *et al.*, 2014; Villamor *et al.*, 2015; Grace B. Villamor and van Noordwijk, 2016) — see section on Gender 3.2.1).

BOX 12**WHY DO SMALLHOLDERS IN SOUTHERN THAILAND ADOPT (OR NOT ADOPT) RUBBER INTERCROPPING SYSTEMS?**

In a survey of 300 smallholder rubber farmers in southern Thailand, 21 rubber agroforestry systems were identified, with variable profitability depending on secondary crop market prices and input costs. Farmers made decisions about rubber intercropping system based on labor availability, knowledge and experience, extension agencies and government policies, marketing opportunities for intercrops, capability of local communities, land topography,

and sustainability. The authors suggests that improving prices and markets for agroforestry products, developing technology to increase productivity on rubber farms, increasing farm efficiency and reducing risk rat the farm level, and better co-ordination among stakeholder agencies at the regional level are needed to further develop smallholder rubber agroforestry systems in Thailand (Somboonsuke *et al.*, 2011).

Rubber-fruit tree intercropping in Southern Thailand

Credit: CC BY-NC 4.0 EWT

4.2 RECOMMENDATIONS FOR WIDER ADOPTION OF RUBBER AGROFORESTRY

4.2.1 GENERAL RECOMMENDATIONS

4.2.1.1 UNDERSTANDING STAKEHOLDER NEEDS AND ASPIRATIONS

Interviewees and experts stressed that it was essential to understand the needs, constraints, and interests of smallholders and plantation managers to effectively implement rubber agroforestry. Recommendations for agroforestry models and best practices will need to be tailored to the diverse situations involved. Plantation managers, absentee landowners, and smallholders will vary widely in their availability in **financial capital and labor, access to markets, their short-term needs** (e.g. do they require certain crops for subsistence? Do they require returns on a weekly/annual basis or are delayed returns

(e.g. timber) practical?), as well as **long term aspirations** (e.g. do they want their children to continue farming?) Understanding smallholder needs and local cultures are also key to improving food security and nutrition as well as other social outcomes (e.g. can intercropping with vegetables or keeping chickens in their rubber farms help them achieve their nutrition needs?) Similarly, tailoring recommendations by gender will likely improve uptake of agroforestry by women and enhance female participation in agroforestry (e.g. by providing women-led training, or by promoting intercropping of medicinal plants traditionally associated with women's roles in some communities).⁷⁶

At the same time, to promote **cultural awareness and knowledge** of rubber agroforestry among both rubber growers and purchasers/consumers, there is a need for better dissemination of information about the benefits of agroforestry.⁷⁷ In particular, it is important to communicate that there are few cases where yield decline was observed when rubber is produced in agroforestry compared to monoculture systems. This information needs to be accessible to local audiences and shareable, e.g. via a documentary, local media debates, video clips, and social media, especially if farming were to be promoted in the younger generation. If rubber agroforestry skills were linked to social reputation, then it would also become more attractive.⁷⁸

⁷⁶ Interview, Michael B. Commons.

⁷⁷ Interviews, Sara Bumrungsri, Linda Preil.

⁷⁸ Interview, Linda Preil.



4.2.1.2 GOVERNMENT POLICIES AND SUPPORT SYSTEMS

In general, government policies are needed to promote agricultural practices that have demonstrated environmental benefits (e.g. agroforestry), and to disincentivise or discourage unsustainable practices (e.g. unnecessary herbicide spraying on large areas of rubber plantations). These policies need to be consistent (e.g. subsidies and technical recommendations should both favour agroforestry practices) and persistent (not subject to changes in government). Policies to support agroforestry also need to account for land-use planning and land tenure policies, to avoid detrimental environmental impacts (e.g. land-clearing for agroforestry) and to support smallholders' investments on the land. In new rubber development frontiers where rubber trees are being introduced as a new crop, proactive measures should be taken to encourage rubber agroforestry models as an alternative to monoculture plantations. Farmers need to be listened to, and farmer-led approaches need to be developed, (e.g. as recommended in Sri Lanka, and attempted in Box 12 in Indonesia), such that farmer knowledge and traditions are sustained, food security and nutrition is ensured, and farmers have flexibility to

meet their own needs.

More specifically, to facilitate wider adoption of rubber agroforestry among smallholders, several support systems are needed:

- Government policies to *allow* innovation and agroforestry systems on farms, and to *encourage* agroforestry, e.g. a special loan system for agroforestry farmers to help them in the establishment phase; provision of planting material and seedlings for intercroops in addition to rubber clones; subsidies
- Dissemination of technical recommendations at the national level via extension services, or via farmer-to-farmer approaches (peer-to-peer learning and farmer visits to other farmers' plots)
- Having demonstration plots or model farms
- Support for marketing of agroforestry or intercrop products, removal of disincentives e.g. in domestic rattan market in Indonesia

- Supporting the formation of farmer networks, associations or cooperatives, including women's groups to enable information exchange and better market access

To improve food security, nutrition and gender equity outcomes, agroforestry policies should also explicitly include nutrition and gender equity based goals (FAO/IFAD/UNICEF/FFP/WHO, 2020). For example, to improve access to healthy diets in rural communities, policies can be designed to support intercropping of nutritious food crops (e.g. vegetables, legumes, fruit) and integration of animal husbandry for protein (e.g. poultry, fish) on existing rubber monocultures.

In addition to supporting smallholders with material assistance and knowledge/training, national rubber research institutes and extension agencies play an important role for **agroforestry research**, including performing experimental field trials and having demonstration plots. In Nigeria, increased adoption of agroforestry by farmers was linked to on-farm trial demonstrations, accessing agricultural knowledge through training, extension contact, education level, membership

of farm organisation and attitudes towards intercropping (Mesike, Esekhadé and Idoko, 2019). Farmers in Sri Lanka were more likely to adopt rubber intercropping if they had more extension contacts and higher education (Herath & Takeya, 2003) in (Hondrade *et al.*, 2017).

Having an initial experimentation phase, conducted by companies or research institutes, that would trial different designs and different farming models and determine best practices, would take the financial risk of experimentation off smallholders. Another option is to fund or subsidise rubber agroforestry field trials on a group of smallholder farms, which can then serve as demonstration plots or model farms for other smallholders.

4.2.1.3 INDUSTRY'S ROLE

Industrial and large-estate plantations should make binding commitments for sustainable rubber production. The sustainability reporting of rubber producing companies should move beyond improvements in energy, water, and carbon emissions,

to embrace **additional indicators** of sustainability around livelihoods, soils, biodiversity, and climate resilience. Agroforestry practices and systems can be a financially viable strategy to increase the environmental sustainability of rubber plantations, and improve livelihood outcomes for estate workers and smallholders. Hence, we suggest that plantation companies invest in research and development to **identify cost-effective agroforestry practices and publish these in their sustainability reports to facilitate knowledge exchange.** Specifically, such practices should encourage efficient water use, prevent soil degradation and erosion, reduce water pollution, and benefit biodiversity at the production site. Specific strategies, some of which do not require agroforestry systems to be fully established, include:

- Reduced weeding;
- Cover cropping;
- Intercropping with crops that require little maintenance;
- Planting of riparian (stream/riverside) areas with a diversity of native and/or productive tree species;

- Temporary intercropping between rubber rows during first three years of rubber establishment.

Plantation companies can trial these rubber agroforestry practices on a portion of their estates, support rubber agroforestry trials among smallholders via their outgrower schemes, or even provide access to parts of the plantation for rubber workers or their families to plant additional crops between rubber rows. Plantation companies could also offer additional training to rubber tapping workers in agroforestry practices, for use on their own plots of land, or within the plantation if provided access.

In their role as **societal enabler**, plantation companies should take a proactive role to facilitate knowledge exchange for small-scale rubber growers through funded workshops and development of best practice guidelines for diversified rubber systems. They should make **contracting arrangements with small-scale farmers that actively support agricultural diversification.** Ideally, companies should encourage access to their plantation land for plantation workers to grow secondary crops. In all contracts and arrange-



ments with small-scale farmers, companies should publish a **code of conduct** on ecological and social standards to ensure fair practices, comply with national and international regulations, as well as spell out clear guidelines for misconduct.

Risk assessments, cost benefit analyses, and eco-certification can aid companies to identify and monetize the financial advantages of agroforestry and other sustainable practices, and should be conducted as a standard practice to highlight the importance of zero deforestation commitments and ecosystem services protection. Many tools to aid businesses in conducting these assessments are available for free. The Global Forest Watch tool ⁷⁹ allows to assess the risk of deforestation in rubber producing areas, while High Conservation Value (HCV) and High Carbon Stock (HCS) approaches are useful for companies to assess the ecological and carbon values in their holdings. The InVest tool ⁸⁰ can help companies to analyse the value of ecosystem services provided by agroforestry and other sus-

tainable practices. Moreover, rubber buyers, such as tyre companies, could **facilitate the adoption of agroforestry rubber** by creating a demand for agroforestry rubber through procurement policies, and/or by facilitating the adoption of rubber eco-certification that grant a price premium for smallholders and industrial growers who implement agroforestry and other sustainable practice.

4.2.1.4 RESEARCHERS

Positive, mutually beneficial relationships between the smallholders (and other non-research stakeholders) and the research community can help facilitate wider adoption of agroforestry. Local and international researchers can co-create and support farmers with well-evidenced agroforestry knowledge and best practices, as well as help to identify and solve farmers' problems, or help to connect farmers to other resources or colleagues.⁸¹ Researchers must make strong efforts to share their research findings with

rubber research institutes, CSOs, and the farmers they collect data from and work with, to ensure knowledge is shared with those who can apply it. Meanwhile, researchers can also learn from the practical knowledge of farmers which can better inform their studies, while at the same time uplifting farmer-produced knowledge and lived experiences. Researchers can assist farmers in gathering evidence and supporting the presentation of evidence, helping to amplify the farmers' voices on local or international policy platforms, particularly in situations and cultures where published or accredited research is perceived as having high value and credibility and where farmer perspectives are underrepresented.⁸² The evidence presented on agroforestry effects on soils needs to be bolstered with more robust studies, that encompass the wide variation among smallholder rubber plots. Lastly, our literature review has highlighted a major research gap in the peer-reviewed rubber agroforestry literature in terms of elucidating the links between rubber agroforestry and food security and nutrition, gender equity and la-

79 Global Forest Watch (available at: <https://www.globalforestwatch.org>)

80 InVest (available at <https://naturalcapitalproject.stanford.edu/software/invest>)

81 Interview, Michael B. Commons.

82 Interview, Michael B. Commons.



bour burdens, land tenure, and other social dimensions (e.g. farmer empowerment, food sovereignty).

4.2.1.5 FARMER NETWORKS

Farmer-to-farmer networks and associations facilitate the spread of agroforestry practices and knowledge in farming communities. A quarter of surveyed farmers in Southern Thailand adopted agroforestry after hearing about successful experiments in their area by their peers (Stroesser *et al.*, 2018). Farmers use diverse sources of knowledge (including informal farmer networking, networking facilitated by formal agricultural knowledge institutions, collaboration between farmers and researchers, and multidisciplinary knowledge networks), but they place high importance on local experiential knowledge because they view such knowledge as personally, locally, and practically relevant (Šūmane *et al.*, 2018). As such, farmers who have successfully adopted agroforestry practices are the best source of locally adapted, practical knowledge; and

farmer networks provide mutual support and more opportunities for accessing resources via collective action, from developing skills and inclusion of women and youth, and scaling out agroforestry practices.

In more general terms, research on farmer networks is still limited. The effectiveness of collaborative networks between stakeholders to address environmental problems are said to depend on individuals' attitudes towards the benefits of knowledge sharing with others (e.g. some farmers may fear that their hard-earned knowledge will be “exploited” by other farmers), differences in knowledge gaps, and whether such issues can be overcome in a foreseeable time period (for a review see (Bodin, 2017)). In cocoa, farmer networks in Ghana have been shown to play an important role for knowledge transfer (Isaac, 2012). For example, rural communities relied exclusively on knowledge exchange for agroecological production knowledge of cocoa. In closer proximity to urban areas, farmers had much closer contact with agri-environmental organizations to facilitate knowledge about agroforestry (Isaac, 2012). Farmers in networks with better access to informa-

Large (top) and small-scale (bottom) rubber smoke houses in Myanmar

Credit: Both images: CC BY-NC 4.0 TCW



tion had higher on-farm crop diversity. The authors argue further that policy promoting diffuse and more innovation prone farmer network structures is strategic for persistent cocoa production systems. In Southern Thailand, rubber agroforest smallholder farmers have formed groups around common interests (e.g. love for trees, wanting to increase income), which have facilitated the spread of agroforestry among peers as well as collaboration with researchers and industry (see case studies in Box 3 and Box 4).

4.2.1.6 COLLABORATION

There is a need for collaboration between multiple stakeholders to find integrated solutions to address the dynamic and complex challenges for sustainable agriculture, not least including the wider adoption of agroforestry. This is because changes at different scales and from different actors are needed – from cultural shifts among smallholders and estate companies, to government policies to

support these transitions. Farmer representatives should be real farmers to ensure effective implementation of agroforestry.⁸³

There should be a multi-way exchange of information regarding agroforestry best practices among and between **farmers, researchers, CSOs, officials and industry**. Some farmers are very knowledgeable about agroforestry and are creatively experimenting with different agroforestry approaches and species – their experience and creativity are valuable sources of practical knowledge. Communication with non-research stakeholders should be done via interpersonal meetings wherever possible, or possibly focus groups. At the same time, agroforestry researchers from international agroforestry and rubber research institutes (e.g. CIRAD, ICRAF, IR-RDB), as well as experts from national rubber institutes⁸⁴ should also come together to consolidate the global base of agroforestry knowledge. Examples of such collaborations include: “Green Rubber” conferences held

in Laos (2014) and Xishuangbanna (2016); joint online workshop on Natural Rubber Systems and Climate Change (2020);⁸⁵ and the upcoming International Workshop on the Resilience of Rubber-based Agroforestry Systems in the Context of Global Change (April 2021).⁸⁶ Input from industry, in terms of both agroforestry best practices and agroforestry transitions and value chain development is another piece of the puzzle. Such collaboration will help **consolidate the global and local knowledge base of agroforestry**, help **prevent pitfalls** (there are many examples of newly introduced promising species turning out in failed projects),⁸⁷ facilitate joint learning and **promote best practices, and scale out agroforestry**. An agroforestry-oriented innovation platform was suggested as a way to facilitate such collaboration and information exchange. Funding or support from climate funders and multilateral agencies could help facilitate this. Farmer to farmer learning is likely to be key, given the experiences of the farmer networks detailed above.

⁸³ Interview, Sara Bumrungsri.

⁸⁴ A lot of agroforestry research has been conducted by rubber research institutes but are not published, are documented in internal reports or in the local language, or are only available on the ground. Physical visits to these locations may be needed to compile this information (interview, Rhett Harrison).

⁸⁵ Workshop materials and recordings are freely available at: <https://www.foreststreesagroforestry.org/fta-event/natural-rubber-systems-and-climate-change/>

⁸⁶ <https://www.rubis-project.org/project-events/current-event/rubis-international-workshop-2021>

⁸⁷ Email consultation, Julia Quaedvlieg.

“All stakeholders, including farmers, need to be recognised as equal co-authors of knowledge generation, and all kinds of knowledge, both formal and informal, need be brought together in innovation processes. Knowledge networking and multi-actor knowledge networks that facilitate knowledge exchanges, joint learning and the generation of new more integrated solutions, are crucial if agriculture is to become sustainable and resilient.”

Šūmane et al., 2018

4.2.2 BEST PRACTICES AND PITFALLS FOR RUBBER AGROFORESTRY

There are **no universal best agronomic practices for agroforestry** that will work in every location. Experts found it challenging to summarise best practices for rubber agroforestry, as they will depend on a **variety of factors** and be highly context dependent, including the local biophysical environment, market availability, smallholder needs and constraints, as well as the objective or reasons for utilising agroforestry strategies. Similarly, **pitfalls occur when these factors are not considered** when implementing rubber agroforestry practices. As discussed earlier, understanding stakeholder needs and aspirations are key. To be effective, agroforestry practices or systems should account for:

1 Constraints of local biophysical environment

When agroforestry practices are not adapted to the local biophysical conditions, it could lead to yield and productivity losses for rubber or the intercrops. For example, intercropping with coffee and cocoa at normal rubber planting density does not work; intercropping in sandy soils would lead to competition for water).⁸⁸

2 Market availability

If the additional products from agroforestry have no market or utility in the area, then it is unlikely to contribute to incomes or livelihoods, even if these crops or livestock can grow well in the

88 Interview, Eric Penot.



rubber plots. Conversely, agroforestry products that already have established demand and local markets, or which can be used directly by smallholders, would be more likely to be successful.

3 Smallholder needs and constraints

Smallholder needs will determine the objective of adopting agroforestry practices and systems (e.g. is it to grow food for self-consumption, or for improving soil quality, or to diversify income?). Gender differences should be considered, particularly in terms of labour constraints which are key, as well as land constraints, tenure conditions, government policies, etc.

4 Agroforestry objectives

Different agroforestry practices or systems

will be needed for different objectives, as determined by smallholders or industrial plantations. Agroforestry strategies for ecosystem restoration and biodiversity may look very different from agroforestry strategies purely to increase economic returns.

Given the diversity of situations and agroforestry systems, this report does not provide a list of technical recommendations for best practices and there is still a lot to do to identify the best practices in the different socio-economic and biophysical conditions. Nevertheless, several researchers and practitioners interviewed maintain that strategies for avoiding reduction in rubber yields and increasing productivity in intercropping systems have been established by prior research.⁸⁹ These include: double-row alley cropping with wider interspacing for intercrops (therefore maintaining overall planting density of rubber across the farm, as rubber is

usually the key cash crop), not planting trees that would shade out the rubber trees, and not planting other intercrops in the rubber line (see earlier section ‘Yields and Productivity’ for a more detailed discussion). For pitfalls of rubber-based intercropping, Langenberger *et al.* (2017) reviews several examples that have not worked well in economic or agronomic terms.

For industrial plantations, interviewees suggested that rubber-timber intercropping systems had the most potential for scaling up due to the high economic returns and lower labour needed.⁹⁰ These systems can also work well for smallholders who wish to invest less labour and who are able to accept delayed returns.⁹¹ However, these may compete with the rubber canopy, and although they could increase profits, no evidence has yet shown benefits for soil, water or biodiversity of rubber-timber systems.

89 Interviews, Rhett Harrison, Eric Penot, and Michael B. Commons. Email consultation, Bénédicte Chambon.

90 Interviews, R. Harrison, E. Penot, and M. Commons. Also discussed in Langenberger *et al.* (2017).

91 Interview, R. Harrison.

“Precautions are therefore needed in designing and managing these systems: farmers’ expectations, in contexts that are determined at once by social, economic and political factors, must not be ignored, and agroforestry systems should not be exclusively geared to productivity. Agroforestry cannot evolve as an environmental concept if it is voided of its most fundamental goal, which is to bring sustainable improvements to farming livelihoods.”

Barisoux, 2017

5 Conclusions

Rubber agroforestry systems are dynamic and versatile, consisting of multiple components that make contributions to smallholder livelihoods, food security and nutrition, provide social advantages, and improvements for soils, water and other environmental and climate outcomes. Research gaps still exist around the ‘best’ practices for agroforestry such as appropriate intercrops, optimal tree spacing, and water usage; as well as the social outcomes of agroforestry such as gender, food security and sovereignty, nutrition, and farmer empowerment. However, one of the take-home messages from this report is that there is already considerable knowledge around agroforestry systems that can be used, and while controlled experimental systems would

be hugely beneficial, these may take decades to produce results. In contrast, the need for action to support smallholder farmer livelihoods and build climate-resilient and more biodiversity-friendly rubber cultivation practices is urgent.

Better information sharing is needed, for example through farmer-to-farmer exchanges, the opening up of rubber research institute reports and knowledge into the public domain, and better translation of scientific studies into user-friendly materials for use by government agencies and businesses. For example, farmers in Lao PDR are already skilled at producing food from diversified shifting cultivation systems – this knowledge is at risk of loss due to restrictive rubber planting con-

tracts. In other locations, such as Southern Thailand, farmers went through a policy-driven transition from cultivating diversified but low-yielding rubber systems to successful cultivation of monocultures, but some are using their prior knowledge, and that from other cropping systems, to inform interplanting techniques in higher yielding rubber agroforestry systems. Meanwhile, scientific studies of soil nutrients, soil carbon and water use from intercropping systems in China can support anecdotal evidence from other locations (e.g. southern Thailand) that permanent intercropping can facilitate water use by rubber trees, although caution is needed in very drought-prone areas (e.g. north-eastern Thailand).

A precautionary approach is needed in the adoption of all agroforestry practices. Agroforestry systems that meet the needs of farmers in specific locations are best designed by those farmers, who know the constraints on labour, land or other resources they already have to manage, and the risks to their livelihoods that they already face. However, better exchange of knowledge could help inform farmers of their options for diversifica-

tion, and choose systems that work best for them. Multiple projects have trialled rubber agroforestry practices, but have found it not to be widely adopted. This may not indicate that rubber agroforestry itself is untenable, because ample evidence suggests that for example rubber yields in intercropping systems are not lower compared to monocultures but income risk is more diversified in agroforestry system. It rather shows that farmers did not have access to the information, knowledge, networks, capital or physical inputs (e.g. seedlings) needed to diversify in the first place, that policy or market conditions were not right for agroforestry to work more widely, or that farmers' preferences and motivations were not well understood. Rubber is a long-term investment, but with short term price volatility. Lessons must be learned from places where rubber cultivation has generated long-term benefits for farmers and where agroforestry practices are reaping rewards for farmers, such as in southern Thailand or China, as well as places where existing agroforestry practices are being lost, such as Indonesia, to inform rubber sustainability efforts now. Similarly, there is much potential for

plantation companies to benefit from implementing agroforestry practices on estates, and rubber buyers play a crucial role in facilitating demand and developing value chains for agroforestry rubber. Lastly, it is important to note that agroforestry is not the only agroecological option to more resilient and environmentally friendly rubber production. Reduced weeding, cover cropping or planting of riparian areas with trees are options independent of agroforestry practices.

Overall, creating an environment where farmers have access to information, capital, markets and importantly, the autonomy to choose which components of agroforestry best suit their needs and constraints would allow them to exercise creativity and sovereignty in their farms and livelihoods. In the UN Decade of Restoration, learning from existing agroforestry systems and taking on the challenge to establish new ones has the **potential to make a substantial contribution to bring sustainable improvements to the environment and farming livelihoods**, if all stakeholders unite to build a better tomorrow.

Methodology

This report was written based on an extensive literature search, interviews and email consultation with experts in rubber production, and based on personal experience researching rubber production systems and agroforests in Latin America, Africa, and Southeast Asia.

6.1 LITERATURE REVIEW

In October 2020, we conducted a literature search on Web of Science and Scopus, using the search terms:

“TITLE-ABS-KEY ((rubber OR hevea) AND (agroforest* OR intercrop* OR inter-crop* OR agroecolog*) OR “jungle rubber” OR “rubber garden”)”.

We included conference proceedings in the search, and also used Google Scholar to supplement our search with recent reports and

other grey literature. We also sought suggestions from interviewed experts and our wider network **for pertinent reports and hard-to-access academic papers. More than 800 articles** were captured in this literature search, which were then filtered by specific topics covered in this report. Around a third of these articles have been published in the past five years alone (2015-2020), representing an upsurge in interest in sustainability of rubber production. The majority of articles covered agronomic and environmental aspects of rubber agroforestry, with much fewer articles on socio-political or cultural aspects, as reflected in our Findings.

We acknowledge there were additional potential sources of rubber agroforestry literature which were not covered by Web of Science and Scopus, particularly journals of national rubber research institutes, which we did not manage to cover.

6.2 INTERVIEWS AND EMAIL CONSULTATIONS

In October 2020, we sent out 35 requests for interview or email consultations to stakeholders with knowledge or experience with rubber agroforestry, from rubber research institutes, CSOs, and industry. We were able to consult with 12 interviewees with agroforestry experience covering Asia (Indonesia, Malaysia, Thailand, Cambodia, China), Africa (Nigeria, Cote d’Ivoire), and South America (Brazil, Peru). We conducted in-depth, semi-structured interviews with 10 stakeholders and received four written responses to a questionnaire (available from authors on request). Regretfully, due to time and logistical constraints, we were unable to consult a broader range of stakeholders, particularly those who would require in-person visits (farmer associations, CSOs, and industry), as well as additional rubber agroforestry experts from other countries not represented here.



Better representation of farmers' ideas and perceptions of agroforestry should be a key focus for further research on agroforestry.

Researchers

Eric Penot, CIRAD (email consultation 8/10/2020; interviewed 12/10/2020)

Bénédicte Chambon, CIRAD (email consultation 9/10/2020)

Gerhard Langenberger, GIZ (interviewed 5/10/2020)

Kenneth Omokhafa, Rubber Research

Institute of Nigeria (email consultation 7/10/2020; interviewed 16/10/2020)

Luciana dos Santos Duarte, Erasmus University of Rotterdam (ISS-EUR) (interviewed 11/10/2020; follow-up email consultation 16/10/2020)

Julia Quaedvlieg, Erasmus University of Rotterdam (ISS-EUR) (email consultation 15/10/2020)

Rhett Harrison (interviewed 9/10/2020)

Sara Bumrungsri (interviewed 12/10/2020)

Uraiwan Tongkaemkaew (interviewed 14/10/2020)

Practitioner/NGO

Michael B. Commons, agroforestry practitioner, Earth Net Foundation (interviewed 15/10/2020)

Anonymous (interviewed 6/10/2020)

Industry

Linda Preil, Head of Rubber Projects, einhorn (interviewed 9/10/2020)

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