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Sustainable development of rubber plantations in a context of climate change

Challenges and opportunities

Vincent Gitz[a], Alexandre Meybeck[a], Salvatore Pinizzotto[b], Lekshmi Nair[b], Eric Penot[c], Himlal Baral[d] and Xu Jianchu[e]

Introduction

Land use is a central issue for the achievement of the Sustainable Development Goals (SDGs) and of the Paris Agreement on Climate Change. Plantations of all major tropical commodities are expanding quickly. This creates opportunities for development. It also raises concerns about the impacts of these plantations on the environment, landscapes and livelihoods. Natural rubber is a particularly interesting example to consider in the perspective of sustainable development of a commodity's producing countries and value chains. This paper is a collaboration between the Forests, Trees and Agroforestry (FTA) research program of the CGIAR (FTA n.d.) and the International Rubber Study Group (IRSG) (IRSG n.d.). FTA works across a range of plantations, value chains and tree crop commodities, from timber, palm oil, cacao, coffee and tea to bamboo, rattan and rubber, among others. It has identified plantations, their development and sustainability as a research priority. IRSG is an intergovernmental organization and the primary source of statistical information related to rubber value chains, policy issues, innovation and technology. IRSG has a leading role in developing a comprehensive agenda for the sustainability of natural and synthetic rubber.

Natural rubber production is dominated by millions of smallholders; by and large, around 90% of the global production and rubber area is under smallholdings (IRSG 2019). There are both monoculture and various diversified systems. The diversity of economic and production models, as well as the diversity of policies and measures in the sector, can lead to useful conclusions for a sustainable future of plantations.

Rubber plantations expanded rapidly from 2005 onward, coinciding with the super-cycle of commodity prices that included natural rubber. The rubber area has grown quickly in the last two decades, with a stronger expansion especially in the last decade (IRSG 2019). This growth has been most apparent in the Mekong region and Côte d'Ivoire. More than 2.5 million hectares (ha) was added to total rubber area during 2008-18, bringing about a 24% expansion in rubber area. Global rubber demand has risen rapidly during the last decade, driven by economic development, especially in China, as the world economy recovered from the 2007-08 financial crisis. This expansion is expected to continue at a decelerating rate driven by increased demand. Predictions suggest a modest growth in global demand (+2.4% per annum) driven by the tyre sector (+2.2% per annum) in the next decade (IRSG 2019).

a Forests, Trees and Agroforestry (FTA)/Center for International Forestry Research (CIFOR)
b International Rubber Study Group (IRSG)
c French Agricultural Research Centre for International Development (CIRAD)
d Center for International Forestry Research (CIFOR)
e World Agroforestry (ICRAF)

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Various authors have raised concerns about rubber expansion and its impacts on biodiversity, soils, water, ecosystem services and livelihoods of local populations (Ziegler et al. 2009; Fox and Castella 2013; Warren-Thomas, Dolman and Edwards 2015). In answer to such concerns, both the industry (IRSG 2014) and researchers (Warren-Thomas et al. 2015) call for a sustainability initiative to mitigate such negative impacts comparable to those for some other commodities like oil palm. Kenney-Lazar et al. (2018) argue it would be more effective to address the most unsustainable practices rather than pursue an elusive concept of sustainable rubber.

This paper[3] considers natural rubber primary production in relation to its sustainability and challenges in order to identify how it can best contribute to sustainable development in a context of climate change. It focuses on issues linked to primary production and land use as part of a research program on plantations. We adopt a pragmatic approach to sustainability: address the main unsustainable points and strengthen the main contributions to sustainability. We first identify and consider some main "unsustainability hotspots" where the challenges and opportunities are the greatest. We then propose how to address them in a comprehensive way.

1 Sustainability hotspots

Several publications have considered the impacts of rubber cultivation and expansion biodiversity, soils, water, ecosystem services and livelihoods (Ziegler et al. 2009; Fox and Castella 2013; Warren-Thomas et al. 2015). Most available studies deduce environmental impacts from a comparison with previous land cover, often natural forest. So, rather than analyzing the impact of Hevea plantations per se, these studies are often more about the impact of deforestation. There is a lack of comparative studies of impacts of various land uses other than comparisons with the original forest. Drawing on these publications, we consider in this section some main sustainability hotspots (environmental, social and economic). These comprise land-use change, impacts on biodiversity, climate change mitigation, impacts on water (quality and quantity) and erosion, social issues and smallholders, resilience to price fluctuations and adaptation to climate change. In this way, we identify the main factors that can influence the sustainability of natural rubber development.

Rubber tapping in Kalimantan, Indonesia.
Photos by Eric Penot from CIRAD/FTA.

1) Land-use change

According to IRSG (2020b), the total amount of rubber planted worldwide as of 2020 was 14.1 million ha. Land under rubber has grown 1.8 times over the past 30 years with rapid acceleration in the last decade. It is the most rapidly expanding tree crop within mainland Southeast Asia (Cambodia, Laos, Myanmar, Thailand, Vietnam and Yunnan, Southwest China) (Fox et al. 2012). As shown in Figure 1, the dynamics of rubber expansion, in the last decade, have significant contrasts:

- a global increase
- reduction in Malaysia and stagnation in Indonesia, resulting from competition with palm oil and with conversion of jungle rubber in Indonesia and clonal rubber to oil palm in Malaysia (Abdullah and Hezri 2008; Feintrie and Levang 2009; Ekadinata and Vincent 2011)
- an increase in Thailand, especially in the north and northeast, in competition with cassava and rice
- a sharp increase in less traditional production countries and areas, which is a challenge in itself.

Warren-Thomas et al. (2015) projected various scenarios of additional land requirements to meet rubber demand in 2018 and 2024. The area needed is of course very much dependent on yield, including on improvement, or not, of yield in low productivity systems such as jungle rubber. Palm oil expansion that replaces rubber drives further land needs for rubber or conversion from seedling- based jungle rubber to clonal rubber monoculture. Depending on these two factors, additional land needs projected by the authors vary from 4,321,704 ha to 8,702,213 ha.

Since the projections on additional land requirement to meet global rubber demand discussed by Warren-Thomas et al. (2015) in their research paper, the global rubber market has totally changed in 2019 and during the forecast period until 2024. Natural rubber demand declined marginally in 2019 (-1.0%) and has falled in 2020 because of the global pandemic. As rubber demand is highly linked to transport of goods and people it is expected to remain lower than before the Covid crisis until 2024 (IRSG 2020a).

Rubber area expanded, especially in the last decade, likely at the cost of forests or on mosaic landscapes, swidden agriculture and agroforest. When rubber replaces swidden agriculture it may, particularly when established by migrants or outside companies, displace agriculture into frontier forests (Li et al. 2007). Such land-use changes have important environmental impacts on biodiversity and on carbon sequestration. They may have very contrasted social impacts depending on the systems that rubber production is replacing and on the way it is itself organized.

There is also a potential for reducing land-use change and deforestation through more intensive systems, by increasing yield of latex (use of rubber clone rather than seedling) and by diversified production systems resulting in higher combined land productivity.

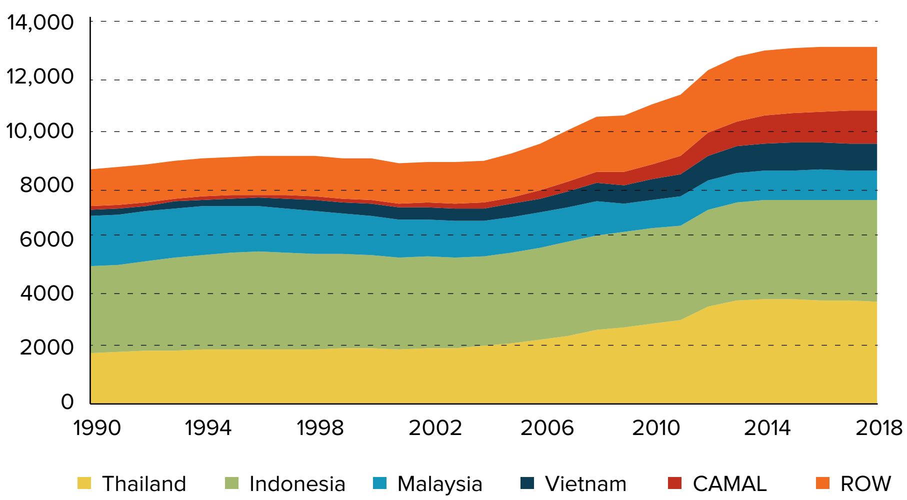

Figure 1. Rubber planted area (in thousands ha) per country.

Note: CAMAL represents Cambodia, Myanmar and Lao People's Democratic Republic (hereafter "Laos"). Row represents the rest of the world.
Source: IRSG 2020a.

2) Impact on biodiversity

There have been fewer systematic studies on the impacts of rubber expansion on biodiversity than for palm oil, but there are convergent results (Diaz-Novelllon et al. 2002; Warren-Thomas et al. 2015; He and Martin 2015). In many areas, the recent rubber expansion has been on former natural forest; in some case, it has been in protected areas.

Effects of conversion of primary and secondary forests to rubber monoculture is quite well-understood: it decreases species richness and changes species composition. However, the biodiversity value of swidden agriculture and of mosaic landscapes is less well known and the effects of their conversion to rubber plantations have not been frequently examined.

There is also some knowledge on the effects of different types of production systems. Agroforest rubber supports a subset of forest species not found in monocultures. There is greater biodiversity in plantations that have greater complexity in habitat structure e.g. the multi-strata complex agroforestry systems with secondary forest regrowth in the interlines or combination of fruits/timber trees.

More studies are needed to compare effects on biodiversity of different spatial organizations. These should, for instance, compare the effects of retention of connected and protected forest patches on a fine scale to intensification with broader protected blocks. There is also a need to better understand and assess interactions between species in complex systems, such as pest control effects of wildlife in plantations. Most interactions would be considered as positive externalities (on erosion, soil fertility, global biodiversity and water catchment). However, sometimes negative externalities may emerge. The increased global moisture of AF systems, for example, may increase Phytophtora panel disease on rubber; this was observed in Jambi in the 1990s.

3) Climate change mitigation

Various studies have been conducted on the potential contribution of rubber to climate change mitigation in diverse situations (Kyono et al. 2014; Nizami et al. 2014; Brahma et al. 2016). There are significant uncertainties in carbon stock estimations at plot, landscape and production levels (Blagodatsky et al. 2016). These studies generally focus on carbon stocked in trees' biomass above and below ground. They show that rubber plantations constitute carbon stocks that can be compared to cocoa plantations, or to some agroforestry or forestry systems. A study modeling carbon sinks in rubber plantations with different rotation lengths concludes that longer rotations show increased soil carbon stocks (Nizami et al. 2014). Such studies generally conclude that rubber plantations can be an effective mitigation measure on degraded lands (Brahma et al. 2016).

However, the global greenhouse gas emissions balance needs to take into account the effects of conversion to rubber plantation, which is strictly dependent on previous land use. Conversion of forests or swidden agriculture can lead to substantial carbon emissions (Li et al. 2008); these, however, are variable (Ziegler et al. 2012; Yuen et al. 2013). For instance, a study in Northern Laos (Kiyono et al. 2014) compares carbon stocks generated by rubber plantation to those generated in the swidden system practiced in the area. It found the length of the fallow, which was about 20 years in the 1970s, decreased to 5 years in the 1990s. The study shows that a rubber plantation standing for 30 years leads to a higher carbon stock, much greater than in a swidden system with a 5-year fallow period. This finding holds even when accounting for emissions generated from soil preparation before rubber planting. However, this benefit is lost if swidden agriculture displaced by rubber in turn translates to an area where it converts natural forest.

The potential contribution of rubber to mitigation thus depends on what it replaces and on how it is conducted:

- Impact is generally negative when rubber replaces forests, primary or secondary.
- Impact is positive when rubber is implanted in severely degraded land.
- Impact can be neutral or slightly positive when rubber replaces swidden systems depending mainly on the length of the fallow period of the system replaced.
- Impact is negative when rubber displaces swidden systems that are then encroaching in forest.
- Systems that are diversified, integrating other trees, can be as efficient to store carbon than secondary forests.

There is also considerable potential in more use of rubber wood. This would also reduce the need for additional wood collection in forests and for timber plantations. Rubber wood, for instance, is the most important raw material for the wood furniture industry in Malaysia (see Box 1 in section 2.4).

4) Impacts on water (quality and quantity) and erosion

Various studies report diverse negative impacts on water resources (quantity and quality) of rubber monoculture as compared to previous land use (generally in comparison to natural forests). There is less fog interception relative to complex canopies (Xu et al. 2013). Conversion to rubber can increase evapotranspiration relative to native vegetation (Tan et al. 2011). Rubber depletes deep-soil moisture during the dry season with risks for groundwater and streamflow (Guardiola-Claramonte et al. 2008; Kobayashi et al. 2014). In mountainous areas of mainland Southeast Asia, plantations on steep slopes have negative impacts on soil erosion, landslide risk and water quality. Basin-scale modeling showed conversion to rubber could reduce annual water discharge by 29% (Guardiola-Claramonte et al. 2010). There are indications of impacts of run-offs from rubber plantations (sediments, fertilizers, pesticides) on water quality with impacts on aquatic biodiversity (Xu et al. 2013; Prasannakumari et al. 2019).

5) Social issues, smallholders

Rubber is produced both in smallholdings using family labor and on large estates with hired labor. Smallholders can be independent or linked to companies by contract or various forms of dependency. These types of production systems are variously represented in countries. For Myanmar and Laos, for instance, production systems could be categorized in three main types: independent smallholder production, estate plantations benefiting from land concessions, and contract farming between companies and farmers (Kenney-Lazar et al. 2018). Each of these systems has specific social sustainability issues.

In the largest rubber-producing countries, production is dominated by smallholders (Fox et al. 2014). It is an interesting opportunity for smallholders as it can be combined with other crops during the maturing years and integrated into diversified agroforestry systems. In many instances, rubber has been an important way to increase smallholders' income and transform their livelihood, especially during the high price period. Several governments see rubber as an opportunity to increase income and alleviate poverty. Establishment of rubber-replacing swidden agriculture has substantially increased smallholder income in Southwest China and Northern Thailand (Liu et al. 2006; Fox and Castella 2013). Two factors have played an important role for smallholders to benefit from the development of rubber. First, national policies supported smallholders (see section 2.3). Second, smallholders benefited from the considerable increase in the price of rubber from 2000 to 2011. Smallholders' income also depends greatly on the way trade is organized, i.e. whether they depend on intermediaries or on contracts with big companies.

In non-traditional areas such as in Laos, or in countries like Cambodia and Myanmar, and some African countries, expansion of rubber often takes the form of larger-scale plantations. Replacing swidden agriculture with industrial-scale rubber plantations in mainland Southeast Asia could disadvantage rural communities (Baird 2010; Ziegler et al. 2011; Fox and Castella 2013). There have been reports of evictions and poor labor conditions in some rubber plantations (OHCHR 2007; Baird 2010; Woods 2011; Global Witness 2013).

In large plantations, the main social issues are linked to working conditions, types of contracts, levels of salaries and social protection. Tapping is generally poorly paid, with a high rotation of the labor force. The labor market is often informal with oral contracts (Bhowmik and Viswanathan 2015). Tappers are also impacted by rubber price fluctuations as large estates tend to reduce collection of rubber when prices are too low. Nevertheless, tapping can be part of more complex livelihood strategies, involving subsistence farming and other activities. It has also been shown that temporary migrations for tapping have played a role in the expansion of rubber plantations, particularly inside country. In Thailand, for instance, tappers bring back to their villages in the North the skills acquired in rubber plantations (Fox and Castella 2013).

Smallholder woman engraving a tree for rubber tapping in Kalimantan, Indonesia.
Photo by Eric Penot from CIRAD/FTA.

6) Resilience to price fluctuations

Rubber price fluctuation (see Figure 2) is complex to follow and understand as many factors play a role. These include supply and demand, large new planting in the last ten years, stock impact, oil price and synthetic rubber price with effect of substitution, etc. From the early 2000s, with the increase in global demand and until the financial crisis of 2008, the price of natural rubber rose steadily, reaching a value of USD 3000 per ton in 2008. At the beginning of the financial crisis, prices collapsed, soaring again to a record high of USD 5000 per ton in 2011. Since then, the price of natural rubber has gradually declined to reach and maintain a value of around USD 1200 to USD 1400 per ton (Free on Board price for SMR 20) since 2015. The price increase of the 2000s led to massive area expansion of more than 1 million ha between 2005 and 2011. These new plantations entered production, on average, five to seven years after. This, in turn, fueled a significant increase in supply, while demand in growth slowed down. Combined with other factors, this led to a decrease in prices.

Figure 2 covers 30 years, the life span of a plantation. It shows the volatility in the price of rubber. This is a concern for long-term investment, especially when costs (here mainly labor) do not fluctuate the same way.

This has important consequences on the sustainability of economic and production models. Smallholders that are purely engaged in rubber are very exposed, especially if they are not supported by public policies or by industry partners as part of their corporate social responsibility programs. However, countries and regions vary on the cost of producing rubber depending on their reliance on wage labor. In Laos, smallholders could still earn money despite the low prices unlike large estates that rely on wage labor, (Kenney-Lazar et al. 2018). Paradoxically, large estates may be more exposed because of monoculture farming and dependence on a hired labor force. In India, for instance, hired labor can represent 70% of production costs, apart from land acquisition (Bhowmik and Viswanathan 2015). This explains some of the rubber area shift to palm oil (especially in Malaysia and Indonesia) as it provides a higher income per hectare. In Malaysia, large estate owners have been reducing their rubber cultivation over the years. They have been replacing it with more profitable commodities, especially palm oil. Meanwhile, smallholders supported by public agencies have better resisted or even increased their extent. As a result, smallholders with diversified production may be the most reliable system to ensure a long-term stable supply (Ratnasingam et al. 2015).

7) Adaptation to climate change

There are few studies on the potential impacts of climate change on rubber production. Until very recently, it was difficult to predict the incidence of climate change on violent precipitations and winds, to which plantations are vulnerable. Observations indicate that climate uncertainties and drought are increasing the number of casualties of young plants immediately after field planting (Jessy et al. 2011). There is also a need for more research on the impacts of climate change on the distribution of pests and diseases.

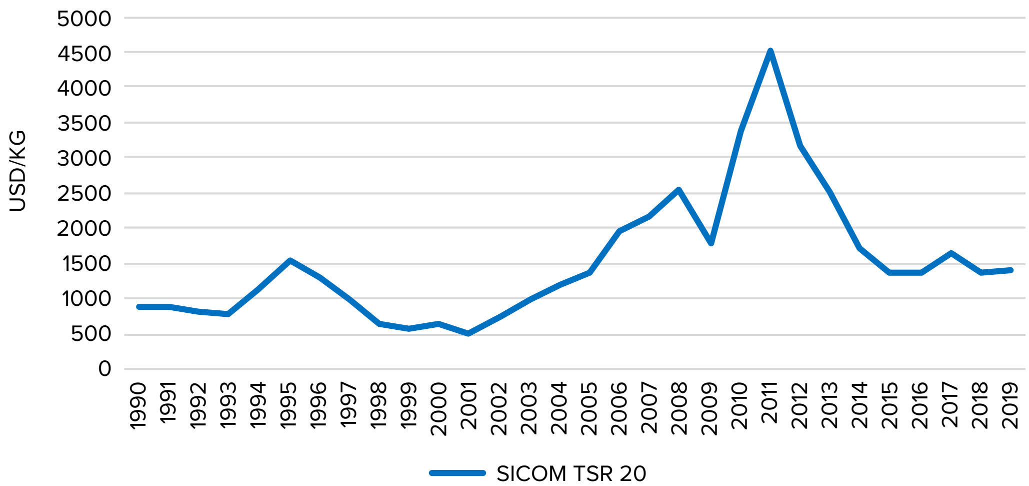

Figure 2. Rubber yearly price – US Dollars per kilogram.

Source: IRSG 2020a.

Young agroforestry rubber plantation in Kalimantan, Indonesia.
Photo by Eric Penot from CIRAD/FTA.

Several studies, in various geographical regions, projected climate change and then used models to determine areas that would be suitable for Hevea plantation in China (Liu et al. 2015), India (Debabrata et al. 2015) and Malaysia (Hafiz et al. 2018). For instance, Liu et al. (2015) analyzed the effects of future climate change on climatic suitability of rubber plantation in China. They consider five main climate factors affecting rubber planting: mean temperature of the coldest month; mean extreme minimum temperature; the number of months with a mean temperature ≥18 °C; annual mean temperature; and annual mean precipitation. Climatic suitability areas of rubber plantation in 1981-2010, 2041-2060 and 2061-2080 were analyzed by the maximum entropy model based on the five main climate factors and the climate data of 1981-2010 and RCP4.5 scenario data. The results showed the climatic suitability for rubber plantation would have a trend of expansion to the north in 2041-2060 and in 2061-2080. The suitable area and optimum area would increase, while the less suitable area would decrease. The climatic suitability might change in some areas. For instance, the total suitable area would decrease in Yunnan Province, and the suitability grade in both Jinghong and Mengna would change from optimum area to suitable area. In many cases, it seems that climate change will increase the marginal areas where rubber can expand. It may also modify the dynamics between rubber and oil palm (Jianchu and Zhuangfang 2015). As oil palm plantations are restricted to the humid tropics, rubber might replace oil palm in areas that are getting dryer, benefiting from clones that are more drought resistant. Diversified systems are more resilient to shocks of any kind, including from climate change, both as a farming system and for households that depend on them. Such systems can also contribute to adaptation at landscape level (erosion, biodiversity).

Identified adaptation options include management measures such as irrigation of young plants in case of drought, rainguards and low frequency tapping systems that can escape extreme events of rainfall and genetic improvement for resistance to drought and diseases.

Main conclusions: Sustainable rubber development

When considering together all the sustainability hotspots, environmental, economic, and social described above it appears that potential impacts of rubber expansion and contribution to the SDGs and to the Paris Agreement depend on three factors:

i. location of future expansion and what land use/land cover rubber is going to replace
ii. type of production system, yield and overall efficiency, including use of rubberwood, as well as impacts on water and biodiversity
iii. benefits for smallholders and local populations.

2 Way forward

We propose a range of principles or objectives for a way forward toward sustainable development. These are to be implemented by the relevant categories of actors according to national, institutional, economic and social contexts, local priorities and along value chains (from local to global). In fact, some measures have already been implemented by some governments and other actors either for rubber or for other types of plantations.

1) Limit negative impacts of land-use change

As shown above, the main potential negative impacts of rubber development, both environmental (impacts on biodiversity and carbon stocks) and social (displacement of smallholders by large-scale plantations) are linked to land-use change. Limiting negative impacts of land-use change is thus a priority to improve sustainability of rubber development.
There are two main complementary approaches: limit

land-use change by reducing the need for new land; and limit negative impacts of land-use change.

There are important differences of yield between countries. Higher yields are obtained with the best clones and good technical practices. Conversely, lower yields are generally explained by lower quality clones, suboptimal practices and aged plantations. Reducing this yield gap is the single most efficient way to reduce the additional land needed and thus land-use change. It is also a very efficient way to increase income and improve livelihoods of smallholders. It generally requires an ensemble of means, including dissemination of quality genetic material and technical support (see following sections). Renewal of plantations deserves particular attention. It reduces the need for new land, but requires appropriate measures to support farmers during the period when the trees are immature (see section 2.3). Additionally, having rubber integrated into diversified systems can reduce the need for additional land clearance for food production.

Most land-use change impacts are local-specific. Land-use zoning and planning can go a long way to limit negative impacts. It can preserve areas that are important for biodiversity conservation or other environmental issues, including biodiversity hotspots and biodiversity corridors, through the establishment of protected areas and by orienting rubber development towards already degraded areas. Such documents and orientations, as well as rubber development projects themselves, need to be preceded by a thorough environmental and social assessment, including of customary and informal activities. Rubber development or replanting projects need to be the object *ex ante* of a transparent consultation process of all concerned stakeholders and ensure the protection of their tenure and use rights. Finally, project design can go a long way in strengthening positive impacts and reducing negative ones by ensuring connectivity (biodiversity corridors); promoting diversified landscapes and agroforestry systems; and ensuring the livelihoods of local communities.

2) Improve the sustainability of large plantations

There are three main points to be considered to improve the sustainability of large-scale plantations: where and how they are established; their relations with hired workers; and practices to improve biodiversity conservation and water quality.

Where and how large-scale plantations are established is probably the most important factor influencing their environmental and social sustainability. Most of the time such new large-scale plantations will benefit from concessions of land from the state. Ideally, the decision would be taken following established land-use zoning and planning documents and orientations. Even in the absence of such documents, the decision to give a concession and the way the concession is formulated should consider local environmental and social specificities. In this case, as there is no framing document, the *ex-ante* assessment of environmental and social issues and potential would be even more important. The project should give communities the right to decide whether to concede lands or enter production contracts by using FPIC (free, prior and informed consent) and provide sufficient compensation for lost assets and use rights. These elements could figure in overall rules for the granting of concessions.

Large-scale plantations rely on a hired workforce. Recruitment, training, wages and working conditions of the workforce are a key component of the sustainability of plantations. Laws and regulations provide an overall framework that needs to be appropriately monitored and enforced. They can be complemented by social protection schemes, as for instance those of the Rubber Board in India (Bhowmik and Viswanathan 2015). Recruitment policies and types of contracts can also hinder or facilitate the participation of local communities and technology transfer, thus contributing to their economic development.

Concessions can also include provisions related to the conservation of a certain amount of forests, of certain areas important for biodiversity or to the establishment of biodiversity corridors. Large-scale plantations can also experiment and develop innovative mixed systems combining various productions such as timber or tea (see section 2.4). Regulations and the dissemination of good practices on the use of agro-chemicals can prevent water pollution.

In addition, large plantations and private companies can play a major role in providing genetic material, inputs and technical support to smallholders, as well as in the organization of collection, first transformation and relations with buyers. This can be part of a broad development plan and be either included in the concession or part of voluntary commitments. It can be supported by regulations or guidelines on contract farming.

In Laos, the development of rubber relies on investments, knowledge and inputs from entrepreneurs from neighboring countries. It has given way to a great variety of institutional arrangements, including a variety of types of concessions and contract farming to manage land, labor and capital (Fox et al. 2014). There are two main types of contracts: 2+3 where farmers provide land and labor and the company provides capital (seedlings, fertilizer and other equipment), technology and access to markets, with benefits split 70/30 between farmer and company; and 1+4 where the farmers provide the land and receive 30% of the benefits. Government officials promote the first one, while companies push for the second one (Fox et al. 2014).

3) Support smallholders and farmer groups

Smallholders have specific constraints that need to be overcome for them to benefit from rubber production. They need support for access to high quality genetic material and associated technologies. This can be provided by government agencies, as in China, India, Malaysia and Thailand, or by private companies as is often the case in emerging producing countries. Smallholders also need financial support to invest in new production or to replace their old trees and to sustain them between the replacement of old trees and the maturity of new trees that can produce latex. They experience challenges in accessing markets, to make their production of sufficient quality after first transformation and relate to buyers. Collective organization can be a way to overcome power unbalances between small producers and bigger buyers. It can be supported by transparent information on prices and rules to make sure contracts are fair and company responsibilities are upheld. Finally, smallholders also need support for diversifying their systems to spread risks and stabilize livelihoods (see section 2.4).

In China, the development of rubber production by smallholders has been supported by successive combinations of policies, both general and specific to rubber (Fox and Castella 2013; Jianchu and Zhuangfang 2015). In the 1980s, rubber development benefited from the Household Responsibility System that dismantled farming communes and promoted farming entrepreneurship. This was supported by provision of cloning planting material and technical training and with protection of domestic rubber prices. In 2002, the Grain for Green campaign provided farmers with grain for eight years if they planted forest cover on degraded slopes. In Xishuangbanna rubber was counted as forest cover making it eligible for the scheme.

Thailand created a dedicated organization supported by the government and funded by a tax on exports, the Thai Office of Rubber Replanting Aid Fund (ORRAF 2015 now RAOT). It provides smallholders with free or subsidized inputs, low cost credit, knowledge and extension services mainly for rubber monoculture. It also supports diversification activities like crops, livestock, fish ponds and handicrafts that help smallholders maintain their income while Hevea trees are maturing. It promotes community organizations and rubber cooperatives (Fox et al. 2014). During the price bust period, various governments have extended support schemes to farmers aiming to assure a stable income. The Thai government provided support to smallholders by buying a certain volume of rubber at a fixed price, above the market. It also encouraged reduction of production through a grubbing-up premium of 1600 USD/ha, within the limit of 1.6 ha per family. In addition, it promotes the use of rubber wood to produce pellets both for domestic use and export. Recently, RAOT also moved to promote agroforestry systems.

4) Promote and improve diversified systems

Numerous authors (Fox and Castella 2013; Langenberger et al. 2016; Penot et al. 2017) note that, for smallholders, rubber production complements rice and other food crops production. In particular, they highlight that rubber brings cash with labor requirements that are compatible with those of other crops, particularly rice. They also note that while rubber production may be lower per hectare in diversified systems than in monoculture, total productivity must be considered, especially given the fluctuations of rubber price. Crops can be interspaced while rubber trees are growing, providing food and a source of income (Jessy et al. 2016; Déo-Gratias et al. 2018). Numerous associations are used depending on countries and local markets like, rice, tuber, chili, pineapple, sesame, cocoa, coffee, fruit trees and even livestock.

Jungle rubber is a diversified agroforestry system derived from swidden cultivation, in which human-made forests with a high concentration of rubber trees replace fallows. Most of the income comes from rubber, complemented with temporary food and cash crops during the early years. Perennial species that grow with rubber provide fruits, fuelwood and timber, mostly for household consumption (Gouyon et al. 1993). It is still important in Indonesia, with between 2-2.5 million ha (Penot et al. 2017) in the 1990s. However, part of this has been cut and replanted either in oil palm or clonal rubber (no statistic available on that trend). Jungle rubber based on unselected seedling with low productivity (500 kg/ha/year) is now economically obsolete. Research in Indonesia and Thailand, focusing on economic sustainability, has shown these systems have been tailored by farmers to best use available resources and benefit from local market opportunities. Clonal rubber was introduced in Indonesia in experimental plots conducted in Rubber Agroforestry Systems (RAS). There was both good rubber and associated tree production, with no negative impact on rubber growth during the immature period and a rubber yield comparable to those from intensive monoculture (Penot 2017). Examples of jungle rubber systems have also been identified in the Bornéo part of Malaysa (Sarawak), Nigeria and Ghana (Penot and Ollivier 2009).

Farmers have developed various associations of rubber trees with perennial crops and trees, including cocoa, coffee, tea and fruit trees. Several types can be identified: association with fruits that have a local or international market in Colombia, India, Indonesia, Nigeria or Thailand (durian for instance); quick growth trees to control through shade the invasive *Imperata* in Indonesia; combining rubber trees with high value slow growth trees; combining rubber trees with rattan at the end of the production cycle as its collection destroys canopy (Penot and Ollivier 2009). Some of these combinations are also used in large-scale plantations (e.g. tea plantations in Sri Lanka).

These complex systems have been established by farmers with long traditions of agroforestry systems. They are characterized by constant innovation, both technical and social. They call for more diverse types of support, involving participatory research, exchanges of practices between farmers, like in Thailand where was recently created a platform for exchanges of practices to promote diversified systems, extension services and input providers for both rubber and other species as well as for the organization of diverse value chains. As they require a range of interventions they are much more difficult to establish ex nihilo and when support to smallholders is provided only by the rubber private sector whose interest and competencies are focused on rubber.

Another way to improve the profitability of rubber production systems is to better use rubber wood as in Malaysia (see Box 1).

Box 1. Use of rubber wood in Malaysia

Apart from latex, the rubber tree also produces biomass: it has been estimated that a standing tree can produce 2.1 m^3 of biomass, including trunk, branches, twigs and leaves (Ratnasingam and Scholz 2009). Biomass production in rubber plantations in Malaysia has been estimated at 180 m^3 per ha of trunk, branches and twigs up to 10 cm diameter, with a replanting at 3% of planted area (Ratnasingam et al. 2015).

Rubberwood is the most important raw material for the wood industry in Malaysia, replacing the dwindling supply from natural forests (Ratnasingam et al. 2015). It was promoted by the Forest Research Institute of Malaysia and the Malaysian Timber Industry Board since the mid-1970s. The commercial success of rubberwood as a raw material at international scale is due to the continuous efforts of industrial players who championed the use of rubberwood for furniture products exported to the United States since 1979 (Ratnasingam and Scholz 2009). Rubberwood furniture makes up 80% of the total furniture exports from Malaysia (Ratnasingam et al. 2011). The success of rubber utilization in Malaysia is due to this partnership between public and private actors and could be reproduced in other countries (Ratnasingam et al. 2012). The second main use of rubberwood in Malaysia is medium density fiberboard. It is also used for other panel products. Demand for rubberwood in Malaysia is regularly increasing. It accounts for almost 86% of the total wood consumed by the value-added wood sector (Ratnasingam et al. 2012). In 2013, Malaysia imported 200,000 m^3 of sawn rubber wood (Ratnasingam et al. 2015).

A study on the prospects of rubberwood biomass energy production in Malaysia (Ratnasingam et al. 2015) concludes that the amount of rubberwood biomass available for energy production is limited. This is because a large portion of the biomass is used in the wood industry, producing a higher value: $890 for a cubic meter of wood products compared to $63 for a cubic meter of rubberwood pellets. The amount is also limited because of the reduction of the area planted in rubber. The study also highlights the issue of transport of the biomass produced from replanting. Other limits include the wider availability of biomass from palm oil and the low cost of energy, inclusive of fossil origin, because of subsidies.

5) Coordinate measures and actors

From the examples described above, it is clear that sustainable development of rubber requires a combination of measures that needs to be deployed by various actors (public, private, public-private partnerships), according to specific national and local situations.

Priority issues and appropriate means to address them need to be identified at both national and local levels, recognizing specific constraints and opportunities, as well as available resources. This process requires the involvement and coordination of all concerned actors (see Figure 3).

In green, from left to right, are figured progressive steps from a shared vision to concrete implementation, based on solid science and evidence (in red). Research and evidence are indispensable to achieve multiple objectives, assess and manage trade-offs. In blue, the various actors can, in a multi-stakeholder platform, build a shared understanding of issues, agree on a shared vision and principles to achieve it. Actors can select from the range of "options by context" that can be provided by science (those options most adapted to their situation and priorities). These good practices can be then recognized through corporate social responsibility and certification, either business to business (B2B) or business to consumer (B2C).

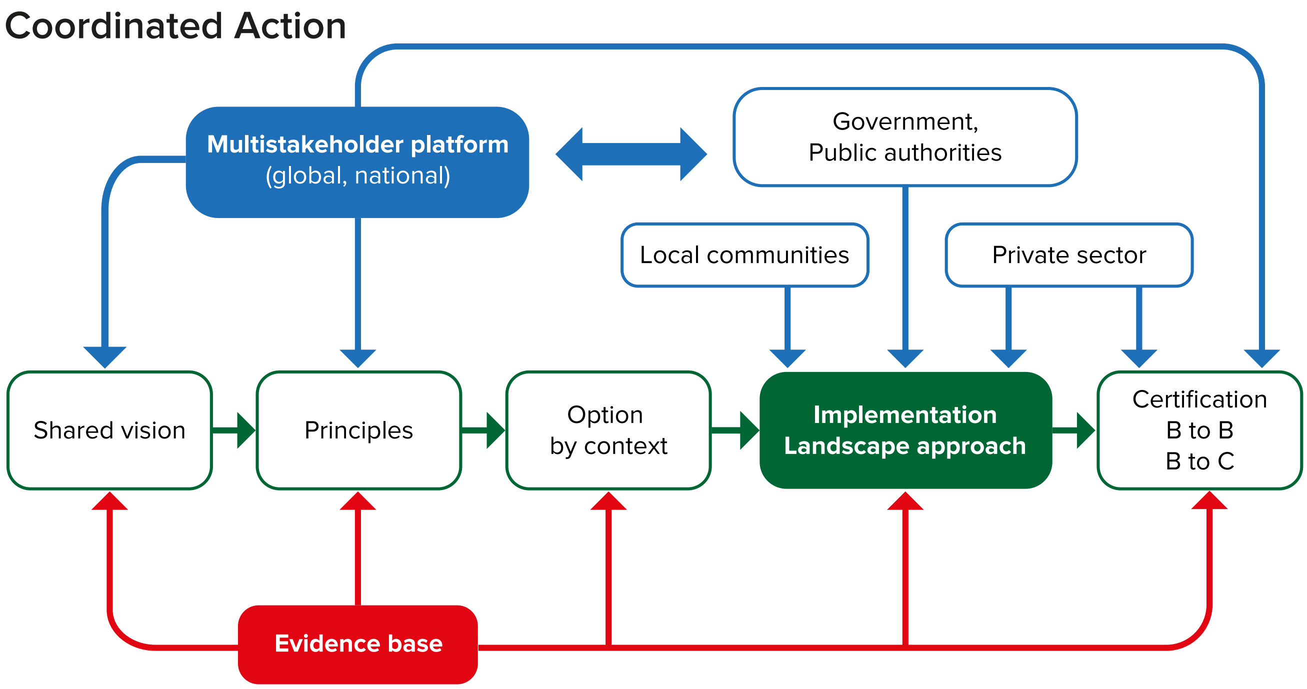

Figure 3. Coordinated action for sustainable development of rubber production.

Table 1. Roles of actors

Objectives	Government and public actors	Research	Private sector: large plantations, big companies	Local communities, farmers' organizations, cooperatives
Limit negative impacts of land use change.	Implement land-use zoning and planning. Provide an enabling environment on tenure and use rights. Consult with local actors.	Provide evidence on potential impacts of land-use change.	Abide by the rules.	
Improve the sustainability of large plantations.	Provide an enabling regulatory environment on concessions and contracts. Include sustainability concerns in the design of concessions.	Provide evidence on sustainability issues and options for improvement.	Private sector: large plantations, big companies. Make voluntary commitments and help support smallholders.	
Support smallholders and farmer groups.	Provide: • genetic material • inputs • technical knowledge • financial support to planting and renewal. Provide an enabling environment for contract farming. Facilitate access to markets.	Provide knowledge to extension services and farmers' organizations. Develop research projects to answer needs of smallholders.	Abide by the rules on farming contracts. Provide: • genetic material inputs • technical knowledge • financial support to planting and renewal. • Facilitate access to markets.	Facilitate exchanges of good practices between farmers. Facilitate access to markets.
Promote and improve diversified systems.		Conduct participatory research with farmers.		Facilitate exchanges of good practices between farmers.
Promote sustainable rubber.	Provide an enabling environment for the recognition of sustainable practices. Promote sustainable practices, including through selective incentives.	Provide evidence for the assessment of sustainable practices (environmental, social, economic).	Recognize sustainable practices, including through corporate social and environmental responsibility and certification. Engage in Business to Business (B2B) and Business to Consumer (B2C), and associated labeling.	Facilitate dialogue with supply chain actors to offer a sustainable price to farmers.

Conclusions

The development of rubber production brings sustainability challenges and a range of opportunities for sustainable development. There is a wealth of knowledge and evidence to make this transition to sustainability effective, in a pro-active way. It requires first that actors agree on priority issues to be addressed, grounded on sound evidence. This can be followed by identification of measures to be implemented and by whom. A key issue is to gather the knowledge and transfer it to actors in a practical way. Very concretely, such a process could be informed at various levels, local, national, global by a *Practical Guide for Sustainable Development of Natural Rubber*. The guide could be elaborated through an interinstitutional and interdisciplinary collaboration that would build upon the breadth of accumulated knowledge from research and actors on the ground, as well as from successful examples for other commodities. It could support the various actors in building rubber development/expansion projects, or improving existing plantations and their renewal, in a wide range of contexts. It would lay down concrete means to: describe and understand the contexts, identify critical issues and construct options to address these issues in a specific situation/context (options by context, landscape approach, etc.). Such a guide should fully integrate consideration of issues related to climate change, including potential impacts, available adaptation options and contribution to mitigation. It should facilitate the appropriate integration of natural rubber into National Adaptation Plans (Meybeck et al. 2020) as well as in the implementation mechanisms of the Nationally Determined Commitments (NDCs) and provide information on the policy and financial instruments that can be mobilized at national and international level.

Any investigation of sustainable rubber would be incomplete without comparing the environmental and social sustainability aspects of natural rubber with synthetic rubbers. Work to improve the sustainability of natural rubber production needs to be complemented by a better understanding of the sustainability of the final products, including comparisons to synthetic rubber products.

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Corresponding author: v.gitz@cgiar.org

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