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Natural rubber and climate change: a policy paper

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Key messages

- There are no sustainable alternatives to natural rubber, which is used in many products.
- Climate change is already impacting the cultivation of rubber trees.
- Farmers need to adapt their systems to safeguard the production of natural rubber.
- Natural rubber has considerable potential to mitigate climate change.
- Natural rubber can contribute to a forest-based circular bioeconomy.

Introduction

Climate change is already impacting rubber production as drier seasons and more variable precipitation threaten the survival of plantations. In addition, most pests and diseases associated with rubber are influenced by climatic conditions. Without adaptation, natural rubber production is projected to decline. At the same time, natural rubber and its production could contribute to the mitigation of climate change.

In its latest report, the Intergovernmental Panel on Climate Change (IPCC) has issued a stronger appeal than ever to control greenhouse gas (GHG) emissions (IPCC 2021). This requires decisive actions to change how we manage our resources, replace energy-intensive non-renewable materials, redesign production processes to reduce waste and ensure that materials are reused as much as possible.

Natural rubber, a group of materials originating from the latex of several plants – the most important being *Hevea brasiliensis* – could answer some of these calls and become part of a forest-based circular bioeconomy. On one hand, it could potentially replace synthetic materials and fossil fuels, therefore reducing GHG emissions, and on the other, it can contribute to climate change mitigation by increasing carbon sinks. It can also support the adaptation of other systems to climate change. As with all agricultural

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a Secretary General, IRSG; b Secretary General, IRRDB; c Director CIFOR, CGIAR Research Program on Forests, Trees and Agroforestry (FTA); d Rubber Value Chain Correspondent, CIRAD.; e IRSG; f CIRAD; g CIFOR/FTA systems, its production needs to overcome various sustainability challenges to fulfil its potential.

The International Rubber Study Group (IRSG), the CGIAR Forests, Trees and Agroforestry (FTA) research programme led by the Center for International Forestry Research (CIFOR), the International Rubber Research and Development Board (IRRDB), and the French Agricultural Research Centre for International Development (CIRAD) organized an open digital workshop on natural rubber systems and climate change from 23–25 June 2020 to review recent research on impacts of climate change on natural rubber production, potential means of adaptation, and the contribution of natural rubber to climate change mitigation. Building upon the rich material and discussions from this workshop, this policy brief presents the available knowledge on these topics to inform and orient climate action in the rubber sector.

1 Overview of natural rubber product development

Natural rubber has been used for thousands of years (Box 1). Today, it is a strategic raw material for which there are no sustainable alternatives. It is a greener

Box 1. History of natural rubber

There is evidence of the use of rubber in Mesoamerica 3,600 years ago, where the Olmecs — and later the Maya and Mexica — were making different grades of rubber using natural latex. The remains of rubber balls found in Veracruz, Mexico, have been dated to 1600 BCE (Rodríguez and Ortiz 1994). The sacred book of the Mayans, the Popol Vuh (Tedlock 1985), refers to them, while Spanish chroniclers recorded seeing rubber in the 16th century when they came across the Mesoamerican Ballgame. The Spanish were fascinated by the game, especially with the bounce of the ball (Benavente 1984; Berdan and Anawalt 1997). Rubber was also used in sandals and latex in joining applications such as hafting and adhesives (Tarkanian and Hosler 2011).

Sixteenth-century chroniclers described the processes that ancient rubber makers used to create the rubber balls (Mártir 1989; Benavente 1984). They harvested latex from the *Ulli* or *Olquáhuitl* tree (Castilla *elastica*) and mixed it with juice extracted from *Ipomoea alba*, which contains chemicals that make the solidified latex less brittle (Hosler et al. 1999). Mixing the ingredients in different proportions gave the rubber varying mechanical properties, from the bounce needed for balls to the durability and dampening needed for the soles of their sandals (Tarkanian and Hosler 2011).

In the 17th century, latex was used to waterproof fabric and leather, and because no method to preserve it had yet been invented, the Mexican state of Veracruz saw the rise of a fabric-proofing industry to prepare the finished product for export (AZOM 2003).

Although small amounts of rubber found their way back to Europe, the rubber industry only started there after 1818, when in Scotland, James Syme found that coal tar naphtha was a good solvent for rubber. Charles Macintosh, used this rubber solution as a waterproofing layer between two pieces of fabric and the mackintosh raincoat was born. In England, Thomas Hancock became interested in rubber and patented elastic fasts for gloves, shoes and stockings. He then discovered mastication, a process that produced a homogeneous ball of rubber that could then be used to make other products including pneumatic cushions, mattresses, pillows and bellows, hose tubing, solid tyres, shoes, packing and springs.

The rubber industry developed rapidly in Britain's temperate climate, but the rubber became sticky at high temperatures and rigid at very low ones. In the 1840s, Charles Goodyear and Thomas Hancock patented rubber vulcanization, which solved these problems. The re-invention of the pneumatic tyre by John Boyd Dunlop in 1888[1] resulted in increased consumption of natural rubber as early vehicles moved away from solid tyres. Pneumatic tyres were first used on aircraft in 1910 and trucks around 1917 (Jones and Allen 1992).

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[1] Robert William Thomson had invented a pneumatic tyre in 1840, but the fitting was rather complex, and it did not enjoy commercial success.

substitute to petroleum-derived elastomers, representing about 47% of the global elastomer market in 2019 (IRSG 2021a). Overall demand for natural rubber is increasing, although it competes with other polymers, including synthetic rubber, that are less expensive, readily available and sometimes more resistant to abrasion and wear (Fortune Business Insights 2020).

Rubber is used in more than 5,000 products, predominantly in the automotive and aircraft industry (Pinizzotto et al. 2021). More than 70% of production is directed to automobile tyres and non-tyre automotive parts (e.g. airbags, padding, tubes, pipes). Non-automotive applications include the manufacture of aircraft tyres; industrial uses such as adhesives, ducting, antivibration and bin linings; construction (e.g. door and window seals, floors); erasers;[2]; footwear; textiles (e.g. expandable clothing, belts, latex gloves) and healthcare products (IRSG 2021b). Natural rubber has many attributes, including its elasticity, mouldability, durability, chemical and thermal resilience, that make it an ideal substitute for plastic in textiles, footwear and construction (Martius et al. 2021). In some countries, timber from the rubber tree is also used for furniture and construction.

2 Natural rubber production

Most natural rubber today comes from the Pará or rubber tree (*Hevea brasiliensis*)[3] (Box 2). Natural rubber is an important economic sector in many countries. Rubber plantations cover around 14 million ha and produced a total of 13.01 million metric tons in 2019 (IRSG 2021), with a compound annual growth rate of 1.8% in the last decade. Thailand and Indonesia produced 56% of the world total in 2019, with Southeast Asia representing 84% of global rubber production (IRSG 2021). Rubber production sustains about 40 million people globally, with around 90% of production coming from the work of smallholders.

There are nine other *Hevea* species with the potential to contribute germplasm for growth and disease resistance. Preliminary research has been conducted on seven of the nine species with the potential to increase timber yields. Rubber wood is an important raw material for the furniture

Box 2. Hevea brasiliensis

In 1735, Charles de la Condamine travelled to South America on behalf of the French Royal Academy of Science. In Ecuador and Brazil, he found several products made of rubber, although he never saw the trees from where latex was extracted. By the 1850s, the Pará or rubber tree (*Hevea brasiliensis*) and some methods for extraction of latex had been identified (Jones and Allen 1992).

Information from the 1860s on *Hevea brasiliensis* caught the attention of Clements Markham from the United Kingdom's India Office, who had introduced the quinine-bearing plant Cinchona to India from Peru. He arranged the collection of rubber tree seeds through Kew Gardens in London. Between 1873 and 1876 Kew Gardens received three collections; the second and largest (70,000 seeds) was collected by Henry Wickham in Brazil. Only 2,700 of those seeds germinated, and about 1,900 seedlings were shipped to the botanic gardens of Colombo (Sri Lanka), Bogor (Indonesia) and Singapore (Baulkwill 1989). The survival of seeds from the two other collections is uncertain, and it is believed that virtually all of the rubber trees in the region descend from Wickham's collection, meaning the natural rubber industry was founded on a very narrow genetic base.

The need to broaden the genetic base of rubber tree production led to a joint expedition by member countries of the International Rubber Research and Development Board (IRRDB) and the Brazilian Government to collect wild *Hevea* germplasm in the form of seeds and budwood in three western states of Brazil (Acre, Rondônia and Mato Grosso) in 1981. This germplasm has been the source of the development of location-specific clones capable of withstanding various diseases, cold, drought and wind damage. The wild Amazonia germplasm acts as a depository of genes for specific attributes, especially tolerance to abiotic stress like drought and cold, and biotic stress like diseases by various pathogenic fungi. Another expedition was organized by the Malaysian and the Brazilian governments (1995), and the IRRDB is planning one to Peru (Othman 2021).

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[2] In 1770, Joseph Priestly discovered that the product could "'rub"' away pencil marks on paper, thus giving the material its name and sparking the production of erasers.

[3] This species was soon recognized as the most effective producer of rubber among the ten 10 Hevea spp. that have been identified, so far. *H. brasiliensis* has been deemed the most suited to rubber production: *H. benthamiana, H. camargoana, H. camporum, H. guianensis, H. microphylla, H. nitida, H. pauciflora, H. rigidifolia, H. spruceana and H. brasiliensis.*

Table 1. Types of natural rubber production systems

Type of System	Criteria
Monoculture	< 1% non-rubber trees
Simple mixed cultivation	1. < 1/3 non-rubber trees that have been deliberately planted. 2. 2-5 varieties that are not rubber trees and are taller than 2m. 3. 5-20 trees that are not rubber trees but are at least as tall as rubber trees.
Complex agroforestry systems	1. > 1/3 non-rubber trees that have been deliberately planted. 2. > 20 varieties that are not rubber trees and are taller than 2m. 3. > 20 trees that are not rubber trees but are at least as tall as rubber trees.
Highly complex agroforestry systems	> 2/3 of trees are non-rubber trees.
Wild rubber	The term 'wild rubber' is used to designate rubber that grows in Peru or Brazil (in its original environment).
Jungle rubber	A system where tree seedlings are planted in cleared areas or in gaps where trees have been felled or have died (most often planted with fruit trees in cleared areas).

industry. Some types of rubber wood, such as the cross-linked (CLT) and glue laminated timber (Glulam), can also be used in construction. Such materials are being used in the construction of high-rise buildings in Europe and Canada.

The vast majority of rubber trees are grown as monocultures by both small-scale farmers and large-scale plantations, but there are also many examples of mixed cultivation (Table 1). The main reason for adopting a monoculture system for rubber trees is to increase yields; monocultures produce up to 300% greater yields than mixed cultivation systems (Villamor 2014). Plantations covering an area of about 700 ha or more are defined as large-scale plantations.

Globally, the area of land under rubber cultivation has grown by a factor of 1.8 over the past 30 years (IRSG 2020). The rubber tree has seen the fastest expansion of all commodities within mainland Southeast Asia (Fox et al. 2012) and has increased sharply in less traditional growing countries (Gitz et al. 2020). Limited rubber area expansion and a sharp contraction in global demand were registered in 2020 due to the economic fallout from the COVID-19 pandemic. Global natural rubber demand is expected to remain lower than before the pandemic in 2021, although it is forecast to increase by 24% by end of this decade compared to pre-pandemic levels (IRSG 2021a).

As is the case with many agricultural systems, there is concern about the impacts of rubber cultivation expansion on ecosystems (Warren-Thomas et al. 2015; Fox and Castella 2013), but these are likely to be addressed through improved management to enhance yields and careful planning of where to cultivate rubber. It must be pointed out that the major rubber growing areas in Southeast Asia have seen at least three replanting cycles. This means that rubber has been cultivated for more than 100 years.

The life cycle of a rubber plantation is divided in two phases: the immature phase – from planting to latex harvesting (after five to seven years) – and the mature phase, which starts with latex harvesting through tapping (Xu and Yi 2015). When latex production declines, old trees are logged and new trees are planted. Rotation lengths are usually 30 to 35 years (Nizami et al. 2014). For the smallholding sector, the immature phase can be even extended from seven to nine years due to the absence of good agricultural practices including the selection of planting materials, application of fertilizers and weed control. These practices are given priority in the extension services provided by various rubber research institutes.

Tapping is done by slicing a groove into the bark of a tree with a hooked knife or a V-gouge and peeling back the bark, allowing latex to flow into a container attached to the tree (FAO 1977). Tapping is a very important activity and is preferably done with a properly sharpened knife to avoid injuring the tree and prevent excessive bark consumption. Trees damaged by poor tapping practices produce smaller amounts of latex and poor-quality timber, which is unsuitable for high-value furniture production. Today, smallholders are unable to fetch high prices for their trees during replanting because their practices lead to low-density and poor-quality timber.

The main component of latex is water, and only about a third of its volume is made up of natural rubber (Haustermann and Knoke 2019). It must therefore undergo a series of processes before it can be turned into rubber products of different qualities (see Figure 1).

3 Impacts of climate change on rubber production

Hevea brasiliensis grows optimally in areas with mean annual temperatures of 25°C–28°C and rainfall above 1,500 mm, with conditions in marginal areas being cooler, drier or both (Gohet et al. 2021). High air moisture content facilitates latex exudation, but excessive rain can hinder harvesting (Compagnon 1986). Soils should be acidic (optimally pH 4.5 to 5.5) and must be well drained to avoid waterlogging, root disease and dieback (Baulkwill 1989).

Climate change will make some traditional areas less favourable because of drought or excessive precipitation (Thaler et al. 2021), while some marginal areas will become more favourable due to warming (Gohet et al. 2021). Several studies predict shifts in land suitability for Hevea in China (Liu et al. 2015), India (Debabrata et al. 2015) and Malaysia (Hafiz et al. 2018). Climate change may benefit future rubber production in currently cooler, humid marginal growing areas such as

Panama Women for Rubber.
Photo by Ricardo J. Fernandez

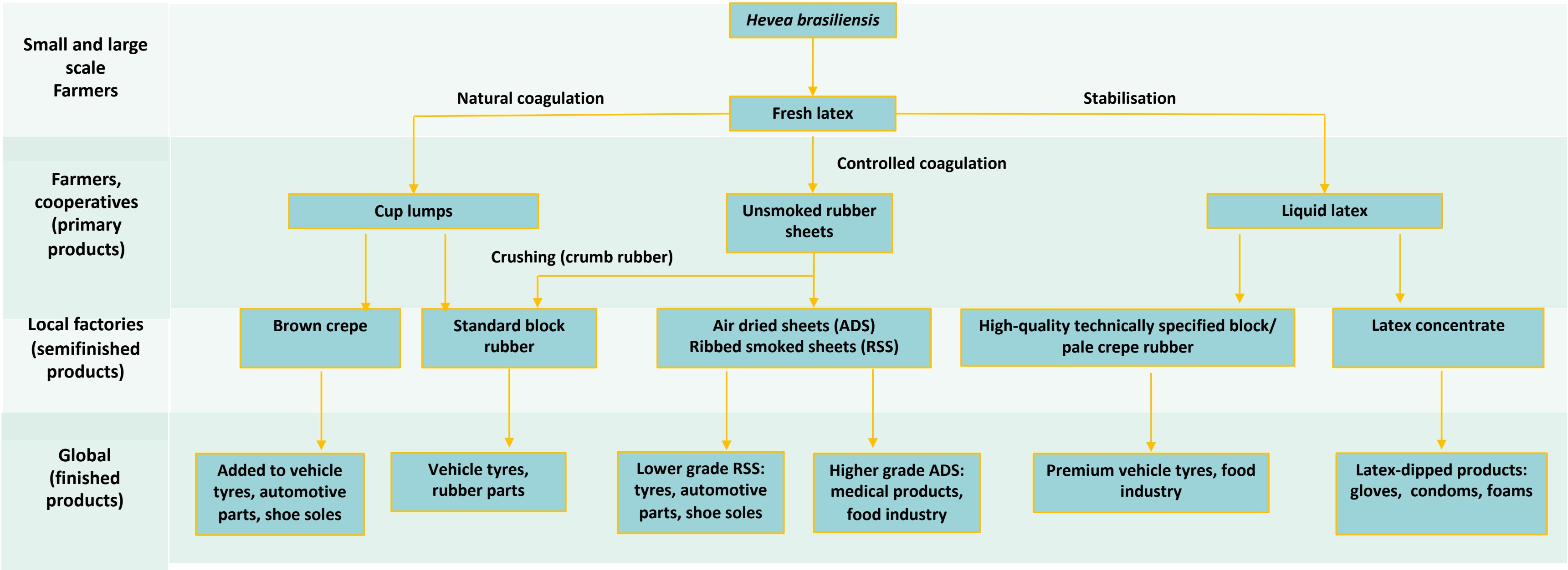

Figure 1. From tree to products: a very general view of the stages in the production of natural rubber products. Adapted from Haustermann and Knoke (2019).

Worker in Shave Season
Photo by Ngo Cong Hoang

northern Thailand, Laos, Yunnan and Hainan provinces of China, southern Brazil, northern Gabon and south-eastern Cameroon. Expansion into higher altitudes and latitudes may also be possible (Blagodatsky et al. 2021, Gohet et al 2021). Changes may also favour the cultivation of rubber over oil palm in areas that are becoming drier (Xu and Yi 2015).

To date, little is known about the direct effects of higher temperatures on rubber tree physiology. Even less is known about the impact on yield under different climate change scenarios. Higher temperatures will likely reduce latex flow and therefore yields (Ismail and Gohet 2021).

Extreme events are also likely to affect rubber production. Information is available about water stress thanks to studies on adaptation to drier conditions in marginal areas, showing that drought can delay growth (resulting in a longer immature period). However, precipitation may increase in some areas, leading to soil runoff and waterlogging (Thaler et al. 2021). Wind damage from the increased occurrence and strength of storms is also a concern. A high incidence of trunk snaps and broken branches within a short period can cause irreversible damage to a plantation (Chen et al. 2021).

There may also be a higher risk of pests and diseases caused by more humid conditions, especially as changes in severity and pattern of occurrence have already been observed. A study on the outbreak of *Pestalotiopsis* (a fungal leaf-fall disease) on *Hevea* in South Sumatra showed the role of wetter and more prolonged rainy seasons in recent years (Febbiyanti 2021). *Pestalotiopsis* was first detected in Indonesia in 2016 and has been responsible for reducing latex yields by more than 30%. It has since spread to Malaysia, Thailand and Sri Lanka (Nghia 2021).

In contrast, the long and abnormally dry season caused by El Niño in 2019 significantly reduced the incidence of disease. However, the prolonged dry season also resulted in stunted growth and decreased latex production. It is evident that more research is needed in this area.

4 Adapting rubber cultivation to climate change

Two types of complementary strategies are available to adapt rubber cultivation to climate change: 1) implementing climate-resilient agronomic practices and 2) developing adaptive traits in clones. IRRDB has been instrumental in organising an expedition in 1981 to collect *Hevea* germplasms from the Amazon jungle in Brazil and incorporating breeding programmes at all member institutes. A total of 49 clones, some derived from the introduced germplasm in Brazil, were made available to all member institutes of IRRDB in 2014 irrespective of their advances in the *Hevea* breeding programme. This is a major development considering that cloning requires time and considerable resources to complete testing cycles before recommendations are being made to growers.

4.1 Implementing climate-resilient agronomic practices

Shading is recommended for plants in nursery and for their first two years in the field. This can be achieved by intercropping with banana, for example (Jacob 2021). In drier marginal areas, recommendations include irrigating immature plants and mulching to conserve soil moisture. Maintaining surface cover by allowing some natural weed flora, intercropping with legumes or leaving part or the entire tree biomass in the inter-rows (Gay et al. 2021) can minimize runoff, reduce soil erosion and increase soil quality and nutrient availability (Blagodatsky et al. 2021).

There is a marked difference between the immature and mature stages, with the soil quality gradually improving during the mature phase (Gay et al. 2021). Efficient nutrient management, particularly during the early stages, can have a strong positive effect on the functioning of a rubber plantation.

Increased rainfall can be addressed through adaptive management of tapping and the use of rain guards to protect the bark (Singh 2021; Wijaya 2021). Tapping management could include a rest period, thus reducing the number of tapping days and associated costs, while preserving annual yield.

Mixing crops or trees with rubber production is beneficial if there are no trees above the rubber canopy (Penot et al. 2021). When rubber production is not in competition with other crops, intercropping using fruit crops, vegetables, legumes, perennial crops, medicinal and ornamental plants, or even maintaining the natural flora have beneficial effects on soil quality, fertility and biodiversity (Jessy 2021). Examples include:

- Low light availability within the plantation during the mature phase limits the choice of crops after canopy closure; therefore, shade-tolerant crops like coffee, cocoa and vanilla may be suitable (Jessy et al. 2015 and 2017; George and Met 2018).
- In Colombia, India, Indonesia, Nigeria and Thailand, farmers grow fruit for local or international markets along with rubber trees.
- In Indonesia, fast-growing trees are grown to control (by shading) the invasive *Imperata*.
- Rubber trees can be combined with high-value, slow-growing trees.
- Rattan can be introduced at the end of the production cycle as its collection destroys the canopy.
- In Thailand, rubber agroforestry systems (RAS) have been developed, either for intercropping during the immature period or, during the mature period, with fruit (e.g., durian, rambutan, longkong), vegetables (pakliang/*Gnetum*) and timber (e.g., teak, mahogany).

Some of these combinations are also used in large-scale plantations (e.g. tea plantations in Sri Lanka).

4.2 Developing adaptive traits in clones

Another approach for adapting rubber cultivation to climate change is to develop climate-resilient, high-yielding clones (Box 3). This can be done through breeding and genomic marker-assisted selection.

Box 3. Hevea brasiliensis propagation

Until the dawn of the 20th century, rubber tree plantations were only established using seeds, which remain the easiest and cheapest way to propagate *Hevea brasiliensis*, but the resulting trees show great variability in vigour and latex yield: Whitby (1919) noticed that 28% of latex was derived from just 9.8% of seedlings. However, large-scale plantations required more reliable and predictable sources of latex. As a result, until the 1940s, seeds collected from trees with the desired characteristics (e.g. high latex yield) were planted in monoclonal blocks to produce more uniform planting material (Priyadarshan 2011).

Clones are genetically identical individuals to a parent plant, which can be obtained in different ways:

- By taking cuttings from an adult plant. The cutting is then planted into moist soil or another moist growing medium. The cutting will produce roots of its own and become a whole new plant identical to the original adult plant. Propagation through rooted cuttings is possible in rubber but generally results in unsatisfactory development of the root system, especially the taproot.
- By grafting. A patch of the bark of a seedling (stock) is replaced by a bud patch taken from the clone to be multiplied (scion). A thin film of polythene is wound over the bud patch and left for 21 days until the bud patch becomes attached permanently to the stock. The stock is then cut off above the bud-grafted portion, which develops into a new shoot (scion) and then a tree.
- By in vitro tissue culture, or micropropagation. A tissue sample is scraped from the parent plant and placed on nutrient media, which develop into plantlets that are then transferred to soil.

By the early 1910s, there was already an apparent need to produce clones to overcome vigour and yield variability. However, due to difficulties in rooting shoots, grafting was used instead. This practice quickly caught on as graft-derived clones produced drastically improved yields. Eventually, budded clones supplanted seedlings in most large-scale plantations. Large companies restricted the use of seedlings for rootstock production, whereas seed-derived rubber trees for latex production, or “jungle rubber”, have been mostly used by smallholders (Webster 1989; Cardinal et al. 2007; Masson and Monteuuis 2017).

Grafting also has its drawbacks: new varieties cannot be developed, it requires specialized skill, the lifespan of grafted and budded plants is shorter than that of seed-propagated plants, and viral diseases can be spread through this method. As a result, efforts continued to mass-produce selected rubber tree clones through rooted cuttings. From the 1970s onwards, priority was given to in vitro methods, but despite 40 years of heavy investment, it remains difficult to micropropagate *Hevea brasiliensis* clones to meet the requirements of large-scale production. The development of new nursery techniques adapted to the mass clonal production by rooted cuttings of any *Hevea brasiliensis* genotype, efforts to improve the techniques, and the establishment of new field trials are currently under way to determine if self-rooted rubber tree clones can be more productive than grafted ones. This is becoming of overriding importance considering the increasing pressure on land availability (Masson and Monteuuis 2017).

Recent work in Thailand showed promising genetic variability among existing commercial clones for breeding drought tolerance (Isarangkool Na Ayutthaya et al. 2017). The Rubber Research Institute of Sri Lanka (RRISL) is carrying out molecular-level screening to identify drought-tolerant clones (Wijesuriya 2021).

Research can further develop the possibilities of using rubber germplasms for climate change adaptation using SNP (single nucleotide polymorphisms) markers for new genetic selection from different *Hevea* species such as *H. Nitida, H. Spruceana* and *H. brasiliensis* (Makita et al. 2021).

The use of modern technologies can fast-forward breeding programmes, but international cooperation is essential to promote clone exchanges and testing.

4.3 Rubber to support adaptation of farming systems

Temperature rise and soil moisture deficits are among the environmental changes caused by climate change. Afforestation can improve local climate conditions through evaporative cooling (reduction of soil surface temperature). A study of rubber plantations in Thailand suggested that well-managed rubber plantations might behave similarly to tropical rainforests in terms of evaporative cooling and moisture recycling to the atmosphere (Nouvellon et al. 2021).

Rubber cultivation has been proposed as an alternative to traditional short-term rain-fed crops in response to climate change in Sri Lanka (Rodrigo and Munasinghe 2021). Potential benefits include the reduction of midday air temperatures by up to 6°C within the rubber plantation, with an average decrease of 3.7°C during the day, and the retention of up to twice the surface soil moisture. This also provides a more comfortable working environment for farmers.

5 Role of natural rubber in climate change mitigation

Rubber can contribute to climate change mitigation in several ways:

- Increasing carbon stocks through the afforestation of degraded areas, the replacement of systems with less capacity to store carbon, or more diversified systems;
- Limiting negative impacts of land use change;
- Improving management practices that increase soil carbon and contribute to reduce GHG emissions from fertilizers and increase yields thus reducing the need for additional land;
- Using rubber wood to replace fossil fuels or to store carbon in long-lived products;
- Using natural rubber in applications where it can replace synthetic elastomer, which relies on fossil fuels as feedstock in its production process.

5.1 Mitigation from cultivation of rubber

5.1.1 Increasing carbon stocks

There are several studies on the potential of rubber to mitigate climate change though increased carbon sinks. A study that measured total vegetation carbon stocks in Hevea plantations (aged 5 to 40 years) found a maximum of 105.73 Mg C ha^{-1} in plantations aged 30–40 years (Brahma et al. 2016). Carbon stocks in plantations aged 10–20 years were comparable to those of 10-year-old cocoa-based agroforestry (Oke and Olatiilu 2011), while those in 20–30-year-old plantations were higher than in semiarid, sub-humid, humid and temperate agroforestry systems (Montagnini and Nair 2004). Carbon stocks for plantations older than 30 years fall within the range of tropical forests in northeastern India (Upadhaya et al. 2015) and mango agroforestry systems in Indonesia (Kirsfianti et al. 2002). Another study of plantations (6 to 35 years) in Xishuangbanna, China, reported the maximum carbon stock in older rubber plantations at 148 Mg C ha^{-1} at elevations below 800 m (Yang et al. 2017 and 2019).

Box 4. Possible uses for recycled tyres

There are a number of innovative ways to reuse and recycle the thousands of tons of tyres that reach the end of their lives every year. For example, used rubber can be ground to a crumb that can be used in a number of applications:

1. As a binder in asphalt, which can improve road durability.
2. Woven into durable and uniform matting products to lower the risk of livestock slippage and injury when managing cattle in high-traffic and wet conditions such as cattle feedlots.
3. In water-permeable pavements such as footpaths, bike paths, tree protection zones, driveways, residential and commercial developments and parking lots. The high permeability allows for better management of stormwater runoff and has the added benefit of an evaporative cooling effect, helping to reduce urban heat island effects during heatwaves and warm spells.
4. Incorporated into a spray-on concrete that is blast-, ballistic- and fire-resistant.

Source: Tyre Stewardship Australia (www.tyrestewardship.org.au)

Rotation length affects the C stocks of both trees and soils. A study modelling the effect of rotation length (25, 30, 35, 40 and 45 years) on the C stocks in rubber plantations in China found that total carbon stocks increased with rotation length up to a maximum of 173.60 Mg C ha-1 for the 45-year rotation, while the lowest was 89.86 Mg C ha^{-1} for the 25-year rotation (Nizami et al. 2014).

Root trainer plants
Photo by VT1

Judicious crop mixing in rubber plantations (also applicable in large-scale plantations) can increase carbon stocks and either improve or do not influence the growth and yield of rubber. They also sustain or improve soil fertility status and reduce costs of cultivation (Jessy 2021). If extending rotation lengths in plantations to 40 years in southwestern China, Nizami et al. (2014) recommend introducing economically and ecologically important species (e.g. *Coffea arabica, Theobroma cacao, Myristica yunnanensis, Bennettiodendron leprosipes, Gmelina arborea, Mesua ferrea, Erythrophleum fordii, Podocarpus fleuryi, Shorea chinensis, Dipterocarpus tubinatus*) between the rubber trees when they are about 35 years old to avoid erosion when replanting *Hevea*; this also increases the carbon stocked by the agroforestry system.

If planted in degraded land, rubber is an effective carbon sink, whereas replacing forests or swidden agriculture can lead to an increase in carbon emissions. These, however, are variable: for example, Kiyono et al. (2014) calculated carbon stocks from rubber cultivation and swidden agriculture in Northern Laos. They showed that a rubber plantation standing for 30 years can result in a greater carbon stock than that of the 5-year-fallow swidden system. However, this benefit is lost if rubber replaces swidden agriculture that then displaces natural forests.

5.1.2 Limiting negative impacts of land use change

There are two complementary approaches to limit the negative impacts of land use change: limiting additional land use change by reducing the need for new land, and by prioritizing degraded land for new cultivation of rubber. Rubber yields vary between countries depending on access to high-yielding clones and efficient management practices. Reducing this yield gap is the most efficient way to avoid further land conversion.

The improvement of genetic material is important to achieve higher and more stable yields. Plant breeders are trying to produce vigorous clones which are high-yielding in both latex and timber and resistant to major diseases, and they are also trying to shorten the immaturity period (Gitz et al. 2020; Makita et al. 2021). Increasing yields can also raise incomes and improve the livelihoods of smallholders (Pinizzotto et al. 2021). As mentioned in the rubber production section, there is still scope to increase yields everywhere.

Furthermore, renewing plantations, instead of moving them to other areas, also reduces the need for new land but requires appropriate measures to support farmers for a number of years until latex can be harvested.

In addition, land use zoning and planning, as well as environmental and socioeconomic impact assessments, can avoid negative effects for communities and preserve areas that are important for biodiversity conservation or other environmental issues. They can also orient rubber expansion towards degraded areas (Gitz et al. 2020).

5.1.3 Improving management practices to increase yield, soil carbon and reduce GHG emissions

The adoption of better management practices (Section 4.1) can also contribute to mitigation in several ways: by reducing the need for additional land thanks to increased yield, by increasing carbon stocks in the soil and also through more efficient nutrient and pest management, and reducing GHG emissions both in the field and during input production processes; often with additional environmental benefits. Integrating rubber into diversified systems can reduce the need for additional land clearance for food production.

5.1.4 Improving management practices to increase yield, soil carbon and reduce GHG emissions

The potential of rubber to contribute to mitigation depends on what it replaces and how it is conducted. In general:

- It generally has a negative impact if replacing primary or secondary forests
- It has a positive impact if planted on severely degraded land
- It can have a neutral or slightly positive impact if replacing swidden systems, depending mainly on the length of the fallow period of the system it replaces
- It has a negative impact when it displaces swidden systems that then encroach into forests.
- Diversified systems can be as efficient as secondary forests in storing carbon
- Improving yields is likely to reduce deforestation
- Positive impacts may be higher if land-use planning identifies areas with the highest environmental and economic returns and includes adaptation concerns

5.2 Mitigation through increasing the use of rubber wood

Natural rubber systems can contribute to a reduction in overall emissions when the wood from plantations is used as a substitute for fossil fuels (Nouvellon et al. 2021). One example from the steel industry involves replacing coke with charcoal from plantations (Fallot et al. 2009). Similarly, rubber biomass has been used in power plants in Thailand (Waewsak et al. 2020). The government of Thailand also promotes the production of rubber wood pellets both for domestic use and export (Gitz et al. 2020). Abandoned or unproductive rubber plantations in West Africa and Malaysia are being exploited for bioenergy production (Gibson 2011; Ratnasingam et al. 2015; Riazi et al. 2018).

There is also scope for using more rubber wood in furniture production. This would reduce the need for additional wood collection in forests and for timber plantations. Rubber wood is the main material for the furniture industry in Malaysia, where it is also used in medium-density fibreboard and other panel products (Gitz et al. 2020), replacing the dwindling supply from natural forests (Ratnasingam et al. 2015). Its use has been possible thanks to partnerships between public and private actors.

5.3 Mitigation through substitution

In addition to traditional rubber uses, there is potential for natural rubber to replace synthetic elastomer in some end-user applications which are more GHG emission-intensive or less 'green'.

Research is underway to produce specialty natural rubber products with enhanced attributes related to damping, oil resistance, gas permeability, wet grip and rolling resistance through the epoxidation and deproteinization of the latex (Rasdi et al. 2021). Further chemical modification of the latex produces liquid epoxidized natural rubber (LENR), which has potential applications including a foam with excellent sound-absorbing and vibration-damping properties (Ramli et al. 2019), toughening agents for epoxy (Tan et al. 2013) and processing aids (Darji 2018). Specialty natural rubber products also have uses in environmentally friendly, low odour paints and adhesives.

Natural rubber is a critical raw material in the EU based on the assessment reference to economic importance and supply risk (EC 2020). Greener biodegradable rubbers are under development for potential use in tyre production (Mondragon 2017; Micu 2019). Circularity and the recycling of raw materials from low-carbon technologies is an integral part of the mitigation strategies. Increasing the lifespan of carbon stocked in rubber products, such as by blending ground tyre rubber with asphalt to produce longer-lasting road surfaces, could be another opportunity (Meybeck and Gitz 2021) (Box 5). Current tyre recycling methods can be viewed as a transitional solution. Ultimately, these will need to be replaced by more effective solutions aiming to reduce raw material usage and carbon emissions.

Demand for natural rubber will continue to increase this decade (IRSG 2021), largely for latex from Hevea species, with likely limited latex production from plants such as Guayule or Russian dandelion.

5.4 Integration of sustainable production and consumption

There is a need to identify innovative solutions to promote a holistic approach to address systemic challenges for climate mitigation and adaptation actions. The reduction of direct and indirect emissions, development of efficient product design, increased efficiency along the raw material supply chain, the use of new technologies at the end of the life of final products and incentives for their reuse are consumption-focused climate actions. Reducing consumption footprints on land, partnering with producers, promoting demand for and the consumption of commodities and products that are not associated with deforestation and forest degradation, and incentivizing financial and economic investors to integrate such concerns into their investment decisions are business strategies that could be further implemented to support sustainable growth in the rubber economy.

6 Taking action

6.1 Co-benefits of climate actions in rubber systems

A co-benefit refers to a socially, economically and/or environmentally desirable outcome that is generated from the implementation of a policy or measure (Crumpler and Meybeck 2020).

Co-benefits may be generated at different scales and across sectors, and their social, economic, or environmental desirability depend on local

Table 2. Co-benefits of climate actions in rubber systems

Action	Adaptation	Mitigation	Other environmental benefits	Other economic and social benefits
Improving plantation management	+++	+++	++	+++
Increasing carbon stocks		+++	+	++
Limiting negative impacts of land use change	++	+++	+++	++
Using rubber wood		+++	+++	+++
Substituting synthetic materials with natural rubber		+++	+	+++

Note: The plus indicates estimated levels of benefits according to the authors based on available information.

circumstances and implementation practices, among other factors (IPCC 2018). True-cost accounting approaches that incorporate the direct and indirect costs and benefits of adaptation measures in terms of economic, social and environmental impacts can contribute to a more "holistic" and evidence-based approach to national policymaking and investments.

Co-benefits of climate action in the rubber sector with other sustainability objectives include:

Ecosystem health

- Biodiversity conservation
- Soil quality and fertility increase
- Restoration of degraded lands
- Evaporative cooling and moisture recycling
- Reduced chemical use
- Reduced impacts on resources

Socioeconomic benefits

- Improved livelihoods
- Integration of food crops
- Diversification of incomes

6.2 Actions in the field and at landscape level

Improving plantation management in small and large holdings is fundamental to adapting rubber to climate change and contributing to mitigation. This implies complying with land use planning, improving agronomic practices, using high-yielding clones, and practices that conserve carbon and reduce the release of chemicals into the environment. Farmers will need different types of support to implement better practices, including receiving information and support from extension services or from companies on how to manage plantations, how and when to use agrochemicals, and how to store them.

Easily accessible information is important at both field and national levels. To date, there is no formalized guidance available for sustainable rubber cultivation, even though there is some experience from various countries. Collecting information on these practices relating to environmental, economic and social concerns would benefit producers, especially in countries that are just starting to produce rubber.

6.3 Actions along the rubber value chain

Actions are not only needed at the field level; successful adaptation and mitigation actions are needed at different points across the natural rubber value chain. Opportunities should be sought to improve at all levels. Figure 2 shows examples of actions along the rubber value chain.

6.4 Research needs

There are numerous potential opportunities for natural rubber to contribute to climate change mitigation and adaptation, as well as to be part of a forest-based circular bioeconomy, although many research and development questions remain unanswered, examples of which are included in Table 3.

Research and development should be accompanied by mechanisms of transfer to the field, with support for producers and manufacturers. It would also benefit from the experience of established national and international organizations, such as IRRDB, IRSG and other institutions.

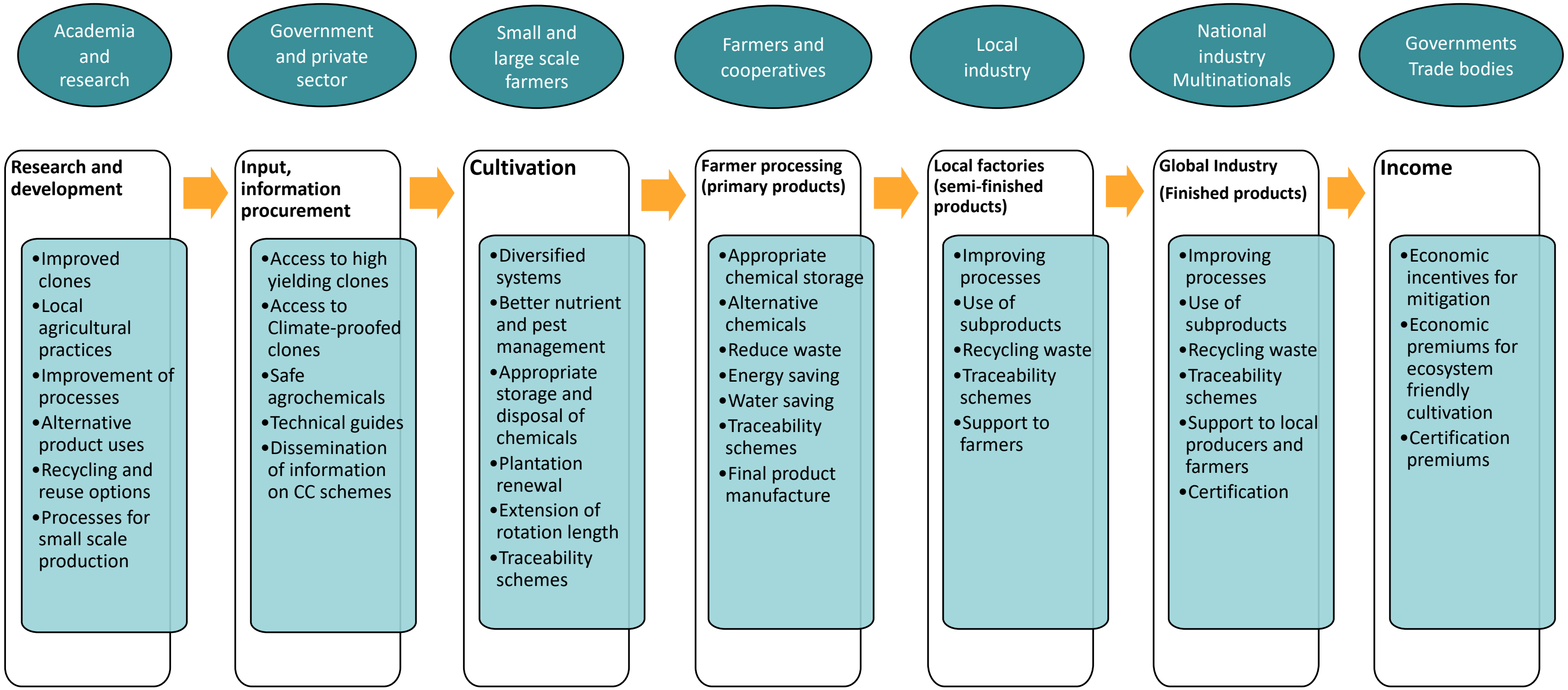

Figure 2. Examples of actions along the rubber value chain.

Table 3. Examples of research needed for sustainable rubber systems

Type of System
Climate change projections in rubber cultivation areas Local climate projections to predict impacts, including potential diseases and water needs.
Impacts of climate change on rubber More specific studies on the impacts of climate change on plant physiology (carbon assimilation, water use, growth, latex flow and latex regeneration) under different conditions, including location (latitude and altitude), as well as plantation and landscape levels.
Impacts of rubber cultivation on ecosystems Studies to understand interactions between species in complex systems and the effects of plantation management practices on ecosystems. Studies on emissions balances to determine the potential effects from specific land use changes, including the effects of intensification and retaining biological corridors.
Development of climate-resilient clones New genomic selection methods with optimized use of germplasm (looking at other Hevea species) to increase yield and resistance to climatic extremes and diseases.
Spatial planning tools Easily accessible spatial databases that enable the determination and monitoring of the impacts of rubber production in different areas and at different production scales, including field and satellite data, especially in complex, fragmented habitats. This should help to identify areas for rubber development and biodiversity conservation and areas where carbon offset projects can be successful.
Development of climate smart practices Research on how natural rubber systems can raise carbon stocks through locally-specific practices that improve yields and are beneficial to farmers. Research on diversified systems that can help farmers to adapt to climate change.
Product development Identify opportunities for using rubber wood in long-lived products or natural rubber for fossil fuel replacement. Further development of replacement applications and sustainability studies for the proposed product replacement. Ways of making rubber processing greener, designing products that are highly efficient over their entire lifecycle and ensuring rubber products can be recycled or used in other production cycles.

6.5 Supportive national policies

Technical solutions, such as raising productivity and fostering climate-smart agricultural practices, cannot achieve the desired climate goals without an enabling environment. Political and structural factors, such as a lack of negotiating power on the part of producers and market prices, are an obstacle to improvements at the start of the value chain. Such a complex network of relationships requires a coordinated approach involving all relevant stakeholders.

Policies must be put in place to enable natural rubber to become part of a forest-based circular bioeconomy and benefit communities, especially in countries where rubber production is relatively new, with particular emphasis on sustainable development in the context of climate change. Policies are required at different levels and need to be supported by appropriate legislation and regulatory frameworks. Some may already be in place for other commodities and their production systems, or in countries with the longest experience in rubber cultivation, processing and marketing.

Farmers need access to high-yielding clones with resistance to pests and diseases, technical support to apply locally adapted practices, access to early warning systems and access to financial support. In addition, large-scale plantation owners need to improve the sustainability of their plantations. Altogether, partnerships between different sectors may result in the largest gains from economic, social and environmental points of views. Tables 4 to 6 contain some examples of policies that are needed to support the different objectives around sustainable rubber production in the context of climate change, which, in principle, should support mitigation, adaptation and other benefits.

6.6 Integrating rubber in instruments from international commitments

Natural rubber production has considerable potential for climate action and sustainable development, which needs to be recognized by national and international mechanisms and plans (Gitz and Meybeck 2021; Brady 2021; Omokhafe 2021; Rodrigo and Munasinghe 2021; Meybeck and Gitz 2021). With the Paris agreement and the Nationally Determined Contributions (NDCs) there is better recognition of synergies and trade-offs between mitigation and adaptation as well as of synergies with sustainable development, opening up additional ways to better integrate land use, and in particular rubber production.

Table 4. Policies to support adaptation, increase productivity and reduce impacts on ecosystems

Objectives	Public sector	Research and academia	Private sector	Extension services and farmer organizations
Improve yields and resistance to climate extremes, pests and diseases	Provide access to high quality genetic material (clones).	Develop clones. Provide knowledge to extension services and farmer organizations. Develop research projects to answer needs of smallholders.	Propagate and provide access to clones.	Provide information on options and cultivation methods.
Use agronomic practices that increase yields and decrease impacts on ecosystems	Promote locally-specific technologies, produce guidance. Promote diversified systems.	Develop locally specific technologies, diversified systems and better water, nutrient and pest management practices.	Develop and distribute ecosystem-friendly inputs.	Provide technical support and facilitate exchange of practices.
Reduce the impacts of pests and diseases	Provide and support the creation of early warning systems.	Provide the scientific basis, identify areas where pests could develop.	Invest in information dissemination.	Train farmers to use early warning information and combat outbreaks.
Promote sustainable rubber	Provide an enabling environment to recognize sustainable practices, including incentives. Engage with and enhance certification schemes. Promote multi-stakeholder initiatives.	Provide evidence for the assessment of sustainable practices (environmental, social, economic).	Recognize sustainable practices, such as through corporate social and environmental responsibility and certification. Engage in business-to-business (B2B) and business-to-consumer (B2C), and associated labelling.	Facilitate dialogue with supply chain actors to offer a stable income to farmers.

Most countries have integrated objectives and measures related to land use, land use change and forestry (LULUCF) into their NDCs. These include reducing deforestation and increasing afforestation and sustainable forest management. Some also include targets regarding the development of bioenergy. Moreover, the periodic revision of the NDCs offer opportunities to explicitly integrate rubber-related objectives.

The implementation of NDCs in rubber-consuming countries could include measures promoting the use of natural rubber to substitute non-renewable products, or increasing the lifespan of carbon stocked in rubber products, such as blending ground tyre rubber with asphalt to produce longer-lasting road surfaces.

Rubber could be better integrated into national adaptation plans (NAPs) and resulting national policies, as has already been done by several countries (Meybeck and Gitz 2021): In Sri Lanka, rubber is part of the agriculture export sector along with other commodities, for which the following adaptation options have been identified: germplasm improvement, the improvement of farm and nursery management practices, sectoral capacity building, research on climate impacts, and monitoring and surveillance for pests and diseases. The NAP of Cameroon contains a measure for strengthening of rubber production capacity in the context of climate change. In other countries there are measures that can inspire the rubber sector. The NAP of Chile includes a specific adaptation plan for plantations, with some measures common to agriculture (monitoring of pests and diseases). Countries like Uruguay and Uganda have conducted multi-stakeholder dialogues that can inspire a similar national process for rubber.

Table 5. Policies to reduce the negative impacts of land use change (contribution to mitigation)

Objectives	Public sector	Research and academia	Private sector	Extension services and farmer organizations
Identify areas for conservation and areas where planting rubber is more sustainable	Support research programmes, maintain and share spatial databases.	Contribute with research and monitoring; promote approaches like high-conservation-value areas (HCVAs) and high-carbon-stock approach (HCSA)[4].	Engage with authorities and research to improve sustainability of rubber systems.	Engage with researchers and share information with farmers.
Implement land use zoning and planning.	Consult with local actors, provide platforms for dialogue, manage information systems to enable local land use planning.	Provide evidence on potential of land use change.	Develop and distribute ecosystem-friendly inputs.	Provide technical support and facilitate exchange of practices.
Provide an enabling environment for tenure and use rights	Revise and implement legislation.	Provide basis to strengthen regulation.	Observe the regulations.	Observe the regulations.
Establish impact assessments and mechanisms to grant permissions that include ecosystem considerations	Design and streamline regulations.	Support farmers to contribute to land use planning efforts.	Recognize sustainable practices, such as through corporate social and environmental responsibility and certification. Engage in business-to-business (B2B) and business-to-consumer (B2C), and associated labelling.	Facilitate dialogue with supply chain actors to offer a stable income to farmers.
Renew plantations	Provide diversification possibilities; support smallholders during the immature phase.	Propose ways to maintain income during the immature phase.	Plan planting times with smallholders. Provide platforms for employment and incentives for renewal. Establish fair partnerships.	Assist farmers to identify options for the immature phase.

Table 6. Policies to support improving community wellbeing and rubber sustainability

Objectives	Public sector	Research and academia	Private sector	Workers and farmer associations
Regulate concessions for sustainability	Include environmental, economic and social concerns in the approval of concessions.	Provide evidence on sustainability and options for improvement.	Make voluntary commitments and support smallholders.	Share knowledge on opportunities and contributions to sustainability with farmers.
Improve working conditions on large-scale plantations	Provide health and safety standards for rubber plantations.	Provide evidence on potential of land use change.	Develop and distribute ecosystem-friendly inputs.	Provide technical support and facilitate exchange of practices.
Ensure smallholders receive a stable income for their products	Establish mechanisms for stable income from intermediates or the private sector.	Contribute to data on price mechanisms.	Ensure smallholders receive stable income.	Ensure that farmers have information on current prices and market conditions, organize to achieve stable income.
Install mechanisms to support farmers during contingencies (e.g. price changes, extreme events) and immature phase of plantations.	Develop financial mechanisms that can be applied immediately (could involve tax incentives for large-scale companies).	Monitor potential changes to warn authorities.	Provide contributions towards emergency funds.	Help farmers identify when field operations could be threatened.
Link rubber production with national and international programmes that are working to address climate change concerns.	Include rubber in NAPS, NDCs and development plans to facilitate access to funds.	Contribute with local information to support participation in programmes.	Partner with smallholders and government to access programs.	Maintain farmers informed of potential schemes.
Support smallholders in manufacturing final rubber products in situ	Create opportunities to manufacture final products.	Develop products and processes that can be carried out at farm level.	Support manufacture and sale of local products.	Transfer knowledge and support manufacturing processes.
Access to markets and competitive prices that award environmental leadership	Ensure farmers have access to fair prices and that environmental leadership is recognised through premiums.	Provide evidence of sustainability.	Partner with smallholders or buy at fair prices.	Help farmers organize.

7 Conclusions

Concerted action from all relevant actors is needed to adapt natural rubber to climate change and strengthen its contribution to mitigation. These include governments, research organizations, producers and industry at both national and international levels.

All actors should thrive to increase the contribution of the rubber sector to climate action by:

- *Increasing and accelerating efforts toward adaptation.* Science-based evidence suggests that because of inertia in the geophysical system, some amount of additional warming is already locked in the system in over the next decade even if emissions decrease immediately. The natural rubber sector needs to fundamentally increase and accelerate efforts toward adaptation to eliminate the more immediate impacts of climate change that have already occurred or are locked in. The preparation and implementation of NAPs and the adoption of NDCs offer opportunities to develop integrated plans to adapt rubber to climate change.
- *Using Hevea trees as carbon sinks*, especially in degraded areas; better land use planning; improving management practices to increase soil carbon and yields; and increased use of rubber wood and natural rubber to replace non-renewable materials. Fulfilling this potential will require research and development and coordinated action in landscapes and along the value chain. It will also require enabling policies and appropriate recognition and support at the international level.
- *Providing support to farmers and communities that depend on rubber.* There is a real risk that the costs and effects associated with a net-zero transition in the rubber sector would be unbearable to many in absence of compensating measures. Farmers and local communities that rely on rubber as a major source of their income must be supported in a spirit of fairness and unity.
- *Developing new ways of working collectively.* It is essential to forge constructive and coordinated international research strategies and new forms of collaboration among various stakeholders, including governments, industry, financial institutions, R&D organizations, universities and NGOs, to enhance the ability to innovate and intervene at scale to support lives and livelihoods.
- *Mobilizing climate finance.* Stakeholders must commit to investing in market-based instruments, capital market transaction in-setting and offsetting, carbon transfer payments and market finance to develop a carbon accounting system under Article 6, and supply chain investment over a long-term period. Financial support must adopt a structuring approach to de-risking investments and increase private-sector investment in landscape initiatives and supply chain value creation.
- *Strengthening the role of the private sector in climate action.* There has been increased emphasis on the private sector as a catalyst for climate action in recent years. This could potentially enhance the visibility and presence of rubber in international negotiations and financial mechanisms. The sector can mobilize its well-organized mechanisms of collaboration between countries and national actors, as well as with the private sector. It can also provide opportunities through the IRSG and between research organizations through the IRRDB.

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