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Eco-climatic challenges and innovations: Navigating the future of rubber plantations

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Abstract
Rubber plantations are essential to the economies and ecosystems of many tropical regions, but they face significant threats from environmental and climatic factors. This review paper examines the impact of soil quality, water availability, and pests and diseases on rubber tree health and latex production. The paper highlights the diverse climatic impacts on rubber cultivation through case studies from major rubber-producing regions, including Southeast Asia, Africa, and South America. Adopting sustainable practices such as soil conservation, efficient irrigation, integrated pest management, and developing resilient rubber tree varieties is crucial for mitigating these challenges. The paper concludes that addressing environmental and climatic challenges through adaptive strategies is essential for sustaining rubber production and ensuring the economic viability of rubber plantations.

Keywords: Environmental impact, climate change, soil quality and Water availability

Introduction

Natural rubber (NR) production and processing from the Hevea (rubber or Pará) tree is a significant economic activity in numerous nations, providing livelihoods for over 40 million people globally. Over five thousand items rely on natural rubber as a key component (Pinizzotto *et al*. 2021) [16]. More opportunities for using NR will arise due to the need to replace energy-intensive and non-renewable materials. For it to reach its full potential and provide benefits to the people who depend on it, it is crucial to ensure it is generated sustainably. In this article, we'll go over two NR sustainability hotspots and offer some solutions to make rubber production more sustainable so it can be a component of the circular bio-economy.

In the last 30 years, the amount of land used for rubber cultivation has increased by 1.8 times globally. The rubber market in mainland Southeast Asia has grown at a faster rate than any other commodity, and it has grown even more rapidly in nations that aren't typically known for growing rubber. Have voiced worries about the effects of expanding rubber cultivation on ecosystems and livelihoods. Research commonly compares the impact to those of the prior land cover, which is often a natural forest (Gitz *et al.*, 2022) [1]. Consequently, the review focuses on the effects of deforestation rather than Hevea plantings themselves. Converting varied land uses other than natural forests to Hevea production has not been well studied to determine its impacts.

Rubber and natural resources

According to Selvalakshmi *et al.* (2020) [2], the amount of extra land needed to supply the demand for rubber by 2024 might range from 4.3 million hectares to 8.7 million ha. Since these predictions were issued, the world's rubber market has shifted, with NR demand marginally down and predicted to stay that way until 2024. Many people are worried that expanding rubber plantations may lead to the monoculture conversion of very biodiverse landscapes like woodland and mosaic landscapes. As with any agricultural monoculture that supplants more diversified systems, this is a worry that is not unique to (Shao-jun *et al.*, 2015) [3] found that species composition changes and species richness diminishes when forests are converted to rubber monoculture (Selvalakshmi *et al.*, 2020) [2].

Plantations, with their more complex habitat structures, support more biodiversity than monocultures, whereas agroforestry systems allow for the survival of certain forest species that would otherwise perish in monocultures. Further, research is needed to determine the effects of plantation management practices (such as pest control) on ecosystems, the interactions between species in complex systems, and the comparison of the effects on biodiversity of different spatial structures (Shao-jun *et al.*, 2015) [3].

Importance of studying environmental and climatic effects

The productivity and sustainability of rubber plantations are intricately linked to environmental and climatic factors. Soil quality, water availability, pest and disease pressure, and weather patterns play critical roles in determining the health and yield of rubber trees. In recent years, climate change has emerged as a significant threat to rubber plantations, with rising temperatures, altered precipitation patterns, and increased frequency of extreme weather events posing challenges to traditional rubber-growing regions (Ahrends *et al.*, 2015) [4].

Economical Perspectives

For many rural residents, rubber plantations provide a means of subsistence and economic advancement. The ecosystems that have been damaged by shifting cultivation can be restored with the help of these plantations. People's living conditions are enhanced through community-based rubber plantations. Due to the financial incentives and benefits, many farmers shifted their focus from conventional farming to rubber plantation. Ling *et al.* (2022) [5] found that biogas can be made from natural rubber processing waste and used to dry the rubber and cook in homes. Habitat and stream hydrology are severely impacted in numerous nations as a result of water contamination caused by rubber processing enterprises. Fish, prawns, turtles, shellfish, and edible flora along stream banks undergo drastic declines as a result. It has a detrimental impact on people's ability to make a living and on the safety of food. Price swings, insecurity in food supplies, and illness all pose risks to the income of smallholder farmers. The income and livelihood of people in various locations are impacted by environmental concerns arising from rubber's intense cultivation (Ling *et al.*, 2022) [5].

Ecological Significance

Rubber plantations have a significant ecological impact on their surrounding environments. On the positive side, rubber trees sequester carbon, which helps mitigate climate change by decreasing atmospheric CO_2 levels. Rubber plantations can also contribute to soil stabilization and watershed protection, preventing erosion and maintaining water quality. However, the expansion of rubber plantations has raised ecological concerns, particularly regarding biodiversity loss and habitat destruction (Chattopadhyay, 2021) [6]. Converting natural forests into rubber monocultures reduces habitat availability for wildlife and disrupts ecological networks. This transformation can lead to the decline of native species, including endangered flora and fauna. Additionally, using agrochemicals in rubber plantations can contaminate soil and water resources, posing risks to both ecosystems and human health. The history and global distribution of rubber plantations underscore their economic and ecological significance. While rubber plantations are vital for the livelihoods of millions and support various industries, they also present ecological challenges that need to be addressed through sustainable management practices (Panda *et al.*, 2020) [7]. Understanding the dual impact of rubber plantations is essential for ensuring their long-term viability and minimizing their environmental footprint. As global demand for natural rubber continues to rise, concerted efforts are needed to promote sustainable rubber cultivation and mitigate the adverse effects on biodiversity and ecosystems.

Environmental factors affecting rubber plantations

Effects on water availability

Since rubber plants have a higher water requirement than other plants, they deplete groundwater supplies and cut into the share that other plants have. Many latex and rubber processing facilities pollute nearby soil and groundwater by dumping partially treated or untreated wastewater into the environment. More and more land is being covered by rubber plantations as part of tribal rehabilitation efforts, which is drastically cutting down on biodiversity and might have serious effects on the region's water supplies. The latex material, which includes water, sugar, proteins, resins, and rubber, can lead to water contamination. This is the primary source of the water utilized for spring cleaning as well as the wastewater produced by processing activities and the rubber sheet manufacturing process. Because of the release of extremely polluting pollutants, (Hazir *et al.*, 2020) [8] the presence of biological oxygen and ammonia makes the waste products from rubber processing considered. The use of acid in the latex thickening, conserving, and blending procedures results in acidic waste liquidated from the rubber manufacturing plant. Due to using sulfuric acid in latex clotting, the processing of rubber results in an effluent with a high concentration of sulphate. Monocultures, the common method of growing rubber, deplete soil nutrients and necessitate extensive use of fertilizers and pesticides. The natural ecosystem may suffer as a result of this, which can lead to water and soil contamination. In addition to hurting the environment and water usage, factories use energy and water-intensive procedures. Due to well-managed topography, gully formation under rubber plantations is limited, which increases the risk of landslides. According to Prasada *et al*. (2021) [9], soil nitrogen and organic carbon interaction is lower in rubber plantation areas compared to forest land. Due to the extensive obstruction of sunlight under rubber plantations, water levels tend to decline in many locations where rubber is dominant. Seasonal variation determines the amount of precipitation. The rubber tree awning's ability to intercept rainfall varies with the seasons. Rubber trees don't have a very high water retention capacity. While water loss from rubber plantations may be small, nutrient loss is quite large. The rubber tree has a drying effect on wet soil and a tendency to slow the flow of water. The control of the hydrological cycle is thus affected by this (Prasada *et al.*, 2021) [9].

Soil quality and composition

Rubber trees prefer loamy soils with a balanced mixture of sand, silt, and clay. Such soils provide good aeration, drainage, and root penetration. Heavy clay soils, which retain too much water, or sandy soils, which drain too quickly and lack nutrient-holding capacity, are less suitable for rubber cultivation. Nutrient-rich soils support vigorous growth and high latex yields. Regular soil testing and fertilization are necessary to maintain soil fertility. Organic matter, such as compost or green manure, can enhance soil structure and nutrient content. The use of chemical fertilizers should be carefully managed to avoid soil degradation and environmental pollution (Golbon *et al.*, 2018) [10]. Deep soils, with a minimum depth of 1.5 meters, allow for extensive root development, which is crucial for the stability and health of rubber trees. Shallow soils can restrict root growth, leading to poor tree anchorage and reduced access to nutrients and water. Soil erosion is a significant concern in rubber plantations, especially in hilly terrains. Erosion can deplete the soil of essential nutrients and organic matter, reducing its fertility. Soil erosion can be avoided and soil health can be preserved by implementing soil conservation techniques like contour planting, terracing, and cover crops into practice.

Effect on soil health

Soil health is negatively affected by rubber plantations, according to numerous researchers. According to (Mangmeechai, 2020) [11] soil erosion is a worldwide issue that rubber plantations can contribute to by reintroducing soil erosion. A rubber tree can significantly lessen soil erodibility. Soil organic matter oxidation can lower soil temperatures, which aids in building. The shade cast by the rubber trees causes this to occur. Rainfall speeds up organic matter breakdown, releases nutrients, and disrupts the surface soil's collective organization (Mangmeechai, 2020) [11].

Rubber and Soil: Problems with management

The clearing of secondary forests to create space for rubber plantations is described in another study conducted in Xishuangbanna Prefecture. Trees were cut down from sloped ground and terraces were constructed by hand in this case. Bulldozers are commonly used to make terraces in other regions. Both methods involve digging down to the subsoil, which exposes the less-absorbent soils below. Soil compacting is another way mechanical terracing decreases water absorption. Surface erosion may speed up, natural streamflows may be interrupted, stream sediments may be elevated, and the likelihood of landslides may increase (Gitz *et al.*, 2020) [1]. Clearing terraces of vegetation before new trees' roots have developed to a point where they can support soil or shield from rain increases the likelihood of problems. When the rubber trees were young, farmers in Xishuangbanna would plant them and then intercrop them with upland crops like rice, corn, groundnuts, and beans for the first four years. Twice yearly or less frequently, chemical fertilizers were spread. The understory vegetation was either pulled out by hand or treated with herbicides after the rubber trees had reached maturity. One reliable indicator is the amount of carbon in the soil, which is the most important component of soil organic matter. When soil contains a lot of organic matter, it has better physical qualities, such as being able to hold water and being more stable. Plants rely on the nutrients and trace elements provided by organic matter in the soil to flourish (Yu *et al.*, 2019) [13]. Soil carbon levels dropped sharply in the first five years following the research site's rubber plantation conversion from secondary forests. After a steep decline, the rate of decline leveled off around 20 years after the rubber trees were first planted. Approximately 68% of the initial level of carbon in the soil's uppermost layer remained under secondary forest conditions at this time.

When taking a regional perspective, (Meijide *et al.*, 2018) [14] found that disruptive soil preparation and management, rather than rubber trees themselves, are the main culprits in the soil degradation caused by rubber plantations. Soil organic carbon losses and severe degradation of soil quality are linked to mechanical terracing. People living in rural areas may be at risk of chemical contamination from pesticides and fertilizers that seep into surface and groundwater sources. Furthermore, without organic soil amendments, the consistent use of inorganic fertilizers can lead to soil acidification and, in the long run, a dramatic reduction in soil quality. In the mountainous region of mainland Southeast Asia, mechanical terracing and extensive fertilization are only used on rubber plantations, even though they might theoretically be used for numerous crops (Meijide *et al.*, 2018) [14].

Pests and Diseases

Pests and diseases are significant threats to rubber plantations, potentially causing substantial yield losses and tree mortality. Effective management of these threats is crucial for maintaining healthy rubber plantations and ensuring sustainable production. Several pests can infest rubber trees, including insects, mites, and rodents. Common pests include the rubber tree lace bug (*Leptopharsa heveae*), the mealybug (*Dysmicoccus brevipes*), and various species of leaf-eating caterpillars [15]. These pests can cause defoliation, reduced photosynthesis, and weakened trees, ultimately affecting latex production. Rubber plantations are susceptible to various diseases caused by fungi, bacteria, and viruses. The most devastating diseases include South American Leaf Blight (SALB), caused by the fungus *Microcyclus ulei*. SALB can cause severe defoliation and tree death, posing a major threat in South America and other rubber-growing regions. Another significant disease is Powdery Mildew, caused by the fungus *Oidium heveae*, which leads to white, powdery fungal growth on leaves, reducing photosynthesis and tree vigor. Corynespora Leaf Fall (CLF), caused by the fungus *Corynespora cassiicola*, results in premature leaf drop and can significantly reduce latex yields.

Integrated Pest Management (IPM) is a sustainable approach to managing pests and diseases that combines biological, cultural, mechanical, and chemical control methods. IPM strategies for rubber plantations include biological control, which utilizes natural predators, parasites, or pathogens to control pest populations. For example, introducing predatory insects to manage lace bug infestations. Cultural practices involve implementing good agricultural practices such as crop rotation, proper spacing, and sanitation to reduce pest and disease incidence. Chemical control involves using pesticides judiciously and as a last resort, ensuring that applications are targeted and follow recommended guidelines to minimize environmental impact and resistance development.

Developing and planting disease-resistant rubber tree varieties is a long-term strategy to combat major diseases. Breeding programs focus on selecting varieties with genetic resistance to specific pathogens, reducing the need for chemical control measures, and enhancing plantation sustainability. This multifaceted approach is essential for maintaining the health and productivity of rubber plantations in the face of environmental challenges.

Breeding and selection of high-yielding and disease and pest-resistant clones

Breeding and genomic marker-assisted selection to create clones that are resistant to climate change and produce abundant crops is another strategy. The NR business was established on a relatively limited genetic foundation; the majority of the *Hevea brasiliensis* trees present in Asian plantations today are descendants of just 22 seedlings gathered by Henry Wickham from the Brazilian Amazon Basin in the 1800s. Commercial rubber production began in Malaysia and spread to other nations that grew the tree's seeds. Subsequently, expeditions were launched to the Amazon in search of fresh germplasm, to increase genetic variety and production. Opportunities for adaptation can be found in expanding the genetic base of cultivated rubber. Wild germplasm has genes that could be useful for breeding rubber to resist climate change stress. While studies in China revealed substantial variation among clones in their susceptibility to hurricane damage, recent work in Thailand demonstrated a promising genetic variability among the current commercial clones for breeding drought-tolerant clones. employing SNP (single nucleotide polymorphisms) markers for new genetic selection from various Hevea species, including *H. Nitida, H. Spruceana*, and *H. brasiliensis*, researchers might further improve the possibility of employing rubber germplasm for climate change adaptation. Modern technology allows for the acceleration of the breeding process. For testing and global clone exchanges, international collaboration is crucial.

Climatic Factors Affecting Rubber Plantations

Rubber systems and climate change

According to Pinizzotto *et al.* (2021) [16], there are numerous ways in which climate change interacts with natural rubber systems. They can play a role in the production or absorption of greenhouse gas emissions and are already feeling the effects of climate change (Pinizzotto *et al.*, 2021) [16]. According to Min *et al.* (2020) [17], rubber is best grown in regions with yearly mean temperatures between 26 and 28 degrees Celsius and rainfall between 1800 and 2500 millimeters (Min *et al.*, 2020) [17]. However, in borderline locations, the weather might be much colder or drier. Droughts and floods brought on by climate change will make life less pleasant in some long-established regions, but warming will make life better in other, cooler, peripheral regions. Another potential avenue for expansion is to move to higher latitudes and altitudes. Additionally, in drier regions, changes may promote rubber cultivation over oil palm. Drought may postpone tree maturity, while more frequent rainfall may decrease tapping days or increase pests/diseases; both extreme weather occurrences are likely to affect rubber production. Another major worry is wind damage, which is becoming more common and more powerful typhoons. The consequences of increasing temperatures on the physiology of rubber trees, as well as their effects on yields and the dispersion of pests and diseases, remain unclear, and additional research is required to fill these gaps. Agronomic practices that are resilient to climate change and the development of clones that are resistant to climate change and have high yields can be used in tandem to adapt rubber cultivation to climate change. The chance to express such actions is presented by developing nations' national adaptation plans.

Impacts of climate change on natural rubber systems

Conditions in peripheral areas can be cooler or drier, or even both, while the majority of rubber plantations are situated in regions with an average annual temperature range of 26–28°C and more than 1,500 mm of rainfall. Global temperatures are anticipated to rise by 2°C to 3°C by 2050, as per the predictions of the IPCC. Climate change will have varying impacts on the several regions that presently grow rubber since the climatic margins of this crop are mostly dictated by rainfall and temperature. Drought will make some traditionally fertile places less so while warming will make other marginally fertile places more (Toriyama *et al.*, 2022) [18]. Rubber Trees however grown in a limited number of regions around the world, therefore finding a suitable location for expanding rubber tree cultivation is required. Policy planners can use information on soil, physiography, and socio-economic characteristics to determine whether to expand or contract rubber trees based on climate suitability (Ray *et al.*, 2014) [30]. Hevea land suitability is predicted to change in several research in China, India, Malaysia, and the broader Mekong subregion. Northern Thailand, Laos, Yunnan, and Hainan provinces in China, southern Brazil, Gabon, and south-eastern Cameroon are some of the marginals producing locations where rubber is now more easily grown due to colder and more humid weather. However, this might all change in the future. Another potential avenue for expansion is to move to higher latitudes and altitudes. Because oil palm farms are only found in the wet tropics, rubber may soon replace oil palm in drier regions. Rapid and severe trunk snapping and branch breaking can do permanent harm to a plantation. Pests and diseases brought on by increased humidity are another consequence of climate change; there have been noticeable shifts in the frequency and intensity of these events. Recent wetter and longer rainy seasons played a role in the outbreak of Pestalotiopsis, a fungal leaf fall disease, on Hevea in South Sumatra, according to a study. Fungicides are most effective when applied during the early stages of Pestalotiopsis infection. Whereas, (Pradeep *et al.*, 2022) Pradeep induced extended and unusually dry seasons considerably decreased the disease's occurrence. Nonetheless, growth stunting and decreased latex production were additional outcomes of the protracted dry season (Pradeep *et al.*, 2022) [19].

Regional impacts of rubber plantations

Impact on major rubber-producing regions

Southeast Asia Southeast Asia is the leading region for rubber production, with Thailand, Indonesia, and Malaysia accounting for the majority of global output. The region's tropical climate, characterized by consistent rainfall and warm temperatures, provides ideal conditions for rubber tree cultivation. However, climate change poses significant threats. In Thailand, irregular rainfall patterns and prolonged dry seasons have led to water stress, reducing latex yields. Conversely, excessive rainfall has resulted in flooding, waterlogging, and increased incidence of root diseases.

In Indonesia, the shifting monsoon patterns have affected the rubber-tapping season, while rising temperatures have stressed rubber trees, making them more susceptible to pests and diseases. Malaysia faces similar challenges, with the added pressure of land competition from palm oil plantations (Hazir *et al.*, 2018) [20]. The country has experienced increased pest outbreaks, such as infestations by the rubber tree lace bug, exacerbated by changing weather conditions.

Africa In Africa, countries like Côte d'Ivoire, Nigeria, and Liberia are significant rubber producers. These countries have vast areas suitable for rubber cultivation, but they face distinct environmental challenges. In Côte d'Ivoire, irregular rainfall and prolonged dry periods have impacted rubber yields, prompting farmers to adopt irrigation systems and water conservation practices. Nigeria's rubber industry suffers from outdated agricultural practices and insufficient pest and disease management infrastructure, leading to lower productivity.

Liberia, with its favourable climate and ample land, has the potential for expanding rubber production. However, the sector is recovering from years of civil conflict, which disrupted agricultural activities and infrastructure. Climate change is now adding to the complexities, with unpredictable weather patterns affecting planting and tapping schedules.

South America South America, particularly Brazil, is the native home of the rubber tree, but the region's rubber industry has faced significant challenges. The most prominent threat is South American Leaf Blight (SALB), caused by the fungus *Microcyclus ulei*. This disease has devastated rubber plantations, leading to a decline in production. The climate in the Amazon basin, with high humidity and frequent rainfall, creates ideal conditions for the spread of SALB, complicating disease management efforts (Ma *et al.*, 2019) [21].

To mitigate these challenges, Brazil has focused on developing disease-resistant rubber tree varieties and implementing strict quarantine measures to prevent the spread of SALB. Other South American countries like Guatemala and Ecuador have also faced challenges related to climate variability, such as irregular rainfall and temperature fluctuations, impacting rubber productivity.

Effect of rubber plantations on climate change

Thailand - Impact of Irregular Rainfall in Thailand, a major rubber-producing country, irregular rainfall patterns over the past decade have significantly impacted rubber plantations. The dry season has extended beyond the usual months, causing water stress and reducing latex flow. Farmers in the Surat Thani province reported a 20-30% decrease in latex yield due to inadequate rainfall during critical growth periods. To combat this, many have adopted micro-irrigation systems to ensure a consistent water supply. Additionally, mulching practices have been implemented to conserve soil moisture and reduce evaporation.

Indonesia - Rising Temperatures and Pest Infestations Indonesia has experienced rising temperatures over the past few years, which have stressed rubber trees and made them more vulnerable to pests such as the mealybug (*Dysmicoccus brevipes*). Farmers in the West Kalimantan region reported a significant increase in pest infestations correlating with higher average temperatures. The increased pest pressure led to defoliation and reduced photosynthetic activity, ultimately lowering latex yields. Integrated Pest Management (IPM) strategies, including biological control agents and cultural practices like regular field sanitation, have been adopted to manage pest populations and improve tree health.

Prolonged Dry Periods in Côte d'Ivoire, prolonged dry periods have posed a significant challenge to rubber cultivation. The unpredictable rainfall has led to inconsistent soil moisture levels, affecting tree growth and latex production. In response, the Rubber Research Institute of Côte d'Ivoire initiated a program to develop drought-resistant rubber tree varieties. These new varieties have shown promising results in field trials, demonstrating better growth and latex yield under water-stressed conditions. Additionally, farmers have been trained in water management techniques, such as rainwater harvesting and efficient irrigation practices, to mitigate the impact of dry spells.

Brazil - South American Leaf Blight (SALB) Brazil's rubber industry has been severely affected by South American Leaf Blight (SALB). The high humidity and frequent rainfall in the Amazon basin create favourable conditions for the spread of this fungal disease. In response, Brazil has focused on breeding and cultivating disease-resistant rubber tree varieties. The establishment of quarantine zones and rigorous monitoring has also been crucial in preventing the spread of SALB to unaffected areas. Collaborative research efforts with international partners have led to the development of fungicides and biocontrol agents, offering new tools for managing the disease.

The impact of environmental and climatic factors on rubber plantations varies across different regions, with each facing unique challenges. Southeast Asia contends with irregular rainfall and rising temperatures, Africa grapples with outdated practices and climate variability, and South America battles devastating diseases like SALB. These case studies illustrate the diverse climatic impacts on rubber production and highlight the importance of adopting adaptive strategies, such as developing resistant varieties, implementing efficient water management practices, and utilizing integrated pest management. Addressing these challenges is essential for sustaining rubber production and ensuring the livelihoods of millions of smallholder farmers globally.

Adaptation and Mitigation Strategies

Rubber system adaptation Research over the last ten to fifteen years has yielded a wealth of information that can be helpful in the adaption process. Two supplementary approaches may be used to adapt rubber agriculture to climate change: first, using agronomic techniques that are robust to climate change; and second, creating clones that are resistant to climate change and have good yields by using breeding and genomic marker-assisted selection. Rubber systems can be adapted to climate change in several ways. For the first two years after planting, nursery plants should be shaded. Intercropping with bananas, for instance, could do this (Panklang *et al.*, 2022) [22]. It has been suggested to use mulching in drier marginal locations to retain soil moisture or to water young plants. Soil water infiltration, reduced runoff and erosion, improved soil quality, and increased nutrient availability can be achieved by preserving surface cover through methods such as allowing some natural weed flora, intercropping with legumes, or leaving part or all of the tree biomass in the inter-rows. A rubber plantation's performance can be greatly improved with careful fertilizer control, especially in the beginning. The soil quality improves gradually during the mature stage of rubber, which is distinct from the immature stage. Rain guards and adaptive tapping management can mitigate the effects of increased rainfall on the bark. A tapping rest time and low-intensive tapping could be part of tapping management to reduce the number of days of tapping and the costs connected with it, all while keeping the annual yield the same.

Rubber trees contribute to the adaptation of farming systems

Some of the environmental changes brought about by climate change include higher average temperatures and reduced soil moisture. Because of its higher actual evapotranspiration (AET) compared to grassland cover, reforestation can enhance local climate conditions through evaporative cooling, which reduces surface temperature. Research on rubber tree plantations in Thailand indicated an annual effective transpiration rate (AET) of around 1,150 mm and an average net radiation utilization rate (RPUR) of 0.73. Based on these results, it may be inferred that tropical rainforests and well-managed rubber tree farms may exhibit similar evaporative cooling and moisture recycling behaviours. As a response to climate change, the production of rubber has been suggested as a substitute for conventional, short-term rainfed crops in Sri Lanka. Among the possible advantages are the following: a retention of up to twice the surface soil moisture; a reduction of midday air temperatures within the rubber plantation of up to 6°C; and an average decrease of 3.7 °C during the day. The farmers will also appreciate the improved working conditions this brings about. In areas that are most susceptible to the effects of climate change, livelihood resilience is crucial. When compared to non-rubber growers, Sri Lankan rubber farmers have more social capital and better access to other forms of livelihood capital. But smallholders whose only income is from rubber are particularly vulnerable to swings in the commodity's price, particularly 6 in the absence of government assistance or CSR initiatives by industrial allies. More stability may be experienced by smallholders whose produce is diverse. A more resilient and sustainable economy is the result of income diversification. An advantage of RAS that may have been discovered in Indonesian trials was this.

Mobilizing climate action to create an enabling environment

National Adaptation Plans (NAPs) were put in place to do two things: a) make countries less susceptible to climate change by making them more resilient and adaptive; and b) make it easier to incorporate adaptation measures to climate change into current and future policies, programs, and initiatives, especially development planning at all levels and in all relevant sectors. These plans and the national strategies that emerge from them may incorporate rubber more effectively. Some examples have already been provided. Among the agricultural exports from Sri Lanka, NAP rubber is one of several commodities that have identified adaptation options, such as improving germplasm, enhancing farm and nursery management practices, developing sectoral capacity, monitoring and surveillance of pests and diseases, and initiating research studies to assess climate impacts. Within the framework of climate change, Cameroon's NAP includes a strategy to increase the country's potential to produce rubber. We can also use other strategies. As an example, Chile's National Adaptation Plan (NAP) includes a section tailored to plantations, along with other agriculturally-related measures (disease and insect monitoring, for example). A national process for rubber could be inspired by certain nations' multistakeholder dialogues, such as Uganda's and Uruguay's.

Role of rubber in climate change mitigation

Vijayan *et al.* (2024) [23] have mentioned rubber as a possible candidate for reducing global warming. It can be shown from these that rubber plantations are carbon stocks similar to cocoa plantations, or even some agroforestry or forestry systems (based on the plantation's age) (Vijayan *et al.*, 2024) [23]. According to (Lai *et al*., 2023) [24], some argue that longer rotations store more carbon. A more comprehensive greenhouse gas emissions balance should take NR's effects into account. While rubber trees, when planted in damaged locations, effectively absorb carbon dioxide, tree replacement projects, and swidden farms can produce varied amounts of carbon emissions (Lai *et al.*, 2023) [24]. Carbon stocks from Northern Laos's rubber and swidden farms, for instance, were determined by (Pinizzotto *et al.*, 2021) [16]. In terms of carbon stock, they demonstrated that a 30-year-old rubber plantation can outperform the 5-year fallow swidden system, taking into account emissions from soil preparation before rubber planting. But this advantage will be for nothing if rubber-displaced swidden agriculture eventually supplants natural forests. Therefore, what and how rubber is replaced are crucial factors in determining its ability to contribute to mitigation. In general: When rubber trees are planted instead of natural forests, a lot of carbon is lost. Planting rubber on highly degraded land increases carbon stocks. Depending on the length of the fallow period of the system replaced, the contribution can be neutral or slightly positive when rubber replaces swidden systems. Why Forests lose carbon as rubber plants push out swidden systems. NR systems, when planted with other trees, can store carbon as effectively as secondary forests. Using rubber plantation wood instead of fossil fuels is another method natural rubber systems could help with mitigation. Additional wood harvest from forests and timber plantations may be mitigated if more rubber wood is used in furniture making. As an example, the primary resource for Malaysia's furniture sector is rubber wood, which has supplanted the diminishing supply from natural forests (Zhai *et al.*, 2019) [26].

Mitigation from the cultivation of rubber

Increasing carbon stocks

Several studies have looked into rubber's ability to reduce greenhouse gas emissions by acting as a carbon sink. The highest total vegetative carbon stock, measured in plantations aged 30–40 years, was 105.73 Mg C ha^{-1}, according to a study conducted by (Zhai *et al.*, 2019) [26]. The plantations in this age range had been in cultivation for 5–40 years. While carbon stocks in plantations that were 20-30 years old were larger than in semi-arid, sub-humid, humid, and temperate agroforestry systems, those in plantations that were 10-20 years old were similar to those in cocoa-based agroforestry that was 10 years old. Tropical forests in north-eastern India and mango agroforestry systems in Indonesia are examples of plantations that have carbon stores older than 30 years. Yang *et al.* (2019) [27]

found that older rubber plantations in Xishuangbanna, China, had a maximum carbon stock of 148 Mg C ha^{-1} at elevations below 800 m, based on their plantations that were 6 to 35 years old. Soil and tree carbon reserves are also impacted by rotation length (Yang *et al.*, 2019) [27]. Total carbon stocks increased with rotation length, reaching 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, according to a study that modelled the effect of rotation length (25, 30, 35, 40, and 45 years) on C stocks in Chinese rubber plantations.

Limiting negative impacts of land use change

Reducing the demand for new land and prioritizing degraded land for new rubber planting are two complementary measures to mitigate the negative implications of land use change. The availability of high-yielding clones and effective management procedures determine the variation in rubber yields among countries. To minimize additional land conversion, it is most efficient to decrease this yield difference. To attain greater and more consistent harvests, it is crucial to enhance genetic material. Scientists in the field of plant breeding are currently focused on developing more robust clones that can withstand severe illnesses, have a shorter immaturity phase, and produce abundant latex and timber.

Contribution to adaptation to climate change

Rubber tree plantations, if properly managed, may mimic the cooling and water recycling processes of tropical rainforests, which is only one way in which the introduction of rubber trees to other agroecosystems helps them adapt. As a response to climate change, the production of rubber has been suggested as a substitute for conventional, short-term rainfed crops in Sri Lanka (Orobator *et al.*, 2020) [28]. Among the possible advantages are the following: a retention of up to twice the surface soil moisture; a reduction of midday air temperatures within the rubber plantation of up to 6 °C; and an average decrease of 3.7 °C during the day. The farmers will also appreciate the improved working conditions this brings about. It is also a way to earn money in many ways.

Seasons

Warmer surface temperatures and limited moisture availability may result in lower relative humidity levels than currently experienced. This could have an impact on humidity-sensitive hydrological and ecological processes like evapotranspiration, runoff, and plant growth. Almost all stations showed strong indications of decreasing trends in daily sunshine hours during all seasons except the pre-monsoon season. Solar radiation (sunshine duration) has an important impact on surface temperature, evaporation, the hydrologic cycle, and ecosystems, therefore the primary source of energy required to sustain life on this planet. It was hence proven that sunshine duration in India has decreased for the entire month, and the decreasing trends were significant (Raj, 2015) [31].

Rubber Processing and By-Products

Rubber processing products like a sheet, crepe, block rubbers, or latex concentrate produce a large amount of effluent. Hevea's most significant product is latex. Rubber trees have primarily focused on obtaining a high latex yield rather than timber production. However, once Hevea's useful latex-producing life is complete, rubber wood can be used as timber, and this commodity is quickly gaining popularity as an alternative to tropical rainforest timber (Samarappuli, 1996) [32].

Policy and management approaches

National policies that are advantageous Without an enabling context, technical solutions like increasing production and encouraging climate-smart farming practices would not be able to accomplish the intended climate goals. Problems with producers' and markets' bargaining positions and pricing structures make it difficult to implement innovations at the beginning of the value chain. The intricate web of interdependencies necessitates concerted effort from all parties involved. For natural rubber to play a role in a forest-based circular bio-economy that benefits communities, policies are needed. This is particularly true in nations where rubber production is still in its infancy, and there needs to be a focus on sustainable development in light of climate change. Appropriate legislative and regulatory frameworks are necessary to support policies at various levels. In nations that have been cultivating, processing, and selling rubber for the longest period, or other commodities with established production systems, some may already exist. Crones that are resistant to pests and diseases and have high yields are essential, but so are early warning systems, financial aid, and technical assistance for farmers to use locally appropriate practices. It is also important for large-scale plantation owners to make their plantations more sustainable. From an economic, social, and environmental perspective, the greatest benefits may emerge from cross-sector collaborations. To achieve the various goals related to sustainable rubber production in the context of climate change, which should, in theory, aid in adaptation, mitigation, and other advantages, policies are necessary, International promises to incorporate rubber into instruments Plans and procedures at the national and international levels should take into account the significant climate action and sustainable development potential of natural rubber production. The Paris Agreement and Nationally Determined Contribution (NDCs), which better recognized the synergies and trade-offs between adaption and mitigation and sustainability departments, have created more opportunities for land use integration, particularly in rubber production.

Conclusion

Rubber plantations, which are vital to tropical economies and ecosystems, are threatened by environmental and climatic factors. Water availability, soil quality, and pest and disease challenges affect rubber tree health and latex output. These components must be controlled well to sustain rubber production and keep rubber plantations profitable. Climate change and environmental variability affect rubber-producing regions like South America, Africa, and Southeast Asia. Due to increasingly unpredictable rainfall and greater temperatures, Southeast Asian countries have needed sophisticated irrigation and pest control measures. To survive extended dry seasons, Côte d'Ivoire and Nigeria are improving water management and developing drought-resistant agricultural varieties. Brazil and South America are breeding disease-resistant plants and enforcing quarantines to stop South American Leaf Blight. Rubber plantation management must use sustainable methods to mitigate climate change and other environmental hazards. These include breeding hardier rubber trees, increasing irrigation, eliminating pests, and protecting soil. Research and collaboration are necessary to develop innovative, cost-effective, and ecologically friendly solutions. Rubber plantations must address environmental and climatic issues to survive. The rubber industry's economic and ecological viability hinges on climate change adaptation. The industry must adopt sustainable and adaptable methods to achieve this.

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