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REVIEW ARTICLE

Sustainable integration of rubber plantations within agroforestry systems in China: current research and future directions

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Abstract

The integration of rubber plantations with agroforestry systems, or the under-forest economy, represents a pivotal shift towards sustainable agriculture in China. This paper reviews the latest research on agroforestry practices and innovations within China's rubber plantation under-forest economy, with a focus on the balance between economic productivity and environmental sustainability. We explore the adoption of diverse agroforestry models that incorporate rubber trees with other valuable plant species, aiming to enhance ecosystem services, biodiversity, and farmers' livelihoods. The review highlights significant advancements in sustainable management practices, including species selection, planting designs, and soil and water conservation techniques that contribute to the resilience of these systems against environmental stresses. Economic analyses underscore the potential for rubber agroforestry systems to improve income diversification and stability for rural communities while also navigating market challenges. Environmental assessments reveal the positive impacts of these practices on carbon sequestration, biodiversity preservation, and soil health, positioning rubber agroforestry as a beneficial strategy for mitigating climate change effects. However, the review also identifies challenges, including the need for supportive policy frameworks, access to knowledge and technology for smallholders, and further research on long-term sustainability outcomes. Future directions for research are proposed, emphasizing the integration of ecological, economic, and social dimensions to fully realize the potential of the rubber under-forest economy in China.

Keywords

Agroforestry systems; diversification; rubber plantations; sustainable climate change; under-forest economy

Introduction

Rubber, an essential raw material in numerous industries, holds a pivotal position in the global economy. Its importance is accentuated in China, a leading player in the global rubber market (1). The rubber plantation economy is not just an agricultural concern but a significant economic driver, influencing various industrial sectors, trade policies, and international relations. China's journey into the world of rubber plantations has been remarkable. Historically reliant on imports to meet its burgeoning rubber needs, especially for its vast automotive and manufacturing sectors, China embarked on a path to reduce this dependency by developing its rubber plantation industry (2). This move towards self-sufficiency in rubber production not only altered the country's agricultural landscape but also had far-reaching economic and geopolitical ramifications. As an important strategic material and industrial raw material in China, natural rubber is widely used (3), but the development of the Chinese rubber industry is in a trough period due to the influence of many aspects such as climate and market (4). Under-forest economy refers to the composite pattern that carries out forestry, agriculture, animal husbandry, or other projects under the forest relying on the forest resources and its ecological environment (5). It allows farmers to make full use of the forest resources while managing them in a scientific way (6). In recent years, the development of the rubber forest under-forest economy in China has some achievements, and numerous rubber forest under-forest economy development patterns have appeared (7), but there are still some problems.

Contemporary research in China's rubber plantation economy spans a wide array of focus areas. Agricultural scientists are continuously exploring innovative farming techniques to enhance yield and quality (8). Economists are examining the market dynamics, including supply-demand trends, pricing mechanisms, and the impact of international trade policies (9). Environmental scientists are deeply invested in understanding and mitigating the ecological footprint of rubber plantations (10), a subject of growing concern in recent years. One of the central themes in current research is balancing economic viability with environmental sustainability (11). As the world grapples with climate change and ecological degradation, the rubber plantation industry in China faces the dual challenge of maintaining its economic momentum while adopting sustainable practices (12). This complex interplay of economics and ecology forms a critical area of study and debate among researchers. Looking ahead, the future of China's rubber plantation economy hinges on several factors. Technological advancements in agriculture (13,14), shifts in global trade policies, environmental regulations, and the evolving demands of the global market are just a few of the variables that will shape this sector.

This review seeks to aggregate and analyze the current body of research on China's rubber plantation economy, offering a holistic view of its status and speculating on its future directions. By synthesizing existing studies, data, and expert opinions, the article aims to serve as a valuable resource for researchers, policymakers, and industry stakeholders invested in the sustainable development of this vital economic sector.

2. Importance of natural rubber

Natural rubber, derived primarily from the latex of the rubber tree (*Hevea brasiliensis*), is a material of immense importance due to its unique properties and wide range of applications (15). As a result, natural rubber is widely used in many areas, including national defense, industry, agriculture, transportation, healthcare, and so on (16). Here are some key aspects highlighting its importance:

2.1. Unique Physical Properties: Natural rubber exhibits remarkable qualities such as high elasticity, good tensile strength, and excellent resistance to abrasion and impact. It has excellent elasticity, high tensile strength, and impressive abrasion and tear resistance, which are crucial for applications like tires, conveyor belts, and footwear soles. Additionally, it exhibits low heat buildup, good vibration dampening, water resistance, and electrical insulating properties. These features, combined with ease of processing and molding, make natural rubber a versatile material widely used in various industries, from automotive to consumer goods. These properties make it ideal for applications where flexibility, durability, and the ability to absorb shocks are crucial.

2.2. Versatility in Applications: It's used in a vast array of products, from everyday items like shoes, balloons, and gloves to industrial products like conveyor belts, hoses, and seals. It is valued for its high elasticity, resilience, and durability. Its largest application is in tire manufacturing. It's also used in industrial products like conveyor belts and hoses, as well as consumer goods such as footwear and gloves. Its biocompatibility is essential for medical products like surgical gloves. This versatility makes natural rubber crucial in both industry and daily life. Its most significant use is in the manufacturing of tires and tubes for vehicles, which is critical for the automotive industry.

2.3. Economic Significance: Natural rubber is a key commodity in the global market. It supports the economies of many countries, particularly those in Southeast Asia, like Thailand, Indonesia, and Malaysia, which are major producers (17). It is crucial for the production of tires, which supports the global automotive industry. Additionally, it's used in the manufacturing of medical supplies, footwear, industrial products, and consumer goods. Major rubber-producing countries like Thailand, Indonesia, and Malaysia benefit economically through export revenues and job creation. The demand for natural rubber continues to grow, driven by industrial development and the need for sustainable and eco-friendly materials. The rubber industry provides livelihoods for millions of small-scale farmers and workers involved in cultivation, processing, and trading.

2.4. Biodegradability and Environmental Aspects: Unlike synthetic rubbers derived from petroleum, natural rubber is biodegradable. This makes it a more environmentally friendly option due to its organic composition, primarily consisting of polyisoprene, a natural polymer. When exposed to environmental conditions, microorganisms such as bacteria and fungi can break down natural rubber, reducing it to water, carbon dioxide, and biomass. This biodegradability significantly mitigates environmental impact, as natural rubber products decompose more readily than synthetic alternatives. However, the rate of degradation can vary depending on factors such as temperature, humidity, and the presence of specific microorganisms. However, the environmental impact of rubber plantations, including land use and biodiversity concerns, is a subject of ongoing research and debate.

2.5. Medical and Health Industry Uses: Natural rubber is a key material in the production of medical gloves, catheters, and other protective gear, ensuring safety and hygiene in clinical settings. Natural rubber's elasticity makes it ideal for products like medical tubing, ensuring secure and leak-free connections. Additionally, its resistance to various chemicals and sterilization processes ensures that medical devices remain safe and effective throughout their use. It is vital in the healthcare industry to manufacture various products like medical gloves, catheters, and tubing. Its elasticity and strength make it ideal for these applications.

2.6. Research and Innovation: Ongoing research into enhancing the quality of natural rubber and developing sustainable cultivation practices demonstrates its continued importance. Additionally, efforts to genetically modify rubber trees to increase yield and disease resistance (18) highlight its significance in agricultural and material science research. Integration of genetic engineering with traditional breeding methods holds promise for developing high-yielding, disease-resistant rubber trees that can thrive in diverse environmental conditions.

3. Current state of natural rubber cultivation in China

In 2022, the Chinese natural rubber planting area is 1.124 million hm2, accounting for 7.1% of the global planting area. Chinese rubber is planted in Hainan, Yunnan, Guangdong, Fujian, and Guangxi provinces (19). Hainan and Yunnan accounted for 39.65% and 58.18% of the total national rubber production, respectively (Statistical Yearbook, 2022). China is the largest rubber consumer and importer worldwide, but Chinese natural rubber production capacity does not match the status of consumption (Fig. 1), and there is a contradiction between supply and demand. The General Office of the State Council of China issued the Opinions on Promoting the Development of Chinese Natural Rubber Industry (Guo Ban Fa (2007) No. 10) in 2007, which clarified the position of natural rubber as an important strategic material and industrial raw material. In April 2022, General Secretary Xi Jinping proposed a policy to improve the natural rubber industry support in Hainan province. The policy was included in Chinese 2023 Central Document No. 1 (20). This shows that natural rubber is very important to China, and it is urgent to stabilize the natural rubber planting area and improve the comprehensive production capacity.

3.1. Cultivation pattern of rubber plantation

The evolution of the agroforestry model within rubber plantations is fundamentally linked to the strategic transformation and modernization of traditional planting methodologies. The conventional rubber plantation design predominantly features a planting matrix with inter-row and intra-row spacing of 3 meters and 7 meters (21), respectively, as shown in (Fig. 2). This configuration permits the cultivation of approximately 480 *Hevea brasiliensis* (rubber trees) per hectare. However, the relatively dense planting scheme of this model limits the under-canopy to cultivation of only shade-tolerant species, thereby restricting biodiversity.

In recent times, there has been a shift towards the wide-narrow row planting structure in rubber agroforestry

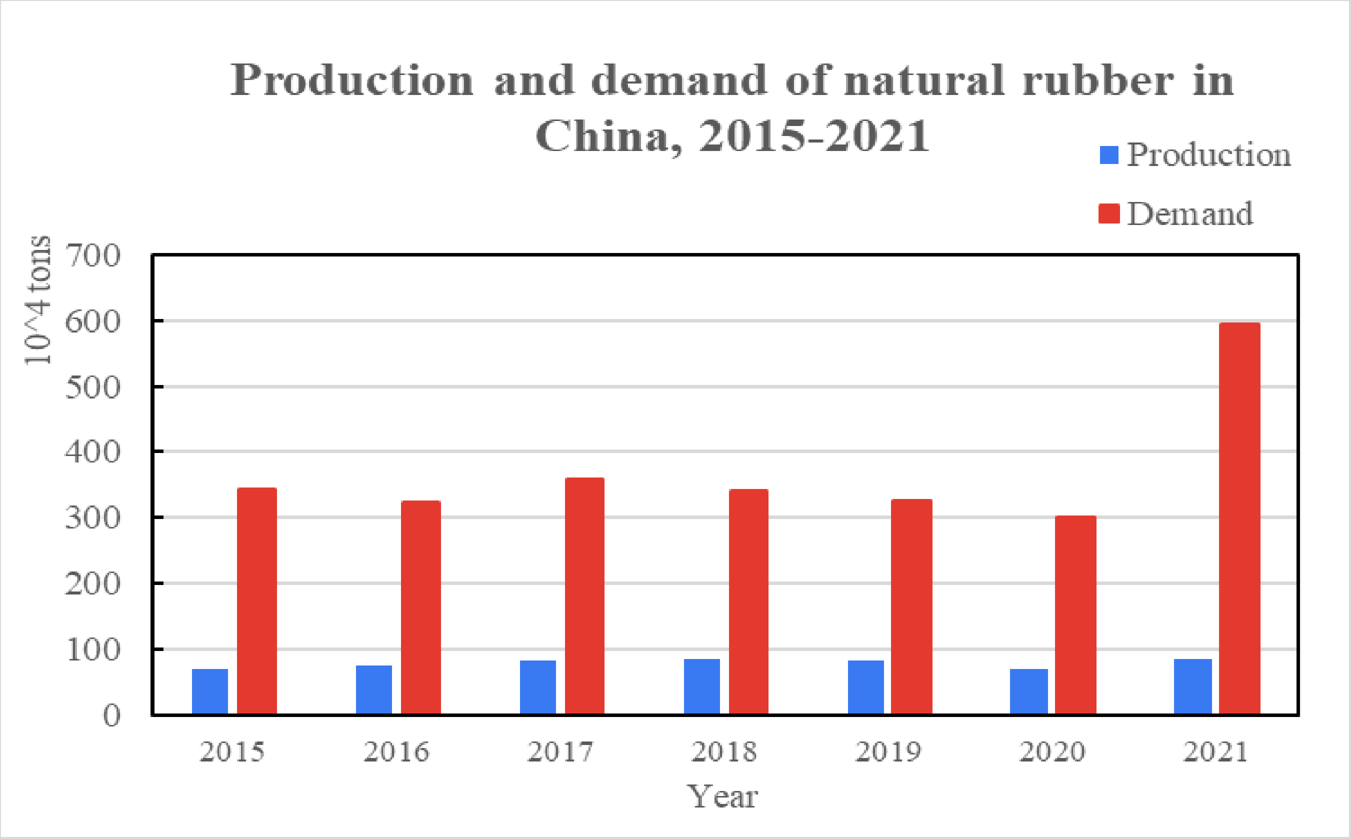


Fig. 1 Production and demand of natural rubber in China, 2015-2021 (Collection from open data)

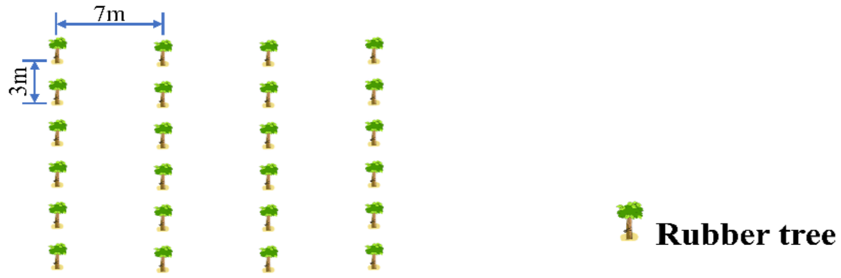
(22). This approach is characterized by alternating row spacings 20 meters (wide) and 4 meters (narrow), with a tree spacing of 2 meters, as shown in (Fig. 2), averaging around 420 rubber trees per hectare (17). Empirical studies indicate that this innovative planting pattern not only yields dry rubber quantities comparable to the traditional model but also offers enhanced resistance to wind, lower incidence of bark necrosis, and maintains tree verticality for extended periods without the need for crown pruning (23). The wide-narrow row configuration significantly improves air circulation and light penetration, thereby augmenting photosynthetic efficiency and reducing susceptibility to pathogen and pest infestations. Furthermore, the wider spacing allows for the intercropping of diverse cash crops such as konjak (24), coffee, potato, sugarcane, pineapple, soybean, banana, and medicinal plants native to southern China (25). These crops are selected based on their compatibility with the local climatic conditions and contribute to an increase in the economic yield per unit area. Despite its benefits, the wide-narrow row pattern is not without limitations. Primarily, its application is constrained to regions with flat topography, as the narrower rows are challenging to cultivate in varied terrain. Additionally, the elongation of the rubber tree canopy towards the narrower rows can result in shading of intercropped species (26), potentially impacting their growth and yield.

3.2. Diversity and Cultivation of Rubber Tree Varieties in China

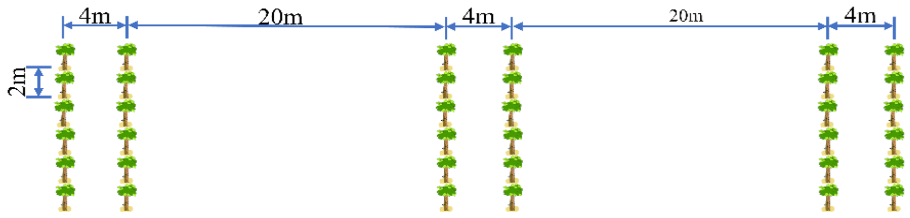
Hevea brasiliensis, commonly known as the rubber tree, originates from the equatorial climate of the Amazon River Basin in Brazil. Its cultivation in China dates back to 1906. The Chinese approach to rubber tree variety selection and breeding adheres to a principle that emphasizes conventional breeding methods as foundational, complemented by trials involving either introduced or indigenously bred varieties. The principal cultivated varieties in China are primarily derivatives of wild species initially introduced by Wei Kehan from the Brazilian Amazon. Additionally, a significant proportion of self-bred varieties in China originates from a few clonal lines introduced from Southeast Asia (27), including PR107 and RRIM600. Currently, over ten varieties, such as RRIM600, PR107, GT1, Reyan 7-33-97, and Yunyan 77-4, are cultivated (21, 28), with traditional varieties like RRIM600, PR107, and GT1 being predominant. The combined cultivation area of PR107 and GT1 accounts for approximately 70%, and the adoption of other novel varieties is increasing annually. Regionally, Hainan Province primarily plants RRIM600 and PR107, with Reyan 7-33-97 increasingly supplanting these (29). In Yunnan Province, GT1 and RRIM600 are prevalent, with newer varieties like Yunyan 77-2 and Yunyan 77-4 gradually gaining prominence (30). In Guangdong Province, the choice of variety varies due to environmental and climatic diversity (31), with Yunyan 77-4 and Reyan 7-33-97 being commonly cultivated.

3.3. Rubber Varieties as Timber: Production and Market Potential

Beyond natural rubber production, rubber trees are also a source of timber. Rubber timber, characterized by its short production cycle, high yield, cost-effectiveness, appealing aesthetic qualities, and moderate density, presents significant market potential (32). The renewal of rubber plantation yields approximately 40 cubic meters of timber per hectare, contributing to an annual production of around 1.2 million cubic meters of rubber logs. As the world's largest importer of wood, pulp, and paper



A:Conventional rubber plantations(row spacing: 7m; tree spacing: 3m)



B: Rubber plantations in wide- narrow rows
(wide-row spacing: 20m; narrow-row spacing: 4m; tree spacing: 2m)

Fig. 2 Schematic diagram of conventional and wide-narrow row rubber plantation planting pattern products, China faces an expanding domestic timber market gap. Therefore, rubber wood's market prospects are extensive (33). The promotion of varieties excelling in both rubber and timber production, such as Reken 523, Reken 525, and Reken 628 (34), could enhance the availability of high-quality rubber wood resources, thereby alleviating pressure on the timber market. These varieties are notable for their early maturity, high yield, rapid stem circumference growth post-harvest, extensive crowns, thick branches, and substantial standing timber volume per plant.

4. Diversified Agroforestry Practices in Rubber Plantations

An Age-Dependent Approach in China's Hainan, Yunnan, and Guangdong Provinces. The current research status in agroforestry practices and innovations for rubber plantations under-forest in China reflects a growing interest and commitment to sustainable agriculture and forestry management. This interest is driven by the need to address the environmental concerns associated with traditional rubber monoculture and to enhance the socio-economic benefits for rural communities.

4.1. Integrated Rubber Agroforestry Systems:

Integrated Rubber Agroforestry Systems (IRAS) under forest conditions represent a sophisticated convergence of traditional rubber cultivation with principles of agroforestry, aiming to harness the synergistic interactions between crops, rubber trees, and forest environments (35). These systems are meticulously designed to mimic natural forest ecosystems, thereby enhancing biodiversity, improving soil structure and fertility, and promoting ecological balance. By integrating rubber trees with a diverse array of plant species, including both agricultural and native forest species, IRAS under forest conditions not only optimizes land use but also contributes significantly to the socio-economic resilience of rural communities. Such systems offer a multifaceted approach to rubber production, emphasizing sustainability, environmental stewardship, and economic viability (17). Through the strategic selection of compatible species and management practices, these agroforestry systems are capable of producing rubber while simultaneously providing ecosystem services, such as carbon sequestration (36), water regulation, and habitat provision for biodiversity, thereby embodying a model of agricultural innovation that aligns with global sustainability goals (37). Research is ongoing to design and evaluate integrated systems that combine rubber cultivation with other crops and trees. These systems aim to mimic natural forest ecosystems, enhancing biodiversity and improving soil health (38).

4.2. Inter-cropping and Diversification:

Studies focus on the inter-cropping of rubber with other crops or trees, such as coffee, tea, fruits, and nuts, to increase biodiversity, reduce economic risk, and improve farmers' income. In the provinces of Hainan, Yunnan, and Guangdong in China, agroforestry systems characterized by the integration of rubber trees (*Hevea brasiliensis*) with various understory crops have been progressively implemented, exhibiting distinct variations according to the age of the rubber plantations (35,36). These plantations are categorized into three age groups: nascent (within two years), intermediate (3-5 years), and mature (over six years). The age classification correlates directly with the canopy density of the plantations, influencing the photic environment and subsequently dictating the selection of compatible understory crops based on their photo tolerance mechanisms. While rubber production may be lower per hectare in diversified systems than in monoculture, total productivity and other environmental benefits must be considered, especially given the fluctuations in rubber prices. Another way to improve the profitability of rubber production systems is to increase the use of rubber wood (39). Several crops and trees can be interspaced at different stages in a rubber plantation, providing food or fiber and an additional source of income (40), including cocoa, coffee, tea, sesame, fruit trees, rice, tubers, as well as livestock (41,42).

In nascent rubber plantations characterized by sparse canopy coverage and ample sunlight, a wide array of crops can be cultivated. This includes species like *Arachis hypogaea* (peanuts), *Saccharum officinarum* (sugarcane), *Coffea sp.* (coffee), *Musa spp*. (bananas), *Ananas comosus* (pineapples) and traditional upland rice varieties, such as Shanlan rice, alongside green manure crops (43). Intermediate-aged plantations, with a canopy density of less than 60%, provide a suitable environment for shade-tolerant species. This category includes various Southern medicinal plants and forage grasses, with examples like *Alpinia oxyphylla, Millettia speciosa, Morinda officinalis,* and *Amomum longiligulare*.

Moreover, these intermediate plantations offer potential for integrated 'Forest-grass-livestock' systems, where grasses planted within the plantation serve as fodder for livestock. In contrast, mature plantations with a dense canopy favor the development of 'Forest-fungus' and 'Forest-fowl' systems. The 'Forest-fungus' model, in particular, capitalizes on the shaded understory to cultivate edible fungi, utilizing agricultural and forestry by-products and optimizing the use of spatial, light, and thermal resources. These agroforestry practices not only contribute to sustainable development and ecological enhancement but also elevate the income levels of local farmers, thereby presenting significant ecological and socio-economic benefits.

4.3. Biodiversity Assessment

Different studies are dedicated to assessing the impact of rubber agroforestry systems on biodiversity, comparing these systems' species richness and ecosystem health to those of monoculture plantations and natural forests. According to a study, the land that has been converted to rubber plantations includes a variety of natural and cultivated lands, much of which were of high value for biodiversity conservation, landscape functioning, and/or food security (44). Rubber plantations under forests can avoid negative effects on communities and preserve areas that are important for biodiversity conservation or other environmental issues (39). They can also orient rubber expansion towards degraded land. Rubber yields vary, depending on access to high-yielding clones and efficient management practices. Reducing this yield gap is the single most efficient way to avoid further land conversion. Using better management practices can also contribute to reducing the impacts of rubber cultivation: efficient nutrient and pest management can reduce pollution of ecosystems; integrating rubber into diversified systems can reduce the need for additional land clearance for food production; and changes in management practices can increase biodiversity (45).

4.4. Ecosystem Services Evaluation

Fig. 3 Rice intercropping under rubber forest

Fig. 4 "Forest-grass-livestock" pattern

Fig. 5 "Forest-fungus" pattern of rubber plantation

There is significant interest in quantifying the ecosystem services provided by rubber agroforestry systems, including carbon sequestration, water regulation, and soil fertility enhancement (46, 47). Different types of production systems have different impacts on the ecosystem, with greater biodiversity in plantations that have greater complexity in habitat structure and agroforestry ecosystems supporting some forest species not found in monocultures. More studies are needed to compare the effects on biodiversity of different spatial organizations, to understand interactions between species ecosystems in complex systems, and to study the effects of plantation management practices (e.g. pest control) on ecosystems.

4.5. Agroforestry effects on climate Change:

Incorporating rubber trees into various agricultural systems can aid in their adaptation, as rubber tree plantations, when properly managed (43), can replicate the evaporative cooling and moisture recycling functions of tropical rainforests (48). In Sri Lanka, rubber cultivation has been identified as a viable alternative to conventional short-term rain-fed agricultural practices, offering a solution to the challenges posed by climate change (45). The anticipated advantages include a potential decrease in mid-day temperatures within the plantation area by as much as 6°C, with an average daytime reduction of 3.7°C, alongside the capability to maintain up to double the amount of moisture in the surface soil. This not only enhances the working conditions for farmers but also serves as a means of diversifying their sources of income (49).

5. Challenges and Adaptive Strategies in China's Natural Rubber Plantation

In recent years, the natural rubber sector in China has confronted multifaceted challenges, significantly impacting its productivity. These challenges, rooted in climatic, pathological, and economic factors, have led to a marked decline in rubber production (50). Concurrently, a decrease in the market value of dry rubber coupled with escalating labor expenses has catalyzed a trend where local cultivators increasingly neglect the maintenance and harvesting of rubber plantations. Illustratively, in 2022, there was a 2.10% reduction in China’s natural rubber output compared to the preceding year. This downturn is primarily attributable to several key factors: the postponement of harvesting activities in Hainan due to an outbreak of powdery mildew disease, constraints on rubber production and raw material logistics amid COVID-19 pandemic containment measures, and the detrimental impacts of a tropical storm.

This decline in rubber prices, paralleled by the withdrawal of farmers from active cultivation and management, has engendered a detrimental cycle, adversely affecting the industry. In response to these challenges and to foster the sustainable and robust development of the rubber industry, innovative composite forest economy models are being proposed and implemented in various regions. A notable example is Baisha in Hainan Province, where local authorities are undertaking proactive measures to rejuvenate and restructure rubber plantations. This includes modifying the spatial arrangement of rubber trees to optimize the under-canopy light environment and introducing intercropping systems with agricultural products such as pineapples, melons, vegetables, and mushrooms (24, 51). This diversification strategy aims to augment the income streams for rubber farmers. Furthermore, the establishment of rubber cooperatives in the region, promoting a "three unification" system - encompassing unified management, marketing, and financial guarantees - has effectively enhanced rubber prices and rejuvenated farmer engagement in rubber plantation management. These adaptive strategies demonstrate a concerted effort to mitigate the current challenges and ensure the long-term viability of China's natural rubber industry.

5.1. Selection and breeding of rubber tree varieties

The advancement of the rubber under-forest economy in China necessitates an optimal under-forest environment, rendering the selection of appropriate rubber tree cultivars paramount. Favoring single-trunk phenotypes for rubber trees is advisable due to their superior wind resistance and reduced canopy coverage, thereby enhancing the penetration of sunlight and warmth essential for the growth and productivity of intercropped species. To maximize the utility of rubber plantations, it is recommended to prioritize varieties that excel in both latex yield and timber quality, enabling the production of superior-grade lumber for industrial applications without compromising latex output. Given the susceptibility of China's rubber-growing regions to periodic cold spells, the introduction of cold-tolerant rubber tree varieties is critical. Such selections focus on enhancing latex yield, disease resistance, climate adaptability, and growth rate. This involves collecting genetic material from diverse sources, conducting traditional and molecular breeding programs, and implementing rigorous field trials to assess performance. Data analysis identifies the best-performing varieties, which are then propagated and distributed to farmers. Sustainable practices, such as integrated pest management and agroforestry, are emphasized to ensure environmental balance. Continuous improvement through ongoing research and collaboration with institutions and stakeholders is essential to meet industry demands and promote profitable rubber cultivation, not only bolstering the resilience of the rubber industry but also serving as valuable benchmarks for the development of cold-resistant strains in other tropical crops, thereby contributing to the diversification and sustainability of tropical agriculture.

5.2. Distribution of light intensity and duration in different locations

Variations in solar irradiance and photoperiod across different positions within the same rubber agroforestry system are attributed to the differential interception of sunlight by the canopy of rubber trees (52). Specifically, when considering a wide and narrow row spacing arrangement, there is a gradational increase in light intensity and duration from the rubber trees towards the midpoint of the wider inter-row spaces. In these central zones, where light availability is augmented, it becomes feasible to cultivate heliophilous (light-demanding) crops such as bananas, pineapples, tomatoes, and peppers. Converse, proximal to the rubber trees (53), where light penetration is limited, sciophilous (shade-tolerant) crops like konjac and tea can be successfully integrated (54,55). This strategic placement of crops, based on their photic requirements, facilitates optimal utilization of sunlight, thereby ensuring the viable growth of intercropped species without compromising the photosynthetic efficiency of the agroforestry system.

5.3. Energy flow and circulation of Forest-grass-livestock pattern

The "forest-grass-livestock" integration model exhibits several advantages in terms of reducing livestock development costs and enhancing economic efficiency. This system leverages the manure produced by livestock as a natural fertilizer for pasture grasses, thereby minimizing the reliance on chemical fertilizers. Additionally, the absence of pesticide applications on pasture grasslands mitigates the risk of drug residues in livestock feed (56). The understory environment of forests presents an optimal setting for the cultivation of pasture, where the root systems of rubber trees contribute to soil moisture retention and erosion prevention. This model capitalizes on solar energy as the primary external energy input, with pasture grasses converting solar energy into biomass through photosynthesis (57). Consequently, these grasses supply energy and nutrients to the livestock, which, through their digestive systems, transform this energy into animal tissues such as muscle and fat, yielding livestock products (58). Moreover, livestock excreta serves as a nutrient source for both rubber trees and pasture grasses. A thorough understanding of the energy flow and cycle within this system, coupled with the appropriate livestock integration, can augment the system's output while safeguarding the ecological environment.

6. Future prospects and research directions

In the future, the development of rubber under-forest economy in China should focus on the selection of rubber tree varieties, exploring the distribution of light in different locations of the under-forest, researching the energy flow and cycle of each under-forest pattern, and utilizing the economic, ecological and social benefits.

6.1. Economic, social and ecological benefits of the Forest-fungi pattern

Utilizing the Agaricus bisporus (large bulbous cap mushroom) as a case study, this analysis quantifies the economic gains derived from the "forest-mushroom" cultivation model based on average yield metrics and prevailing market valuations. The calculated minimum yield per hectare for a single cultivation cycle is estimated at approximately 4,500 kilograms. With the national floor price set at 12 RMB per kilogram, and after accounting for the comprehensive cost of production, the resultant net income increment per hectare is projected at 30,000 RMB. This figure significantly surpasses the financial returns associated with the cultivation of alternative forest-based economic crops, underscoring the substantial economic advantages offered by this model.

The advancement and implementation of the "Forest-fungus" model offers a multifaceted income stream for agriculturists, enabling revenue generation beyond the traditional agricultural harvest season and during periods of dormancy in latex-producing arboreal species. This approach enhances livelihood stability and economic resilience, playing a pivotal role in reinforcing poverty alleviation outcomes and catalyzing rural revitalization. The integration of edible fungi cultivation within forest ecosystems not only generates additional employment prospects, particularly in agrarian communities, thereby mitigating the surplus labor issue and elevating socio-economic conditions but also fosters comprehensive rural development (59). Through engagement in the agro-processing and marketing sectors, agriculturists are exposed to and encouraged to adopt, innovative technologies and skills, thereby enhancing their professional competencies.

Moreover, the utilization of agricultural and forestry by-products as primary substrates in the cultivation of edible fungi addresses environmental pollution by mitigating the accumulation or leaching of waste, thereby promoting the circular economy and resource conservation. Concurrently, this cultivation practice under forest canopies fosters the proliferation of diverse companion flora, contributing significantly to the maintenance and enhancement of biodiversity.

6.2. Economic challenges and future perspective

The sustainable integration of rubber plantations within agroforestry systems in China faces several economic challenges from a future perspective. First, the fluctuating global rubber prices pose a significant risk, affecting the financial viability of rubber agroforestry practices for smallholder farmers and investors. Such volatility can deter the adoption of sustainable practices, which often require upfront investments and time to become profitable. Second, the transition to agroforestry systems demands substantial knowledge, skill development, and initial financial outlay, potentially limiting accessibility for small-scale farmers with limited resources. Additionally, market access for diversified products from agroforestry systems remains a hurdle, as does the establishment of value chains that fairly compensate farmers for ecological services and sustainable practices (60). Moreover, the need for policy support and incentives to encourage the shift towards sustainable agroforestry is critical yet currently insufficient. Addressing these economic challenges requires a multi-faceted approach, including stabilizing rubber prices through policy interventions, enhancing market access and value chains for agroforestry products, and providing financial and technical support to farmers transitioning to sustainable agroforestry practices. Without concerted efforts to overcome these economic barriers, the potential for rubber plantations to be integrated into sustainable agroforestry systems in China may not be fully realized, posing a threat to both the environment and the long-term economic sustainability of rural communities.

6.3. Social Impacts of rubber plantation

The sustainable integration of rubber plantations within agroforestry systems in China holds profound future implications for social impacts, particularly in terms of rural livelihoods, employment opportunities, and community well-being. As this integration advances, it is poised to catalyze a transformative shift in the socioeconomic fabric of rural areas. By diversifying income sources beyond monoculture rubber plantations (49), agroforestry presents an avenue for enhancing economic resilience among smallholder farmers and rural communities. This diversification is not merely economic; it also fosters social cohesion and empowerment by encouraging collective management practices and knowledge-sharing among communities. Furthermore, the enhanced environmental sustainability of agroforestry systems promises to stabilize ecosystem services that rural livelihoods depend on, such as water regulation, soil fertility, and biodiversity, thereby reducing vulnerability to climate change and environmental degradation (38). In the longer term, the integration of rubber plantations with agroforestry systems could serve as a model for rural development in China, aligning economic development with environmental stewardship and social equity. This approach underscores the necessity for inclusive policies and supportive institutional frameworks that recognize and facilitate the multifaceted contributions of rural communities to sustainable development.

6.4. Innovation and Technological Advances:

Innovation and technological advances hold transformative potential for the sustainable integration of rubber plantations within agroforestry systems in China, charting a promising path toward a resilient and environmentally harmonious agricultural future. As we look ahead, cutting-edge research and development in genetic improvement, precision agriculture, and ecological monitoring are poised to revolutionize rubber cultivation practices. Genetic engineering and selective breeding are expected to produce rubber tree variants with enhanced yield, disease resistance, and adaptability to diverse climatic and soil conditions, ensuring productivity while minimizing ecological footprints. Precision agriculture technologies, including satellite imagery, drones, and IoT-based soil and crop monitoring, will enable precise resource management, optimizing water usage, nutrient application, and pest control, thereby reducing waste and environmental impact. Moreover, innovations in ecological monitoring will facilitate a deeper understanding of agroforestry systems' dynamics, empowering stakeholders to maintain ecological balance, enhance carbon sequestration, and preserve biodiversity (61). These technological advances, coupled with a strong policy framework and stakeholder collaboration, will be crucial in realizing the full potential of rubber agroforestry systems in China, ensuring economic viability, ecological integrity, and social equity for future generations.

6.5. Natural rubber: A key resource for sustainability in the modern world

Developing low-emission strategies necessitates creative approaches to utilizing our finite resources, replacing energy-intensive non-renewable materials, and rethinking production processes to minimize waste (39). Within this framework, natural rubber (NR) emerges as a potential cornerstone for a forest-based circular bioeconomy, thanks to its renewable nature. There's a need for further investigation into the environmental and social sustainability of natural rubber compared to synthetic alternatives. To maximize its role as an eco-friendly substitute, research is underway to enhance the properties of NR, with applications in foam and adhesives being tested in pre-commercial environments (62). Importantly, diversifying the applications of natural rubber can open up new markets and reduce its reliance on the fluctuating tire industry, potentially stabilizing prices. Significant advancements are also being made in the reuse and recycling of natural rubber, particularly in tires, to improve raw material efficiency and foster a circular economy, thereby creating long-term carbon sinks (63).

6.6. Role of rubber in climate change mitigation

A range of research has explored how rubber might play a role in combating climate change, revealing that rubber plantations can act as carbon reservoirs, comparable to those of cocoa plantations or certain types of agroforestry and forestry systems, with the effectiveness varying by the age of the plantation (64). It has been suggested that extending the growth cycles of rubber plantations could lead to increased carbon storage (63). The contribution of natural rubber (NR) to climate change mitigation must be evaluated against a broader backdrop of greenhouse gas emissions. Rubber plantations (47) can serve as valuable carbon sinks when established on previously degraded land, but converting existing forests or swidden (slash-and -burn) agriculture into rubber plantations may result in net carbon emissions, with the degree of impact being variable (65). An example of this is research by (66), which assessed carbon storage in rubber cultivation compared to swidden agriculture in Northern Laos, finding that rubber plantations maintained for 30 years can secure a larger carbon stock than a swidden system left to fallow for five years, even when accounting for emissions from soil preparation before planting rubber. Nonetheless, this environmental advantage is negated if the expansion of rubber plantations leads to the displacement of swidden agriculture, which then encroaches on natural forest areas.

6.7. Adaptation to Climate Change

Adaptation to climate change is a critical future perspective for the sustainable integration of rubber plantations within agroforestry systems in China. As global climatic patterns become increasingly unpredictable, the resilience of agricultural and forestry systems to these changes is paramount. In the context of rubber plantations, integrating agroforestry practices offers a promising avenue for enhancing system adaptability and mitigating climate change impacts. By diversifying plantation ecosystems with a mix of tree species and crops, these systems can buffer against extreme weather events, reduce vulnerability to pests and diseases, and maintain soil health and water availability. Furthermore, such diversification can improve carbon sequestration, contributing to climate change mitigation efforts. As China looks to the future, research and policy must focus on developing agroforestry models that are not only economically viable but also climate-resilient. This entails investing in breeding programs for climate-adapted rubber varieties, exploring innovative water-saving irrigation technologies, and fostering farmer knowledge and capacity in sustainable land management practices. The goal is to create a rubber plantation economy that is both productive and sustainable, securing the livelihoods of rural communities while preserving the ecological integrity of the landscape.

Conclusion

The sustainable integration of rubber plantations within agroforestry systems in China offers economic, ecological, and social benefits. By combining rubber trees with other crops like bananas, pineapples, medicinal plants, and fungi, farmers can diversify their income and enhance biodiversity. These systems improve carbon sequestration, soil health, and water retention, aiding climate change mitigation. Despite benefits, challenges such as fluctuating rubber prices and limited market access persist. Addressing these requires policy support, financial incentives, and technical training for farmers. Overall, this integration promises balanced economic growth, environmental sustainability, and social equity, securing rural livelihoods and preserving ecological integrity for future generations.

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