Environmental and socio-economic impacts of rubber cultivation in the Mekong region: challenges for sustainable land use

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Abstract

More than 90% of the global natural rubber production originates from monoculture plantations in tropical Asia, especially from countries forming the Greater Mekong Subregion (GMS). Rubber cultivation is expected to further increase strongly in the near future, particularly at the expense of natural forests, and is accompanied by various problems and threats to farmers and the environment. Implications on carbon balance and hydrological conditions as well as socio-economic consequences referring to the situation in the GMS are reviewed. Results indicate considerable changes in ecosystem functions and services at different spatial and temporal scales with impacts on carbon stocks and sequestration, water quality and quantity, runoff and soil erosion. The long-term dependency on rubber as a single crop affects the socio-economic conditions and livelihood of the farmers and exposes them to economic and ecological hazards. Solutions for these interrelated problems require the development of alternative land-use systems and safeguarding important ecosystem functions and services on the one hand as well as providing economic viability on the other. Common suggestions include crop diversification and improved plantation management on the farm scale, and alternative land-use strategies including conservation and restoration of forest on the landscape scale. Successful implementation of more sustainable concepts is only feasible within a socio-economic framework, involving farmers and political decision-makers in the conceptualization process and the identification of trade-offs between ecological requirements and economic feasibility.

Keywords: Land-use change, Land-use scenario, Intercropping, Deforestation, Livelihood

Review Methodology: We used the Scopus bibliographic database for the current state of knowledge, and 'rubber' as the basic keyword in combination with various other terms related to our review topic. We also considered relevant references from the articles obtained by this method. All authors are researchers in the presently (2012–2016) conducted German–Chinese joint project SURUMER (Sustainable Rubber Cultivation in the Mekong Region, https://surumer.uni-hohenheim.de) and contributed further information according to their specific background and literature sources.

Introduction

Natural rubber is an important primary product in the global economy and is found in many commonplace items. It is obtained from latex, the sap of the rubber tree (*Hevea brasiliensis* Muell. Arg). By far the biggest proportion (70%) of this natural resource is used in the tyre production [1, 2]. Considering all rubber-based products, the vehicle industry claims around three-quarters of the world production.

Although the rubber tree is native to Amazonia, more than 90% of the total natural rubber originates from tropical Asia [3]. The top five producing countries presently are Thailand, Indonesia, Malaysia, India and Vietnam. Demand for rubber increased enormously with the economic upturn in Asia and is expected to further increase strongly in the near future. In 2011, China used one-third of the natural rubber produced worldwide – more than the consumption by the European Union member states, USA and Japan combined [2]. Consequently, rubber cultivation has grown enormously within the last few decades, especially in the so-called Greater Mekong Subregion (GMS), comprising the countries bordering the Mekong River (Cambodia, Laos, Myanmar, Thailand, Vietnam and the Chinese province of Yunnan).

In Vietnam, the plantation area covered about 910 000 hectares (ha) by the end of 2012, including about one-third of trees too young for tapping [4, 5]. This is twice the area compared with 2004 [6]. In the north-eastern provinces of Thailand, the rubber cultivation area expanded from 42 000 ha in 2002 to 288 000 ha in 2011, an increase of 580%. In the same period, the forest area in this region declined by 18% and the area of agricultural land by 50% [7]. In Laos, about 140 000 ha of rubber were planted by 2008, and this area is expected to double within the next decade [8]. In Cambodia and Myanmar, the cultivation area is expected to grow strongly in the near future [9]. In Xishuangbanna, in the southern part of Yunnan Province (China), rubber cultivation area increased from 153 000 to 424 000 ha between 2002 and 2010, equivalent to 175%. This expansion mainly occurred at the expense of natural forests [10, 11]. In 2012, the total harvested area of rubber in the GMS countries was more than 3.5 million ha[1]. Li and Fox [9] estimated additionally more than 500 000 ha of young trees not yet producing rubber. If the present expansion of rubber continues, the cultivation area in the GMS could quadruple by 2050 [12]. Expansion is also likely to shift rubber production further into higher altitude and latitude. New genotypes (clones) of rubber are able to tolerate dry periods and lower temperatures without important loss of latex yield. Plantations have now expanded to 27°N latitude, to elevations up to 1100 m [13]) and into dry subhumid areas of the GMS [14]. Furthermore, projected impacts of climate change in Xishuangbanna indicate that the area conductive to rubber plantations, currently limited by climatic conditions, expands to approximately 75% of the total area [15].

The large expansion of rubber cultivation and the additional yield expected from the developing young trees, however, lead to an increase in harvested rubber stocks, because the global yield is higher than the industrial demand. The global natural rubber market was oversupplied with a surplus of 220 000 tonnes (t) in 2011, and with 410 000 t in 2013. This trend is expected to continue. In consequence, global natural rubber prices declined [18].

In the GMS, rubber is produced almost exclusively in monoculture plantations (unlike in Indonesia, where rubber is often part of mixed agroforestry systems). New plantations are usually established on bare soil after clearing the former vegetation, terracing is carried out on slopes. Latex harvest begins at a tree age of 7 years, maximizes at 20 years and typically ceases at around 35 years, leading to the end of the economic lifespan. Finally, the trees are cut and a new cultivation cycle starts.

Consequences of the Rubber Boom

Natural rubber is a renewable resource. This characteristic is often stressed by national and private companies, the rubber industry as well as by traders of rubber products (e.g. mattresses, toys and rubber wood furniture) to suggest that rubber cultivation is climate-smart and environmentally friendly. However, renewable does not necessarily mean sustainable. The shift from tropical forests and traditionally managed swidden fields to large-scale rubber monoculture results in a loss of ecosystem services [19] and significant changes in ecological functions, socio-economic conditions and human welfare. In the following, important indications for these effects referring to the situation in the GMS are reviewed.[2]

Impacts on carbon balance

Deforestation and burning of natural tropical forests has significant impact on the global carbon cycle by decreasing the above- and below-ground carbon stocks and by increasing rates of carbon emissions to the atmosphere [20]. Deforestation contributes 12–15% of the total

[1]Based on FAOSTAT data of 2012, Area harvested [16]. The specifications for China include Hainan island with a plantation area of around 500 000 ha [17]. For Laos, no FAOSTAT data are available, here the data of Douangsavanh *et al.* [8] of 140 000 ha in 2008 were used.

[2]Impacts of rubber cultivation on biodiversity are reviewed in a separate article submitted to CAB Reviews (He P, Martin K. Effects of rubber cultivation on biodiversity in the Mekong Region).

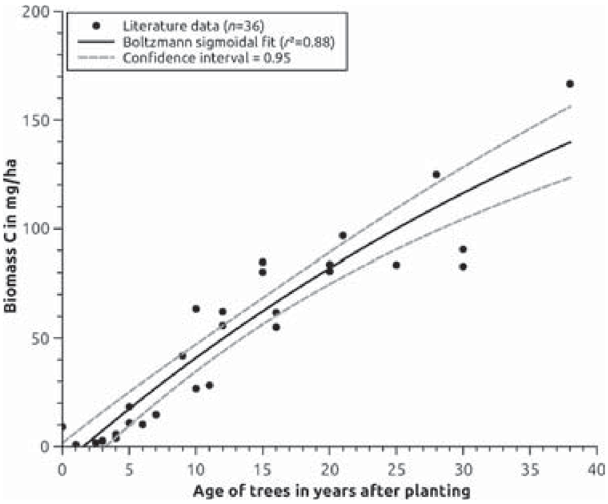

Figure 1 Above-ground biomass in rubber plantations. Sources [25–32]

anthropogenic CO_2 emissions, from both biomass and soils [21]. Li *et al.* [22] estimated changes in biomass carbon stocks in Xishuangbanna (Southern Yunnan, China). They found that in the past, when the region was completely forested (1.9 million ha), the total carbon biomass would have been approximately 212 Tg. Owing to deforestation and forest degradation, the total carbon stock decreased to 81 Tg in 2003.

However, there are great uncertainties in carbon in the total ecosystem for several major land covers that are related to important land-use transitions (including rubber) in Southeast Asia [23]. For example, there is a high variability in below-ground woody carbon. Data from naturally grown forest in the GMS and Malaysia range between 11 and 74 Mg C/ha, and rubber plantations from GMS countries show 5–32 Mg C/ha in root biomass [24].

The changes in carbon balance by conversion of natural tropical forest into rubber plantations depend on the amount of carbon released by forest destruction and the amount of carbon sequestered by the plantations. We used 38 data sets on biomass accumulation in rubber to calculate a single graph (Figure 1). It shows a steady increase of carbon stock in young and mid-age rubber plantations. Integration of the fitted equation returns a time-averaged rubber biomass of 120 ± 40 Mg C/ha for 30 years after planting. Yang *et al.* [33] calculated a time-averaged rubber biomass of 97 Mg C/ha in a Xishuangbanna study site for a 25-year period. This result falls in the range of our calculated curve.

For Southern Yunnan, Cotter *et al.* [34] estimated that clearing of 1 ha of relatively undisturbed tropical seasonal rainforest releases about 438 t of CO_2. A rubber plantation in the same region below 800 m sequesters approximately 192 t C/ha (equivalent to 703 t CO_2/ha) during its lifetime of 30 years (given a litter mass of 107 t C/ha and a latex output of 23 t C/ha). Consequently, a fully grown rubber plantation needs around 20 years to re-sequester the amount of CO_2 released by forest clearance. However, this balance ignores changes in the soil carbon pool, i.e. the amounts of carbon released by forest conversion and the soil carbon sequestration under rubber plantations. The extent of change in soil carbon pools strongly depends on mean annual precipitation and dominant soil clay mineralogy [35]. Land-use change in the tropics from forest to plantation usually reduces total soil carbon stocks by roughly 5% on average [35].

For change of secondary forest into rubber plantations in Xishuangbanna, Yunnan, de Blécourt *et al.* [36] found a reduction of nearly 20% of the initial soil carbon in a total soil depth of 1.2 m. In the topsoil (0–15 cm), the largest decrease was in the first 5 years following land-use change, when soil carbon stocks declined to approximately 80% of the original amount. The carbon stock reached a steady state after approximately 20 years at 68% of the original stock. Similarly, Yang *et al.* [37] found soil carbon losses of 24% in a 3-year-old plantation and 21% in a 7-year-old plantation within a depth of 0–6 m. Zhang *et al.* [38] confirmed that the soil carbon level decreases in the growth phase of the plantations, but found that it begins to rise again after an age of 26 years to reach its maximum at 40 years. This change in soil organic pools correlated negatively with latex yield.

Furthermore, there is evidence that conversion of secondary forest into rubber plantation significantly decreases soil microbial biomass carbon [39]. According to Werner *et al.* [40], 20-year-old rubber plantations show a lower CH_4 uptake and lower CO_2 emissions compared with primary and secondary forest sites. However, they suggest that the soil moisture and litter fall are important factors influencing carbon emissions which depend not only on climate, but also on rubber plantation age.

Quantification of rubber plantation carbon stocks and sequestration also provides a base for carbon trading options. Yi *et al.* [41] estimated the carbon payments required to equal the potential rubber revenue for local farmers by comparing three land-use scenarios. They conclude that the prices in the carbon market would have to be considerably larger than they are currently to compete with the profitability of rubber.

Besides the conversion of forests, rubber plantations in the GMS also expand on the expense of various types of open land such as grassland, fallows and abandoned swidden fields. Preparation of such land-use types for rubber releases significantly less carbon from plant biomass into the atmosphere than forest. For Southern Yunnan, Cotter *et al.* [34] estimated a release of 110 t/ha CO_2 from shrub-land, 19 t/ha from grassland and 438 t/ha from seasonal rainforest. For soil carbon, Powers *et al.* [35] found that the establishment of perennial tree plantations on lands that were previously grazed or cropped increased soil carbon stocks, whereas the conversion of grasslands shows no change. Fallow or swidden land may include a wide range of different stages of natural succession between degraded grassland and secondary forest. Therefore, according to analyses of Ziegler *et al.* [23], transitions from swidden agriculture to rubber plantations do not necessarily produce positive carbon outcomes.

Studies from Zhou *et al.* [42] in Xishuangbanna indicate that in tropical seasonal rainforests carbon export via stream flow changes the carbon balance only modestly. The carbon stock in rubber plantations is affected by factors such as fertilization, the management of the undergrowth vegetation and site characteristics.

Large-scale rubber plantation in Xishuangbanna has increased the rate of soil loss by more than 50% [43]. Nuanmano *et al.* [44] report erosion rates of about 100 Mg/ha/a from a rubber plantation area in Thailand. This rate can be considered as severe erosion. It is twice as much as shown from the erosion data summarized by Wiersum [45], who states median values from below 1 Mg/ha/a for tree crops planted with cover crops or mulched to over 50 Mg/ha/a for clean weeded plantations with removed litter. Erosion in rubber plantations on sloping land depends on management practices and varies in a wide range. Terraces parallel to contours may alleviate soil organic carbon losses caused by the conversion of secondary forest to rubber plantation [46] and may reduce soil erosion. Rubber planting induces not only soil carbon loss, but is also found to lead to extensive humification [47], acidification and changes in the composition and quantity of nitrogen compounds [48–50].

Impacts on the hydrological cycle

With proceeding land-use, conversion of forest into rubber plantation, effects on climate as well as on water availability are reported. The average temperature of rubber-producing areas in Xishuangbanna increased significantly since 1960s, while the regions without rubber in Yunnan showed no change [51]. There was also strong reduction in the number of fog days in Xishuangbanna since the 1950s [52, 53]. Observations in Xishuangbanna also indicate a reduced streamflow and dried up wells [54]. Such circumstances suggest that rubber cultivation affects the local and regional water balance through the eco-physiological characteristics of rubber trees and by the plantation design and management.

Comparative studies in different catchments of Xishuangbanna by Tan *et al.* [55] confirmed that evapotranspiration from rubber plantations is 15–17% higher than in primary rain forest and therefore considered rubber trees to act as ‘water pumps’. Tan *et al.* [55] concluded that soil water storage during the rainy season is not sufficient to maintain the high evapotranspiration rates in rubber plantations, resulting in zero flow and water shortages during the dry season. Studies by Liu *et al.* [56] showed that rubber trees extract their water mostly from the top 30 cm of the soil in the rainy season. During the late dry season, the depth of water uptake shifts to deeper soil levels. Rubber is a brevi-deciduous tree, because trees older than 3–4 years shed senescent leaves. After leaf shed, trees remain nearly leafless for up to 4 weeks. Whether this process is induced by drought [57] or day length [58] is not yet clear.

Guardiola-Claramonte *et al.* [58] indicated that at a secondary forest site root water uptake is linked to water availability in the form of rain. In Xishuangbanna, native forest trees rehydrate after occasional rain events during the dry season, or shortly after the start of the rainy season [58]. In the same region, leaf flushing in rubber occurs at the midst of the hottest and driest period, weeks before the rainy season starts. Flushing leaves during the dry season imply that the tree must have access to sufficient reserves of water for leaf expansion. Therefore, Guardiola-Claramonte *et al.* [58] claimed that the additional stem potential needed for flushing is acquired through deep subsurface water uptake. Water storage depletion from the subsurface soil during the dry season increases water losses through evapotranspiration and reduces discharge from the catchment [59]. Carr [57] found the validity of these assumptions difficult to reconcile. In a review, on studies on water requirements of rubber, he found that few publications concerning water requirements of rubber trees exist, but they all show (maximum actual) evapotranspiration rates lower than might be expected for a tree crop growing in the tropics. Kobayashi *et al.* [60] used sap flow measurements to study variations in transpiration rate in a rubber stand in Cambodia. Their results indicate that rubber trees actively transpire in the rainy season, but become inactive in the dry season. Kobayashi *et al.* [60] argue that depletion in deep-soil moisture or stream desiccation due to large water uptake by rubber trees may partly be explained by the low ability of rubber trees to conserve the soil water, but high evapotranspiration could also be attributable to other water loss components, e.g. wet-canopy evaporation, soil evaporation and transpiration of understory vegetation. To obtain a clear picture of the water budget of a rubber plantation and predict the sustainability of rubber cultivation with regard to its water use, processes at different scales, i.e. canopy, trees and leaves, need further investigations in a comprehensive manner [60].

Another approach to explain the reduction in fog and streamflow is the diffuse reflection of light (albedo) from the canopy of rubber plantations, expressed through the ratio of the reflected solar radiation to the incoming solar radiation. Among other parameters, it depends on plant cover, i.e. leaf area index [61]. Rubber plantations were found to have a lower leaf area index than secondary forest [62], leading to the assumption that the albedo of rubber is higher than natural forests. With a higher albedo, radiation transfer increases back to space, reducing clouds and rainfall [63]. Therefore, canopy characteristics rather than water use patterns of rubber plantations might account for the observed hydrological changes in the Xishuangbanna region.

Rubber plantations in Xishuangbanna show an increased surface water runoff [64], resulting in a soil erosion rate that is 40 times higher than in tropical forests [52]. Since rubber cultivation largely expands to steep elevations, this will increase the probability of landslides, the risk of destructive flooding of rivers and hydraulic stress for aquatic species. Increasing amounts of deposited sediment on the river bed reduces living space for macro-invertebrates and juvenile fish by clogging the pore space of the river bed. This results in a loss of fish habitats and in a reduction of biodiversity in the aquatic fauna [65]. Rubber cultivation areas could also affect downstream regions, including effects on hydropower projects planned or existing in the Mekong river basin (see [66]).

The conversion of natural forest and traditionally managed swidden fields into rubber plantations also affects the quality and quantity of ground- and surface water. According to Tang *et al.* [67], farmers in Xishuangbanna reported changes in the water resources in the last few years, especially a drop of the groundwater level, and the villagers have to buy bottled drinking water [68]. Many farmers approve that rubber cultivation is one of the factors causing potable water shortage [69]. In addition, rubber production in monocultures requires the use of high amounts of pesticides and chemical fertilizers [54, 70]. These agrochemicals enter the aquatic system by rainfall-induced wash-off, threatening water quality for humans and aquatic organisms.

Effects on socio-economic conditions and livelihood

In the GMS countries, three types of producers cultivate rubber: state-owned companies or farms, private entrepreneurs and smallholder farmers with portions varying by country. Smallholders comprise between 20 and 40% in Laos, Cambodia and Vietnam, 50% in China and about 90% in Myanmar and Thailand [71]. Free market and the lure of cash encouraged numerous private smallholders to give up their traditional land-use and turn to rubber over the last two decades.

Rubber cultivation can result in significant increases in household income and is hence a possibility to move households and communities out of poverty. Manivong and Cramb [72] found positive net present values for investments in smallholder rubber production in northern Laos, and Liu *et al.* [73] observed a threefold increase in per capita income and expenditures over a period of 15 years due to rubber production in a township of Xishuangbanna, Yunnan. Farmers switching from swidden agriculture to rubber cultivation profited the most, and ethnic minorities in Southern Yunnan even expanded rubber cultivation into neighbouring Laos [74].

In addition to smallholders, private entrepreneurs from China, Vietnam, Malaysia and Thailand invest heavily in rubber plantations in non-traditional rubber-growing areas of neighbouring Laos, Cambodia and Myanmar. Vietnam and Thailand also expanded in their own countries in areas where rubber is not yet grown [75]. In Laos, up to 75% of the investment in rubber comes from foreign companies [76].

Especially in Laos, Cambodia and Myanmar such companies either establish large-scale plantations under land concessions, or they use a contract-farming model with smallholders. In the first case, investors fully control the management, there is only low cooperation with local people, turning farmers into landless labourers. In the case of contract farming, farmers are still landowners and maintain their decision-making. According to the kind of contract, farmers either provide land and labour, and the company provides seedlings and equipment or the company hires additional labour, sometimes the contracted farmer or workers of foreign origin. The benefits for the farmer are between 30 and 70% [71]. Overall, small-scale farmers are the backbone of natural rubber production in the GMS.

However, by deciding to grow rubber, farmers are committing themselves for decades to come, and are thus dependent on a single product, which exposes them to further risks. Rubber is almost exclusively used for industrial purposes, so its demand depends strongly on the dynamics of the world economy. This means that there are bust-and-boom cycles in rubber prices, exposing farmers to income insecurity. In the period from 2011 to 2013, natural rubber futures prices in China plummeted by 41%, and are expected to decline further [18]. With rubber tree plantations, other than with annual crops, farmers are not able to react with a short-term production strategy on changing market situations. In addition, there are ecological hazards due to crop diseases, pests, unfavourable weather conditions or changes in climate.

Furthermore, Xu *et al.* [77] concluded that rubber plantations in Yunnan eroded the capacity of farmers to manage ecologically diverse landscapes and to participate in market networks. The abandonment of traditional land-use practices in favour of a single crop may have severe implications for food and nutritional security of the rural population. Fu *et al.* [78] stated that smallholder rubber producers suffer from livelihood vulnerability due to excessive rubber cultivation. Rural food security is predicted to become more tenuous in the Mekong region [10]. This also includes the availability of natural resources, such as non-timber forest products, which rubber plantations do not provide.

Expanding rubber cultivation affects not only farmers in the rural areas, but also the urban population. In a survey conducted among local residents of Xishuangbanna [79], it turned out that nearly 90% of respondents perceived an improved economic situation as a consequence of rubber cultivation in the region. At the same time, nearly 80% of respondents think that the environmental situation has deteriorated. Virtually all respondents consider

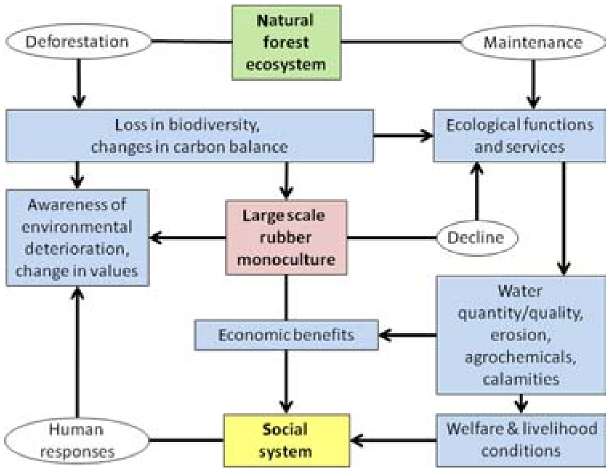

Figure 2 With evidence from this review, land transformation of forest into rubber monoculture triggers a shift in a variety of direct and indirect effects on ecosystem functions and services provided by the natural system. Changes in the local climate, the carbon and the hydrological cycle imply a higher liability of rubber cultivation to various ecological risks, affecting economic benefits as well as the welfare and livelihood conditions of the people. An increasing awareness of negative effects of rubber cultivation on the local environment among farmers and leading to changes in the value system among the population.

observed problems such as reduction and pollution of water resources, loss of natural vegetation and species, soil erosion and alterations in weather and climate as consequences of rubber cultivation. The study also shows that many respondents would be willing to contribute financially to a project that would improve the situation by converting a part of the present rubber farmland back into forest. An average household would be willing to pay nearly 0.5% of the annual income, on average, to such a project [79]. Another study found that even among residents of Shanghai exists a non-negligible willingness to contribute financially (about 0.3% of the annual income) to the preservation of natural forest or a specific rare tree species in Xishuangbanna [80], indicating a non-use value of the natural environment there.

Towards Sustainable Rubber Cultivation

The review of studies clearly indicates that increasing rubber cultivation in the GMS is accompanied by various problems and threats to farmers and the environment, though an increasing awareness of environmental deterioration leads to a change in values (Figure 2). This situation therefore requires the development of more sustainable land-use concepts. Generally, most concepts and studies are aiming at improved land-use and management and centre on the conceptual framework of ecosystem services, suggesting classification, indicator and assessment schemes [81–86]. However, most research on ecosystem services so far focused only on biophysical and valuation assessments of putative services and is not embedded in a social process for implementation [87], and many problems concerning the practical implementation of concepts remain unsolved [88–90].

In consideration of this background, solutions for the specific problems of monoculture rubber cultivation should comprise: (1) the interdisciplinary analysis and quantification of ecological processes and services affected by rubber cultivation compared with natural forest conditions; (2) the development of alternative land-use strategies including the identification of trade-offs and synergies between safeguarding functions and services on the one hand and the socio-economic viability on the other; and (3) the identification of incentives of acceptance and implementation of the concepts by farmers and other stakeholders.

Different aspects of these challenges are recognized in various studies. Among the ecosystem services affected by rubber cultivation, regulation and quality of water is a major concern of the local people [67–69]. A better understanding of the hydrological cycle in rubber-dominated landscapes is necessary for the prediction of interrelated effects on the local climate and the fate of leached pesticides. To examine options for carbon trading schemes, more detailed information on carbon stocks and sequestration over time from rubber plantation is needed [41].

Referring to alternative land-use strategies, a common suggestion to mitigate the ecological shortcomings of rubber monocultures as well as their economic risks is to practice intercropping and diversify farmers' product portfolio [41, 91]. Under present conditions, farmers prefer rubber monocultures with high returns over rubber intercropping with lower returns [92, 93]. The suggested development of rubber agroforestry systems or 'jungle rubber' particularly in locations with high ecological values for watershed protection and soil erosion reduction [41] involves the same economic problems. In Indonesia, where 'jungle rubber' is common, rubber productivity is very low, and farmers clearly prefer the shift to high-yielding monocultures [94]. On the landscape scale, Yi *et al.* [95] recommend the conversion of rubber plantations into forest in high elevations and on steep slopes as well as buffer zones along streams, but this would require payment for compensation.

Overall, the existing ecological and socio-economic problems of rubber cultivation in the Mekong region are widely acknowledged. Concordantly, suggestions for land-use change are based on system diversification and forest restoration, and that both require economic incentives for the farmers. Although rubber prices presently show a downward tendency, the main obstacle to change is still the high economic attractiveness of rubber production coupled with too few alternative income sources. Beyond that, farmers need more education on economic risks of rubber monoculture production, and on its ecological consequences for their environment and livelihood [92]. An implementation of alternative concepts also requires the strong involvement of policy makers at the national and provincial level and the general public by communication of concepts, costs and benefits of alternative land-use strategies [10, 92].

In consideration of these challenges, an approach to develop an integrative, applicable and stakeholder-validated concept for sustainable rubber cultivation is undertaken by the German-Chinese joint project SURUMER (Sustainable Rubber Cultivation in the Mekong Region, https://surumer.uni-hohenheim.de), conducted in Xishuangbanna 2012–2016. The basic project approach is the assessment and the quantification of major ecosystem processes and services in forest and rubber plantations, especially water balance and carbon dynamics. Along with results from economic analyses and valuations, these data are used to develop alternative land-use strategies.

To create economic and ecologically viable solutions, the SURUMER project aims at integrating ecologically suitable and economically valuable wild plants from the natural forest into rubber plantations. Candidates are species which are traditionally used as medicinal plants in that region [96, 97]. Among these, e.g. wild *Asparagus* species [98] and *Paris polyphylla* [99] are of high value in traditional Chinese medicine and have become rare due to overexploitation and the loss of forest areas. On landscape scale, different land-use scenarios on the future development of rubber cultivation are generated and analysed with multiple disciplinary and interdisciplinary modelling approaches, leading first to a bio-physical assessment of each scenario. In a second step, this assessment is supplemented with socio-economic appraisals on expected changes in household income and economic welfare of the rubber farmers. Scenario development involves different stakeholder groups including farmers, regional decision-makers and provincial policy levels. By catering the needs and wants of these groups, awareness of the consequences of different scenarios will be raised.

Conclusion

In the GMS, expanding rubber cultivation changes structure and function of natural ecosystems at different spatial and temporal scales and affects the socio-economic conditions and livelihood of the farmers in different ways. Solutions for these interrelated problems require not only a focus on ecosystem services according to common concepts [100], but also entail a broader understanding of interlinked ecosystem functions. Solutions from the ecological point of view in designing experimental rubber cultivation systems to mitigate undesirable effects on ecosystem processes may not necessarily generate added value for the farmers. In order to create ecologically and economically sustainable rubber farming and management schemes, trade-offs between the ecological and economic requirements and expectations need to be identified. In addition, the challenge is to consider effects of spreading rubber cultivation on the landscape scale, where they directly affect people and their livelihood. Transferring scientific concepts into practical land-use requires a social–ecological systems approach, and valuation must consider equally the social, bio-physical and economic dimensions within a multi-scale framework [10, 101, 102]. Successful implementation is only feasible if relevant stakeholders (farmers and policy makers) of different levels are involved during the entire conceptualization process, ranging from a joint definition of development goals to evaluation, in particular the joint assessment of trade-offs between ecological requirements and economic feasibility.

Various substantial approaches and concepts for the development of sustainable rubber cultivation within a socio-economic framework have been developed in the recent years, with most research conducted in Xishuangbanna, Southern Yunnan. Taken together, these studies provide a promising base for practical implementation not only in that region, but also in other potential rubber cultivation areas across the Mekong region facing the same problems.

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