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Rubber intercropping: a viable concept for the 21st century?

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Abstract The last decades brought along a tremendous expansion of rubber plantations as well as respective socio-economic transformations. This paper reviews the historical development of rubber cultivation with special reference to intercropping and illustrates the major development steps. The agronomic challenges of intercropping are analyzed and a management classification scheme is suggested. Though the topic of labor always accompanied rubber management, it is nowadays of even higher relevance due to alternative income options, be it due to competing crops such as oil palm, or be it off-farm income opportunities. This development challenges labor intensive permanent intercropping systems. It can thus be concluded that the permanent integration of additional plants needs either to be highly profitable or at least be labor extensive to be adopted on a considerable scale. Given the large area of rubber plantations the latter seems to be more realistic. In this context timber trees might offer promising options if tree selection is properly adapted to site and plantation conditions. Nevertheless, without external interventions, such as land-use planning and implementation, or incentives, the development will be difficult to control.

Keywords Cover cropping · Ecosystem services and functions · Jungle rubber · Initial intercropping · Permanent intercropping · Rubber diversification, rubber-timber intercropping

Introduction

The natural rubber of the Pará-rubber tree *Hevea brasiliensis* (Willd. ex A. Juss.) Müll. Arg. is one of the most important renewable resources of modern times, being a pillar of industrialization and classified as a strategic resource. Originally collected from Amazonia's old growth forests, it is nowadays mainly produced in Asian plantations.

In the twenty-first century the cultivation of rubber faces considerable challenges. The rise of the emerging markets, notably China, which consumed in recent years on average more than one third of the worlds natural rubber (NR) production (32 % on a 5-years average), together with the increase in oil price, resulted in a new rubber-planting boom since the turn of the millennium. Especially in Mainland South East Asia (MSEA), including China's Yunnan Province, Laos, Cambodia, Myanmar and Vietnam, a tremendous extension of the rubber area could be recorded, often on behalf of forests and sites formerly assumed

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Table 1 Data bases accessed for this review

AGRICOLA	http://agricola.nal.usda.gov/
AGRIS: Agricultural database	http://agris.fao.org/agris-search/index.do
BioOne	http://www.bioone.org/
JSTOR: Journal Storage	http://www.jstor.org/
SciELO	http://www.scielo.org/php/index.php?lang=en
Scopus	http://www.scopus.com/
SpringerLink	http://www.springer.com/?SGWID=1-102-0-0-0
Web of Science	http://thomsonreuters.com/thomson-reuters-web-of-science/

as marginal (Fox and Castella 2013; Priyadarshan et al. 2005). According to FAO-data the harvestable area in Asia increased by one third to about 10 million ha since the year 2000, which represents about 92 % of the annual world production of nearly 12 million Mg. Based on predicted demands, Warren-Thomas et al. (2015) calculate a needed additional rubber plantation area of 4.3–8.4 million hectares, depending on the scenario, to satisfy that demand until the year 2024—with considerable impacts on the environment (Häuser et al. 2015).

Rubber plantations are usually managed as monocultures. Given the extent of land covered by plantations it seems to be essential to rethink this practice in order to mitigate associated negative environmental impacts and economic dependency and assess potential alternative management options. Therefore, this paper analyses historical developments and current trends with special reference to intercropping with the aim to synthesize potential solutions for a more eco-friendly rubber cultivation in the twenty-first century.

Materials and methods

This paper combines a literature review in scientific databases with a search for grey literature in Google and Google Scholar (Table 1), since practical agricultural aspects are often covered by grey literature rather than by scientific journals. Only information has been referenced which was comprehensible and seemed plausible. The results are amended by our personal experience gained in the framework of the SURUMER-project.[1] The following search terms have been used: ‘rubber intercropping’, ‘rubber “and” intercropping’, ‘*H. brasiliensis* “and” intercropping’.

The gathered information has been screened for the following themes:

- History of rubber cultivation and intercropping, respectively
- Management scheme considerations and framework conditions
- Reference to ecosystem services (ESS)

Based on this analysis, a historical time line of rubber management and intercropping, respectively, is drawn in the first part of the result presentation. In the second part, different intercropping practices are presented and a classification is suggested. Finally, the results are synthesized and discussed in the light of recent developments.

The beginnings: a short history of Rubber exploitation

The use of *H. brasiliensis* as a source of natural rubber (NR), derived as latex from milk channels in the bark of the tree, has a long history. Its large-scale exploitation and global usage started with industrialization and related technical innovations (e.g. vulcanization) in the middle of the nineteenth century. Until that time, production of NR was mainly based on the exploitation of old forests in Amazonia, the original homeland of Pará rubber (Dean 1987; Stanfield 1998). Naturally, *H. brasiliensis* is a component of the annually flooded riverine habitat, the Varzea forest (Prance 1979). It is often scattered at very low densities of only one or two tappable trees per hectare (Dean 1987). In the past, several species of the genus *Hevea* and even other taxa were exploited on a variety of sites (Schultes 1992; Ule 1901a, b). All in all, latex collection was labor intensive and not very efficient,

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[1] SURUMER—Sustainable Rubber Cultivation in the Mekong Region: www.surumer.uni-hohenheim.de.

being the mining of natural resources rather than a properly managed system. It soon became obvious that *Hevea,* and with increasing taxonomic distinction, *H. brasiliensis* provided the technically most suitable and yielding raw material (Challen 2014; Ule 1901a). Due to Brazil's monopoly, the country's efforts to increase efficiency and develop rubber into a professionally managed crop were limited (Dean 1987). After all, the industrializing countries were dependent on deliveries from South America; synthetic rubber (SR) only became a considerable competitor after the Second World War.

Since rubber (as a generic term) was—and still is—a strategic resource, industrializing countries originally tried to exploit a range of natural resources in their colonies, e.g. the vine *Landolphia owariensis* (Apocynaceae), the 'Congo rubber' or 'red rubber' of the infamous 'Congo Free State' (Clarence-Smith 2013). In Southeast Asia Gutta-percha (*Palaquium* spp./Sapotaceae), Jelutong (*Dyera costulata*, Apocynaceae), or *Ficus elastica* (Moraceae) where common forest sources for rubber and often faced tremendous depletion (Dove 1994; Feintrenie and Levang 2009) as it is expressed in the term 'slaughter harvesting'. Nevertheless, these sources could not compete with Brazil's pará rubber due to its higher quality, productivity and availability. Therefore, the industrializing countries were seeking to safeguard their own sources to become independent from Brazil's monopoly. To this end, they obtained *H. brasiliensis* seeds to establish plantations in their colonies by financing expeditions to Amazonia (c.f. Fenske 2013; Ule 1903a). In contrast to the often claimed illegal smuggling of the seeds, these expeditions where officially at least tolerated or even approved of (Baulkwill 1989; Dean 1987), as can be seen from published reports on the progress of such expeditions (e.g. Ule 1901a, b; 1903a, b). Finally, the trials in SE Asia were tremendously successful (Baulkwill 1989) and were further enhanced with the development of an effective tapping method. They provided the starting point for the importance of SE Asia as the major producer of NR with a share of 92 % of world production in 2011 (FAO 2013).

The post World War II era

The second World War not only showed the importance of rubber as a strategic resource "after the Japanese had seized most of the world's *Hevea* in early 1942" (Clarence-Smith 2013, p. 199) by cutting off the allied forces from their SE-Asian rubber supply, but also marked the end of colonialism in its aftermath. As a crucial result, the former control of the local rubber production chains shifted from colonial forces to local powers. Despite a very heterogeneous development—in Indonesia 54 % of the rubber planting area were already managed by smallholders in 1940 (Clarence-Smith 2013)—the smallholder sector was increasingly strengthened such that today smallholders play a dominant role in NR production, in some countries being responsible for 90 % of the NR production (e.g. Byerlee 2014; Fox and Castella 2013; Tharian George et al. 1988).

After some stagnation in the second half of the twentieth century (e.g. Iqbal et al. 2006) NR experienced a remarkable expansion due to globalization and the economic growth of the BRICS countries at the turn of the millennium. According to FAO-statistics, the area under tapping rose by more than 30 % from 7.3 to 9.7 million hectares between the years 2000 and 2011 (FAO 2013). According to remote sensing analyses the real figures are even higher since statistics lag behind the development and do not adequately represent the heterogeneous dynamics of smallholder activities (cf. Fox 2009; Li and Fox 2012; Xu et al. 2014). Additionally, the FAO-statistic refers to productive plantations, which means older than 5–7 years. The extension of NR in Mainland South East Asia were chargeable especially to traditional land-use types, as well as secondary and old growth forests, sometimes even protected areas (Ahrends et al. 2015; Li and Fox 2012; Xu 2006). Rubber expansion has also been promoted and subsidized in the Golden Triangle by regional governments in the wake of poppy replacement programs (Cohen 2009; Fox 2009). Additionally, while in the past rubber was restricted to areas below ca. 800 m a.s.l., new clones specifically selected for cold resistance are becoming available. It can be observed that rubber 'climbs up' the mountains and can sometimes be found up to 1400 m a.s.l. Another development is the extension of rubber into new agro-ecological zones, such as the dry areas of northern Thailand (Fox and Castella 2013), where the crop faces both water and temperature challenges, thus continuing a trend that started in the 70s of the last century (Priyadarshan et al. 2005).

Although rubber expansion had undeniable and considerable beneficial impacts on the livelihood of a large number of rural people, the negative impacts have increasingly become a matter of concern, (cf. Ahrends et al. 2015; Guardiola-Claramonte et al. 2010; Häuser et al. 2015; Mann 2009; Qiu 2009; Stone 2008; Warren-Thomas et al. 2015; Yi et al. 2014; Ziegler et al. 2009). Expansion has led to a tremendous homogenization of large tracts of a former highly diverse landscape (Fig. 1) accompanied by a respective simplification of biodiversity and the loss of specialized guilds on behalf of universalistic ones, but also new exotic organisms (e.g. Aratrakorn et al. 2006; Meng et al. 2012; Phommexay et al. 2011).

Besides the physical impacts of intensive large scale agriculture, such as soil erosion and the related siltation of streams and rivers, such as the Mekong River—its siltation doubled from the 60th to the 80th of the last century (Shapiro 2001), the impacts on landscape hydrology are of upmost importance. In addition to consequences for local water availability and quality, the changes in regional climate, such as the reduction of foggy days, has been associated with the expansion of rubber plantations in SW China (Guardiola-Claramonte et al. 2010; Li et al. 2007; Shapiro 2001). While the discussion on the above mentioned impacts of the rubber boom on Ecosystem Services (ESS) so far took place largely in scientific journals and academic circles, it now starts to trickle down into the awareness of the general public. In reaction, the International Rubber Study Group (IRSG), "an inter-governmental organisation composed of rubber producing and consuming stakeholders",[2] initiated the Sustainable Natural Rubber initiative (SNRi).[3] It remains to be seen to what extend this commitment based on voluntary participation will be mirrored by effective action. In Table 2 an attempt is made to synthesize the complex history of rubber production.

Intercropping: a historical perspective

The exploitation of natural stands was by far the prevailing practice in Amazonia, although early descriptions of rubber tree planting and intercropping with cocoa can be found (Ule 1903b). At the beginning of rubber cultivation in Asia, technical aspects like tapping schemes, habitat suitability, and selection/breeding for higher yields were prevalent in research activities, and intercropping was not much of a topic. Only erosion attracted considerable attention and led to the recommendation to maintain the undergrowth instead of practicing the common clean-weeding (Haines 1934, cited in Baulkwill 1989) or, later, to use leguminous cover crops to prevent erosion (Baulkwill 1989). For Indonesia there are documentations of smallholder intercropping experiments with coffee and tobacco. It is also documented that smallholders changed their traditional agricultural practices by integrating rubber in slash and burn agriculture or home gardens (Baulkwill 1989; Dove 1993; Gouyon et al. 1993; Lawrence 1996) thus actually becoming the originators of 'jungle rubber', a "balanced, diversified system derived from swidden cultivation, in which man-made forests with a high concentration of rubber trees replace fallows" (Feintrenie and Levang 2009; Gouyon et al. 1993, p. 181). In plantations, they also used the time before canopy closure to practice intercropping (e.g. coffee and pineapples) (cited in Clarence-Smith 2013). All in all, it can be concluded that intercropping in the beginning of rubber-plantation development was a hybrid between subsistence agriculture and cash crop economy, whereas cash crops and income generation became more and more important with the professionalization and intensification of rubber management (cf. Barlow 1997).

The diversification of NR-plantations in Asia received considerable attention after the Second World War. For state- or industry- based rubber estates, an intensive monoculture scheme was a common feature, supplemented by leguminous cover crops to mitigate erosion and supply nutrients during the first years after establishment. In contrast, smallholdings usually practiced intercropping with light-demanding crops such as maize, pineapple or banana in the first 2–3 years (Baulkwill 1989). For the introduction of rubber in China in the 1950s, initial intercropping with food crops is mentioned as a way to provide subsistence food for the rubber growers (Zeng et al. 2012). With the growing role of smallholders, rubber research institutes strongly promoted intercropping and established trials, especially from the 70s to the 90s of the last century (e.g. Herath and Takeya

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[2] http://www.rubberstudy.com/aboutus.aspx.

[3] http://www.snr-i.org/.

Fig. 1 Rubber landscape in Xishuangbanna, Yunnan Province, SW China. The picture was taken in February, when rubber trees are not yet fully foliated and the common terracing is still visible

2003; Li 2001; Shapiro 2001; Zeng et al. 2012; Zhou 2000).

Zhou (2000), for example, describes the development of intercropping on a state farm in Guangdong Province, China: While intercropping experienced a boom in the 1980s, it had completely disappeared again in the 1990s due to a more market-oriented policy. On Hainan Island, intercropping was strongly promoted in the 1970s and 1980s to diversify the product portfolio and thus reduce the impact of typhoon damage on income security. Nevertheless, promising intercropping species, such as the medicinal ginger plant *Alpinia oxyphylla*, were soon abandoned due to low market prices (Zeng et al. 2012). The same happened to the strongly promoted (Zhou 1993) ginger plant *Amomum villosum* in Yunnan. At last, during that period, all common annual crops, forage plants, grasses and legumes, but also perennials like fruit- or timber-trees found their way in trial plantings (Table 3). The integration of livestock, such as sheep, chicken or cattle, into rubber plantations also received considerable attention (Ng et al. 1997; Payne 1985; Shelton and Stür 1991; Waidyunatha et al. 1982). Remnants of such trials can still be found today dispersed in traditional rubber growing areas (Fig. 2). Zhou (2000) comes to the conclusion that adoption of intercropping is purely market driven, and that the consideration of other aspects needs government intervention.

Despite comprehensive field trials by practically all rubber research institutes as well as an ongoing promotion of intercropping, information about actual adoption rates can hardly be found. Actually, proof of major adoption beyond an initial integration of crops in the first 2 years is limited. One of the very few published figures on the share of intercropped rubber in the overall plantation area mentions 10 % for Thailand (Delarue and Chambon 2012), which is remarkably low given the number of reports on intercropping for Thailand and the advantages usually cited. In a household survey in Xishuangbanna, southern Yunnan, China, only 14 % of the assessed rubber plantation area was intercropped, showing a positive correlation with elevation. The assessment comprised the initial intercropping with annuals (Min et al. 2015).

An aspect of upmost importance for intercropping is the availability of work force. Labor related issues, including the availability in general or the required skills in particular, accompany rubber exploitation from the very first days (Baulkwill 1989; Fenske 2013; Murray 1992; Stanfield 1998; Ule 1901a), and pose a

Table 2 Evolution of rubber management from exploitation of natural stands in Amazonia to the establishment of rubber monocultures in marginal areas of MSEA

A synthesis of rubber management history			
Nineteenth century: exploitation of natural resources	First half of twentieth century: colonial plantation production	Post-colonial time to turn of millennium	Rubber in the twenty-first century?
Production: Amazonia, Africa[a], SE Asia[a]	Production: SE-Asia	Production: SE-Asia	Production: SE-Asia, (Africa, America?)
Management: exploitation of natural resources Labor intensive—slavery[b] Rather inefficient, extensive Supply of world market—industrialization	Management: monoculture plantations (trial & error)—testing of physiological optimum Selection/breeding/cloning towards higher yields Investors > smallholders Labor intensive—exploitation of colonial work force[c] “Jungle rubber” in Indonesia Supply of colonial industries	Management: clonal propagation leads to tremendous productivity gains Adoption of chemical fertilizer & pesticides Systematic intercropping trials Initial intercropping (2–3 years) for food security + bridging first unproductive years is rule All in all still mainly monocultures Improved labor conditions Smallholders > investors ‘Jungle Rubber’ on the decline Development of rubber timber industry Supply of world markets + own (producer countries’) industries	Managements: further clonal improvements: yield increase, cold resistance? Rubber-timber clones Tremendous extension of production Smallholders> investors Labour shortage problem Supply for own industries + production for world market
ESS-aspects Renewable resource Income generation Exploitation of human resources[b] ESS no topic	ESS-aspects Renewable resource Income generation Transformation of (near-) natural ecosystems, esp. forests Erosion already a well-considered problem (esp. of young plantations on slopes) ESS except erosion no topic	ESS-aspects Renewable resource Strong impacts on rural livelihoods Considerable impact on: Biodiversity C-storage Regional hydrology & water Rise of ESS-discussion	ESS-aspects Renewable resource Strong impacts on rural livelihoods Public awareness of ESS-provision Land sharing versus sparing discussion Implementation of land-use policies Improvements due to changed management schemes New Management schemes towards forest restoration???
Major Product(s) latex	Major Product (s): latex, (NTFP)	Product(s): latex, timber, cash crops	Product(s): latex, timber, seed oil (?), cash crops

[a] Non-Hevea species

[b] cf. Stanfield 1998

[c] cf. Murray 1992

Table 3 Plants evaluated and tested in the context of rubber intercropping

Initial intercrops

Annanas comosus (L.) Merr. / pineapple / f
Arachis hypogaea L. / groundnut / f
Cannabis sativa L. / hemp / r-m
Capsicum annuum L. / chili pepper / f
Citrullus lanatus (Thunb.) Matsum. & Nakai / water melon / f
Colocasia esculenta (L.) Schott / taro / f
Cucurbita spp.
Cymbopogon citratus (DC.) Stapf / lemon grass / f
Dioscorea alata L. / purple yam / f
D. cayenensis Lam. /yellow yam /f
Glycine max (L.) Merr. /soybean/ f
Gossypium spp. / cotton / r-m
Ipomoea batatas L. (Lam.) / sweet-potato / f
Manihot esculenta Crantz / cassava / f
Morinda officinalis F.C. How / morinda / m
Musa x paradisiaca L. / banana, plantain / f
Nicotiana spp. / tobacco / d
Oryza sativa L. / upland rice / f
Osteospermum spp. / African Daisy / o
Pachyrrhizus tuberosus (Lam.) Spreng. / yam bean / f
Passiflora edulis Sims / passion fruit / f
Phallus indusiatus Vent. / bamboo fungus/ d
Pisum sativum L. / pea / f
Pogostemon cablin (Blanco) Benth. / patchouly / d
Saccharum officinarum L. / sugarcane / f
Sorghum bicolor (L.) Moench / sorghum / f
Vigna radiata (L.) R. Wilczek / mung bean / f
Voandzeia subterranea (L.) Thouars / bambara groundnut / fs
Zea maiys L. / maize / f

Cover Crops (all Fabaceae)*

Calopogonium caeruleum (Benth.) C. Wright
Cassia cobanensis (Britton) Lundell
Centrosema pubescens Benth.
Crotalaria sp.
Desmodium ovalifolium (Prain) Wall ex Ridley
Flemingia macrophylla (Willd.) Kuntze ex Merr.
Mimosa invisa Mart. ex Colla
Mimosa invisa var. inermis Adelb.
Mucuna bracteata DC. ex Kurz
Mucuna cochinchinensis (Lour.) A. Chev.
Psophocarpus palustris Desv.
Psophocarpus tetragonolobus (L.) DC.
Pueraria phaseoloides (Roxb.) Benth.
Senna sp.
Stenolobium brachycarpum var. brachystachyum Benth. (Fabaceae)
Stylosanthes gracilis Kunth

Permanent intercrops

Acacia mangium Willd. / acacia / t
Afzelia sp. / t
Alpinia oxiphylla / Izhe / m
Amomum longiligulare T.L. Wu / hai nan sha ren / m
Ammomum villosum Lour. / sha ren / m
Amorphohallus konjac K. Koch / konjac / f
Anacardium occidentale L. / cashew nut / f
Annona reticulata L. / custard-apple / f
Aquilaria sp. / eaglewood / d
Archidendron pauciflorum I.C. Nielsen / dogfruit / f
Areca catechu / betel nut/ d
Artocarpus sp.
Azadirachta indica A. Juss. / neem tree / d, t
Betula alnoides Buch.-Ham. ex D. Don / alder birch / t
Calliandra sp. / false mesquite / t, r-m
Carica papaya L. / papaya / f
Cinamomum verum J. Presl / cinnamon / f
Cofea sp. / coffee / d
Dalbergia sp. / i.a. rosewood / t
Dipterocarpus sp. / t
Durio zibethinus Rumph. ex Murray/durian/f
Endospermum malaccense Benth. ex Müll. Arg. / t
Eucalyptus sp. / eucalyptus / t
Fagraea fragrans Roxb. ex Carey & Wall. /t
Garcinia mangostana L. / mangosteen / f
Gliricidia spp. / gliricidia / t
Gmelina arborea Roxb. ex Sm. / gmelina / t
Gnetum gnemon L. / gnemon / f
Hopea sp. / t
Lansium domesticum Corrêa / langsat / f
Macadamia sp. / macadamia nut / f
Mangifera indica L. / mango / f
Morus sp. / fig / f
Nephelium lappaceum L. / rambutan /f
Nyssa yunnanensis W. Q. Yin ex H. N. Qin & Phengklai*/ protection*
Paraserianthes falcataria (L.) I.C. Nielsen / white albizia / t
Parashorea sinensis H. Wang / wang tian shu / t
Parkia speciosa Hassk. / stink bean / f
Peronema canescens Jack / t
Piper nigrum L. / pepper / f
Pterocarpus sp. / padouk, narra / t
Rhus sp. / sumac / ?
Ricinus communis L. / castor bean / d
Salacca zalacca (Gaertn.) Voss /snake fruit/f
Shorea macrophylla P.S. Ashton / light red meranti / t
Swietenia mahagoni (L.) Jacq. / mahogany /t
Taxus mairei (Lemée & Lév.) S.Y. Hu ex T.S. Liu / / d
Tectona grandis L. f. / teak / t
Thaumatococcus daniellii (Benn.) Benth. / f
Thea sinensis L. / tea / d
Theobroma cacao L. / cacao / d

Plants assessed, but not actively planted
(all Poaceae, except *Mikania*)

Axonopus compressus (Sw.) P. Beauv.
Brachiaria brizantha (Hochst. ex A. Rich.) Stapf
Brachiaria mutica (Forssk.) Stapf
Imperata cylindrica (L.) P. Beauv.
Mikania micrantha Kunth (Asteraceae)
Ottochloa nodosa (Kunth) Dandy
Panicum maximum Jacq.
Paspalum conjugatum P.J. Bergius

This compilation is based on the references cited below. Sometimes species citations were fragmentary, and only the genus was mentioned. If in another paper a respective species name was given, only the species has been mentioned, otherwise the genus with 'sp.' has been listed, although several species of the same genus might have been involved. Species authors were often missing and nomenclature was heterogeneous simply due to the time span of the papers reviewed. Therefore, plant names have been standardized and updated using the online database 'Tropicos' (Tropicos.org). Where Tropicos didn't offer a common name Wikipedia (Anonymous, 2015)has been consulted.

The species cited for initial and permanent intercropping are mostly intended for use, be it as staple food, stimulant, timber, etc. Since they usually have a common or vernacular name, this is added together with the use. The following use-categories have been distinguished:

f: food - staple food & spice
t: tree – timber and multi purpose trees
d: drug – stimulant & medicine
r-m: raw material
o: ornamentals

Source: Chee and Faiz (1991), Chong et al. (1991), Ekanayake (2003), Herath and Takeya (2003), Li (2001), Ng (1991), Ng et al. (1997), Pathiratna (2006a, b), Priyadarshan (2011), Rantala (2006), Sanchez and Ibrahim (1991), Shelton and Stür (1991), Shigematsu et al. (2013), Waliszewski (2010), Watson (1989), Wibawa et al. (2006), Williams et al. (2001), Zhou(2000), as well as information by F. Harich (pers. com.), own observations and trials major challenge today.[4] Thus the required labor input per management unit is four times higher for rubber than for oil palm (Schwarze et al. 2015). Actually, there is a global trend, especially of young rural people, to migrate to the cities, reflecting enhanced off-farm income options. Migration became a major constraint for agriculture in general (Rigg 2005; Xie et al. 2014) and in running rubber plantations in particular (Giroh et al. 2013), especially against the background of a tremendously increased rubber area (Fox and Castella 2013). The proper management of rubber is a demanding task requiring skilled workers. Intercropping not only requires additional labor input, but also a specific understanding of the ecological requirements of the intercropped plant under the given environmental conditions (e.g. Feike et al. 2012; Guo et al. 2006; Snoeck et al. 2013). Unfortunately, this aspect is hardly considered in publications promoting intercropping during the productive phase of rubber (Beer et al. 1998). The analysis of the decline of a multitude of intercropping systems based on perennial, but also on annual, crops in the North China Plain by Feike et al. (2012) reflects well the observed developments in rubber: The economic development leads to increasing off-farm income options, which are positively correlated to the proximity of cities and industrial centers. On the other hand, the implementation of sophisticated intercropping systems is correlated with the abundance of labor, lack of alternative income options and land scarcity. These factors encourage sophisticated management schemes that lead to high land equivalent ratios (LER). In our research area in SW China, we obtained similar results, but additionally identified altitude, ethnicity and household wealth as driving factors (Min et al. 2015). As an option to maintain intercropping in the North China Plain, Feike et al. (2012) suggest mechanization. Nevertheless, mechanization strongly depends on site conditions and farm size. It might be technically feasible in the traditional rubber growing areas on flat land, for example in southern Thailand or Malaysia, but difficult to implement in the recent expansion areas of Thailand's North, China's Xishuangbanna Prefecture, Laos, or Vietnam on hilly areas. Where mechanization can be applied, the required investment can be a limiting factor, since the majority of rubber land is cultivated by smallholders. Nevertheless, this might be overcome by the establishment of farm machinery cooperatives.

Intercropping options and constraints

The integration of additional plants in rubber plantations faces several bio-physical challenges, mainly related to light availability and competition. Rubber plantations induce a fast drop in light transmission rates with age, i.e. with the development of tree crowns. Additionally, they show very low light levels at the ground after canopy closure (Chee and Faiz 1991; Rodrigo et al. 2005; Sanchez and Ibrahim 1991; Wilson and Ludlow 1991). Furthermore, the rubber canopy affects light quality within the stands by changing the spectral composition (Wilson and Ludlow 1991). Given the standard single-row spacing of rubber of ca. 7 (5–10) m × 3 (2–3.5) m, the canopy is more or less closed at the age of 5–7 years. The unshaded area then falls below 10 %, and light transmission rates (e.g. of photosynthetic active radiation—PAR) down to 2 % have been measured in 8 years old plantations (Chee and Faiz 1991; Newman 1985; Rodrigo et al. 2004; Sanchez and Ibrahim 1991) (Fig. 3). This rapid decline in light transmission is typical for rubber plantations, and is similar though somewhat slower for oil palm. Rubber maintains low light transmission rates throughout its entire production cycle, while oil palm shows a light transmission low between 10 and 15 years (Wilson and Ludlow 1991). Wolff and Coltman (1989), for example, showed a linear yield decline in peanuts with increased shading. The same was true for other annual crops (eggplant, soybean, sweet potato). Only lettuce (*Lactuca sativa* L.) showed a positive reaction, but this only under 'little' shade. For maize, Karim (2006) modeled the impact of rubber planting density (400, 600, 800 trees/ha) on yields on a time line. He showed that planting density strongly affects maize yields in the first year after planting already, leading to a yield reduction of 45 % (800 trees) compared to the lowest planting density of 400 trees/ha. In the third year, yields collapsed independently from planting density, leading to a yield decline of 41 % (400 trees) and 99 % (800 trees), respectively. As will be shown later, even so-called shade tolerant crops suffer considerable yield declines depending on shade level. When discussing intercropping options it is therefore crucial

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[4] Fernandez, Tej (2012): The future of natural rubber hinges on research. Asian Rubber Journal June 27, Selangor Malaysia.

Fig. 2 Intercropping of rubber with the medicinal *Alpinia oxyphylla* (Zingiberaceae) on Hainan Island, China

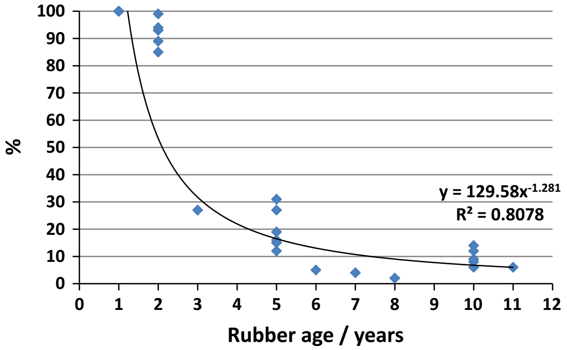

Fig. 3 Light decrease in young rubber plantations. Source data: Chee and Faiz 1991, Sanchez and Ibrahim 1991; modified. Data refer to planting densities between ca. 300–600 trees/ha

to not only talk about shade tolerance in an ecological sense, but to also consider productivity (cf. Snoeck et al. 2013).

Intercrops do not only compete with rubber for light but also for water and nutrients. Rubber, although forming a remarkable taproot, is considered a so-called surface feeder, which establishes a dense root mat in the uppermost 30 cm of the soil (George et al. 2009; Newman 1985). The roots of neighboring rubber rows meet quite early in plantation life, and while this is usually reported for the age of canopy closure, there is also a record mentioning this as occurring in the first and second year after planting already (Broughton 1977). The argument that competition between rubber trees and intercrops can be avoided by selecting intercrops with a differing root strategy is therefore dubious. For example cocoa, often suggested as rubber intercrop, shows a similar root strategy as rubber, developing a tap root and a feeder-root system in the upper 20 cm of the soil, extending in a radius of up to 7 m from the stem (Toxopeus 1985; Wood 1985a), thus overlapping with the rubber root system. And while Wood (1985b) claims that root competition in the production of cocoa needs to be avoided, Newman (1985) concludes that permanent intercropping of cocoa (and also coffee) in mature rubber plantations was not very successful. For coffee, which explores the root space more homogenously than cocoa, Wintgens and Descroix (2009) stress that root competition in the uppermost 75 cm of the soil needs to be avoided. In trial plantings by the Dehong State Farm, Yunnan Province, SW China, this is done by digging trenches which act as root barriers (Fig. 4). Due to these obstacles, George et al. (2009) suggest restricting intercropping to the first 2–3 years, which reflects smallholderś practice (Priyadarshan 2011; Rajasekharan and Veeraputhran 2002; Webster and Paardekooper 1989). Blencowe (1989) gives cause for concern that the harvesting of root

Fig. 4 Avoiding root competition between rubber and coffee by trenches in a trial planting on Dehong State Farm, Yunnan, China

Fig. 5 Initial intercropping, the case of maize and pine apple: *Left*—intercropping of young rubber with maize. The rubber terraces are visible on the slope on the left (*red arrow*). *Right*—Young rubber with pineapple. The rubber trees (*red arrows*) are *bright green*, wile pineapples are grayish-green. Naban River Watershed National Nature Reserve, Xishuangbanna, Yunnan, China

intercrops, such as sweet potato or cassava, might lead to considerable soil disturbance and even rubber root damage. Additionally, harvest residues from cassava, for example, which belongs to the same family as rubber (Euphorbiaceae), might promote root fungi. Nevertheless, although e.g. ‘white root rot’ (*Lignoporus lignosus*) causes considerable problems in some regions, especially in young plantations, and although typical intercrops such as cocoa, coffee, or tea can be similarly affected by this fungus (Lass 1985; Muller et al. 2009), no reference could be found documenting enhanced rubber fungi infestation through an intercrop.

As mentioned above, intercropping with light demanding crops during plantation establishment is a common practice (Fig. 5). This improves resource capture (Rodrigo et al. 2001) and allows for economic returns before the rubber can be tapped, thus considerably contributing to livelihoods. For Malaysia, 85 % of rubber farmers have been reported to practice this kind of intercropping (Bagnall-Oakeley et al. 1996). In remote areas, crops such as upland rice, maize, vegetables, peanuts or chili peppers cultivated for subsistence purposes may be found. Where market access is good, cash crops like pepper, bananas or pine apples are planted (Bagnall-Oakeley et al. 1996). On the whole, a wide variety of crops suitable for open land can be encountered, depending on local conditions and traditions (cf. Table 3). This kind of 'initial' intercropping might have beneficial impacts on rubber itself. Due to the maintenance of the intercrops, costly weed management is usually unnecessary. Additionally, growth and yield stimulations in rubber have been reported. This can be caused by the elimination of weed competition, the application of fertilizer, but also irrigation of the intercrops (Alvim and Nair 1986). In an intercropping trial with banana on Sri Lanka, positive effects on rubber without fertilizer have been reported (Rodrigo et al. 2005). Given the experimental layout, though, farmers were permitted to do weeding and watering, which might explain the positive effects on rubber trees.

The so-called cover cropping with leguminous creepers might be classified as special case of initial intercropping. The intention of cover cropping is to reduce erosion, especially on mountainous terrain, or to act as green manure providing nutrients, especially nitrogen, to reduce competition by weeds, e.g. the grass *Imperata cylindrica,* but also to provide fodder as forage plant (Bagnall-Oakeley et al. 1996; Blencowe 1989; Broughton 1977; Chong et al. 1991). Cover cropping has long been promoted, and experiments with legume cover crops date back to the early beginnings of plantation development (e.g. Wright 1912, cited in Baulkwill 1989). Broughton (1977) presented a synthesis of long-term trials with leguminous but also other cover crops and stressed the advantages of legumes, especially a long-lasting rubber yield increase. The long-term beneficial effects are described as specifically pronounced on poor soils, while on good soils and newly cleared forest land the naturally occurring ground cover has similar positive effects as leguminous cover crops (Blencowe 1989; Broughton 1977). In contrast to oil palm plantations, where the use of *Mucuna* spp. is often standard practice, it's hardly possible to find any proof of considerable adoption of cover crops especially in the smallholder sector. In an assessment of clonal improved rubber in Malaysia, only 15 % of farmers practiced cover-cropping (Bagnall-Oakeley et al. 1996). It can be hypothesized that higher adoption rates in palm oil plantations are the result of the more favorable light regime and thus more efficient from a biophysical and economic point of view. Either way, the unarguably positive effects of cover cropping do not seem to compensate smallholders for the required inputs such as labor, seeds, herbicides or fertilizer. Phosphorous in particular is sometimes applied to acid soils to improve the efficiency of the cover crop (Fageria et al. 2013; Somado et al. 2003).

The second intercropping approach is to establish or keep perennial crops when rubber plantations start to develop a shade environment, and maintain the crops during part or even the whole rubber production cycle. Typical examples are cocoa, tea, coffee, or species belonging to the ginger family (Zingiberaceae) as *A. oxyphylla* (c.f. Figure 2) or *A. villosum* (e.g. Zhou 1993). A species with a promising potential is *Thaumatococcus daniellii* (Marantaceae) which provides an extremely efficient sweetener without calories. It has been tested in African rubber plantations with good results (Waliszewski 2010). Typically, crops grown together with shade trees are traditionally managed under moderate shade of 20–50 %. These crops are original components of the forest understory, and the respective systems evolved from forests by reducing competition from unwanted trees, resulting in still diverse agro-ecosystems with tree remnants of the previous forest (Pathiratna 2006a; Ruf 2011). Thus, in the past, it was more or less taken for granted that these crops need shade. Nevertheless, that assumption has been challenged in recent years, and practical examples show a much more diverse picture. Disregarding the requirements during the establishment phase (cocoa e.g. needs shade (Wessel 1985)), none of the three species really requires shade but rather shows highest productivity under very light shade or full sun (Carr and Stephens 1992; Descroix and Snoeck 2009; Wessel 1985; Wood 1985b). Additionally, new, high yielding varieties of coffee, cacao, or pepper need more light to fully realize their economic potential compared to traditional ones. However, the advantages of mono-cropping only materialize under species-specific optimal environmental conditions (elevation, microclimate, nutrients). Then, intensive management with high fertilization rates, especially nitrogen, is very efficient with regards to productivity (Descroix and Snoeck 2009; Wood 1985b). Under suboptimal and marginal growing conditions, shade can provide considerable advantages. It protects the species from overheating, which can stop assimilation, or cold spells, and also contributes to fruit quality, e.g. in coffee (Chaudhuri et al. 2013; Descroix and Snoeck 2009; Muschler 2009; Wintgens 2009). DaMatta (2004) provides an excellent example of the complex environmental interactions affecting the productivity of coffee plantations. Anyway, where modern crop varieties are planted, systems are strongly simplified. Ruf (2011, pers. com.) calls these new systems "soft agroforestry". Referring to the permanent intercropping of rubber, even shade tolerant plants such as tea suffer an early decline in production after 6–7 years (Ekanayake 2003; Iqbal et al. 2006) and have thus been considered a temporary mixture. According to Wood (1985b), experiments with rubber as shade trees for cocoa failed economically, although cocoa trees survived in the shade. And Wintgens and Descroix (2009, p. 220) claim that rubber "has never been a successful shade tree for coffee".

With a strongly reduced number of rubber trees (160 trees or ca. 1/3rd of the standard) cocoa could be grown with economic success (Wood 1985b). Consequently, a considerable increase in rubber row distance, to e.g. 16–20 m, is a common feature of permanent rubber intercropping, often accompanied by the establishment of narrow rubber double rows with a row distance of only 2–2.5 m. This results in a similar number of rubber trees with a respective yield per hectare compared to the standard spacing and, together with the intercrop, allows for a better land use efficiency (LER) (e.g. Guo et al. 2006). In the case of rubber-coffee plantations of the Dehong State Farm (cf. Figure 4) 2.5 m wide rubber-double rows alternate with 10 rows of coffee with a respective row distance of 2 m. This results in a spacing of 24 m between rubber rows. Another approach based on considerably increased (double-) row distances is permanent-seasonal intercropping with annual crops. On Hainan Island, China, bamboo fungus (*Phallus indusiatus*), a highly praised and priced mushroom used for cooking but also Traditional Chinese Medicine (TCM), is planted between rubber rows during the dry season on Guangba Farm of the Hainan State Farm Group. Since mushrooms are a very sensitive crop, their production requires sophisticated management and considerable skills. The soil needs to be sterilized, humidity controlled, and the harvest needs to occur on time (Hainan State Farm, pers. com.). Such approaches integrating high value crops recently received considerable attention (Snoeck et al. 2013; Zeng et al. 2012). They require a high level of technical expertise and respective labor and usually go along with mechanization, thus confirming the findings of Feike et al. (2012) for the developments in the North China Plain. Even the widened row spacings cannot avoid distinct light gradients between the rubber rows, where the middle of the interspace receives the highest amount of light. Based on trials, Snoeck et al. (2013) conclude that for a row distance of 16 m, profitability of selected tree intercrops (coffee, cacao) can only be expected for the first 12 years. Additionally, the intercropping went along with a considerable rise in labor demand. In the respective trial the yields of lemon and cola had dropped to such a low level that they were no longer recorded after year 13. Guo et al. (2006) conducted an economic case study for rubber-tea intercropping on a state farm on Hainan Island, China, where tea was kept as permanent mixture during the lifespan of rubber. According to their calculation, rubber-tea shows a higher land-expectation value than tea or rubber monocultures. Nevertheless, they also remark that this system is highly dependent on a skilled work force and is thus very sensitive to labor costs. They conclude that increasing labor costs combined with low tea prices are responsible for an observable transformation of rubber-tea into rubber monocultures (Guo et al. 2006).

As a special case of permanent intercropping, Indonesia's 'jungle rubber' might be mentioned, although, in a narrow sense, it doesn't represent intercropping but rather the toleration of a controlled secondary succession. Being probably the most extensive system besides the exploitation of natural stands, it reflects a highly diverse man-made ecosystem which is praised for its diversity, provision of non-timber forest products (NTFP), and positive effects on ecosystem services (ESS) in general (Beukema et al. 2007; Beukema and Noordwijk 2004; Diaz-Novellon et al. 2004; Dove 1993, 1994; Gouyon et al. 1993; Penot 1998, 2004). Originally, it is the result of the integration of *H. brasiliensis* seedlings in the fallow period of a shifting cultivation cycle (Feintrenie and Levang 2009). This system allows only one initial intercrop, originally upland rice, and, probably due to its application in near-natural environments, faces considerable risks of wildlife damages (wild pigs, cattle, tapirs) (Bagnall-Oakeley et al. 1996). Nowadays, this originally subsistence-based system suffers from several out-of-time features, and farmers opt for monocultures if they have enough capital to afford the expensive clonal material (Feintrenie and Levang 2009). Originally, the establishment of jungle rubber was based on cheap, naturally propagated or self-produced seedlings. The heterogeneous planting material, and surely also the extensive management, resulted in a late tappability after 8–12 years compared to the 5–7 years of clonal rubber, and also a very low productivity. The yields reached only one third or one half (650 kg/ha/year) of modern plantations (Bagnall-Oakeley et al. 1996; Wibawa et al. 2006). The use of high-yielding clones led to an increased care-taking in the form of fertilizer application as well as an intensified competition control with herbicides instead of the traditional manual weeding, which was increasingly abandoned due to opportunity costs (Dove 1994; Michon et al. 2007; Penot 2004; Ruf et al. 1999). As a general rule it can be stated that high yielding crops increase the risk of economic losses if the crop is not properly managed, which consequently leads to a higher management intensity (Williams et al. 2001). The above mentioned provision of NTFPs seems to be largely overrated. The only figure to be found on their importance for the household economy dates back to the beginning of the 1990s and states a contribution of 15 %, with the remaining 85 % of income were provided by rubber (Gouyon et al. 1993). It can be assumed that in recent years with considerably improved clones, better infrastructure supporting labor-market access and thus off-farm income options, this contribution further declined. Finally, it needs to be stressed that jungle rubber was developed during a time of low population density and sufficient land resources for expansion (slash & burn!), which often took place at the cost of old growth forests (Feintrenie and Levang 2009). Table 4 suggests a classification of rubber management and intercropping concepts, respectively, based on the rubber life cycle, rather than referring to species used for intercropping.

All in all, the high expectations pinned on intercropping in the past do not seem to have materialized thus far, and the trend goes towards intensification. In general it can be concluded that nowadays intercropping concepts need to economize on labor and/or considerably increase the economic potential of a rubber plantation. Otherwise, farmers or investors might consider the replacement of rubber rather than choosing intercropping, as can currently be observed in Indonesia and Malaysia, where oil palm plantations ousted the traditional rubber systems, or in Xishuangbanna, where bananas replace even middle-aged rubber plantations. Nevertheless, any assessment needs to consider the local environmental as well as socio-economic framework conditions. Monocropping can be very efficient and lucrative as long as the respective commodity price is high. But if farmers limit their portfolio to a single crop and the market price collapses, considerable socio-economic problems arise. A comprehensive farm analyses in our research area in Xishuangbanna (southern China), shows that 30 % of rubber farms above 800 m currently yield below the breakeven point, while the figure for plantations below 600 m is still 16 %. Especially at higher elevations and for lower income farms, tea intercropping safeguards a considerable contribution to livelihood security (Min et al. 2015).

Trends and new approaches in the light of Ecosystem Service (ESS) provision

The consideration of ESS in the assessment of land-use practices is rather new. All papers reviewed as well as our own experience show: So far, where intercropping is practiced, it is basically economy driven (e.g. Zeng et al. 2012; Zhou 2000). The considerable contributions of 'jungle rubber' to environmental conservation were unintentional as Feintrenie et al. (2010) appropriately noted, being a by-product of agricultural evolution, which explains why farmers readily adopt alternatives when higher gains are obvious. When it comes to an immediate support of ESS such as soil integrity and biodiversity, the abandonment of clean-weeding and tolerance of the natural undergrowth, respectively, at least between the rubber rows, would be a big improvement. This is a well-known measure to reduce erosion (Haines 1934) and to maintain soil integrity (Abraham and Joseph 2015), but would also contribute at least to some extend to the conservation of biodiversity (Aratrakorn et al. 2006; Beukema and Noordwijk 2004).

Table 4 Classification of rubber management schemes

	Monoculture	Intercropping -temporary-	Intercropping -permanent- 'short rotations'	Intercropping -permanent- 'long rotations'	Mixed System -permanent- "Jungle rubber"	Timber oriented systems
Plantation establishment	Intensive soil preparation; standard spacing	Intensive soil preparation; standard spacing	Intensive soil preparation; adapted spacing[a]	Intensive soil preparation; adapted spacing[a]	Derived from slash & burn	Transformation of existing plantations
"Light phase" year 1–3	Products: None	Products: annual/bi-annual crops—light demanders: corn, pine apple, banana, chili, … Alternatives: soil protection with cover legumes	Products: annual/bi-annual crops: corn, pine apple, banana, …	Products: annual/bi-annual crops: corn, pine apple, banana, … Products: perennial crops: tea, coffee, cacao, pepper, … Timber trees	Products: annuals (bi-annuals) , staple food: upland rice, corn, Cassava …	Products: annual/bi-annual crops—light demanders: corn, pine apple, banana, chili, … Alternatives: Soil protection with cover legumes
Transition phase year 3–7	Products: None	Products: perennial crops—shade tolerant: tea, coffee, pepper, … Alternatives: soil protection with cover legumes	Products: annual/bi-annual crops—light demanders[a] annual/bi-annual crops—shade tolerant: gingers, mushrooms, …	Products: perennial crops: tea, coffee, cacao, pepper, … Timber trees	Products: NTFP	Products: perennial crops: tea, coffee, cacao, pepper, … Timber trees Latex
"Shade Phase" year 7–30	Products: Latex	Products: perennial crops—shade tolerant: tea, coffee, pepper Until age 10–13! Latex	Products: annual/Bi-annual crops—light demanders[*] Annual/Bi-annual crops—shade tolerant: gingers, mushrooms, … Latex	Products: perennial crops: tea, coffee, cacao, pepper, … Timber trees Latex	Products: Latex (after year 10!) NTFP	Integration of tree species at an rubber age of 10–20 years Products: Latex Timber 'Species protection'
Replacement year +/−30	Products: Timber	Products: Timber	Products: Timber	Products: Timber	Products: Timber NTFP	Products: Timber transformation into forest???

[a] Only with adapted plantation design and widened row spacing, respectively

Nevertheless, the traditional aversion of farmers towards undergrowth, as described by Baulkwill (1989), doesn't seem to have weakened. One reason is the assumed competition for nutrients and water. This is definitely, region- and site specific, a valid point, especially where rubber is planted on predominantly dry sites. Another often quoted reason for farmerś aversion towards undergrowth is the fear of wild animals, especially snakes. We regularly heard this argument when asking farmers their opinion on maintaining undergrowth. It has also been reported in Amazonia (Pierini et al. 1996; Schroth et al. 2003). Although no specific studies for Asia could be found, data on snake bites of rubber tappers in near-natural rubber sites in the Amazon (Pierini et al. 1996) but also in rubber plantations in Nigeria (Umar et al. 2008), where 10 % of the interviewed tappers reported snake bites, suggest that this argument might not be too far-fetched if a dense undergrowth is allowed to thrive between the rubber rows. Aesthetic considerations and facilitation of field work have also been mentioned as reasons against undergrowth (Abraham and Joseph 2015).

Besides the commonly promoted intercrops such as tea, coffee, or cocoa, timber trees recently receive attention. While rubber timber itself developed from a waste-product into an economically important component of rubber plantation management (Killmann and Hong 2000; Shigematsu et al. 2011, 2013), there are also reports on the integration of timber trees into rubber (Jongrungrot and Thungwa 2014; Jongrungrot et al. 2014; Somboonsuke et al. 2011). Although the available information is scarce and sometimes disputable, trees maintained throughout—or beyond—the rubber life-cycle show considerable positive features. There are a wealth of valuable tree species in SE-Asia, exemplifying different ecological strategies and suited to a wide variety of site as well as plantation conditions. If properly selected and established, only little labor input might be required to maintain them. Since regular harvests as in food crops are of no concern, the labor challenge is mitigated. Ecologically, trees permanently stabilize the soil, represent additional structural elements in a plantation, and, depending on the species, can support different animal guilds. Socio-economically, they add to farmerś product portfolio and represent a kind of a bank which might be able to buffer the consequences of price volatility of rubber (Jongrungrot and Thungwa 2014; Jongrungrot et al. 2014). Reported tree species are for example teak (*Tectona grandis*) and Neem (*Azadirachta indica*) in Thailand (Somboonsuke et al. 2011). Since teak is a light demander, its integration needs to be done during the early establishment phase of rubber and requires an adapted light regime throughout the rotation. The Xishuangbanna Tropical Botanical Garden (XTBG) reportedly also conducts trials with the integration of different tree and shrub species. The search for economic improvement also leads to the identification of 'miracle trees', promising a fortune to farmers, such as eaglewood (*Aquilaria* spp.) which is promoted for short-term agarwood production.[5] Agarwood is a highly aromatic and highly priced incense and perfume wood usually found in old trees as a result of a fungal infection and related wood tissue reactions (Persoon 2007). To what extend this not yet fully understood process can be efficiently induced into juvenile trees and thus be the source of additional income in an intercropping concept needs to be seen. Another concept integrating the above findings is currently being tested in the framework of the SURUMER-project. The concept is based on the integration of economically and environmentally valuable trees in middle aged rubber. Middle-aged rubber plantations are well established and provide a shade environment, which is needed by the majority of primary forest tree species at least in their juvenile stage. Weed competition, which is often a big obstacle in tree planting, is thus considerably reduced or even eliminated. The expected slow growth rates are deliberately accepted. This avoids early competition with rubber trees and presumably makes such a system more acceptable to farmers. The approach also provides considerable options to protect endangered species (Langenberger et al. 2015). A careful selection process is definitely required. The biophysical and economic modeling of such alternative options will be a challenging task for the future, especially since only very few local tree species are ecologically and agronomically well studied and understood.

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[5] Lanka Business Today 2014: Agarwood Investment presents higher returns within just 8 years. Global Media Networks Ltd, Colombo, Sri Lanka.

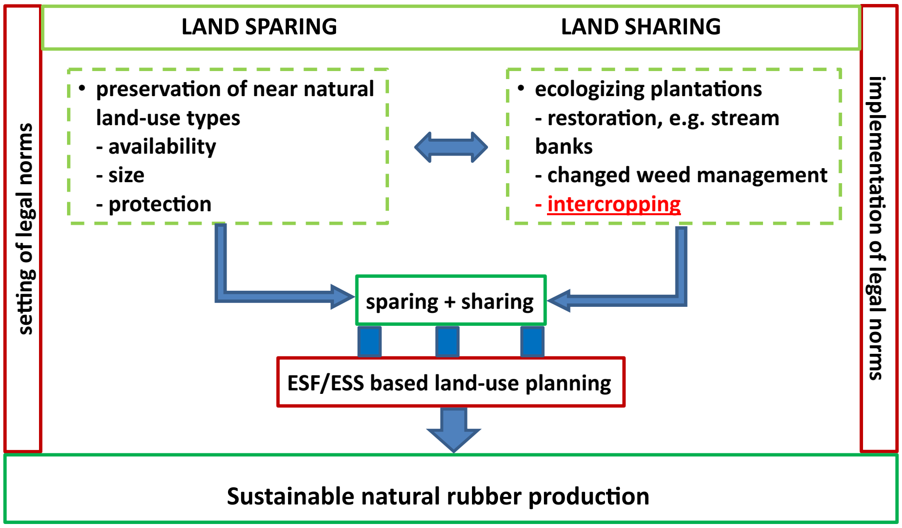

Fig. 6 Pathway to environmental friendly rubber

Discussion and conclusions

Considering the tremendous socio-economic progress as infrastructure development, land and labor valorization or off-farm income options in SE Asia, it becomes clear that traditional land-use concepts need to be updated and adapted to the new conditions as well as an improved scientific understanding. Externalities of monoculture production as the impacts on water availability and quality, stream sedimentation, or biodiversity, need to be considered. Given the sheer dimension of rubber expansion in SE Asia, it is obvious that any kind of intercropping can only be one pillar of a necessary much more comprehensive strategy to mitigate the environmental impacts of rubber plantations. Such a strategy must be based on an ESS-oriented land-use planning, as it is suggested in Fig. 6. In this regard, discussions on land-sharing versus land-sparing concepts sometimes sound a bit academic. In large tracts of MSEA there is not much left to 'spare', and thus, besides potential ecological restoration measures, whose funding is dubious (cf. Yi et al. 2014) at least at a considerable scale, land-sharing might be crucial to maintain ecosystem services.

Due to the mentioned global changes land owners might rather opt for land transformation than for land extensification, as currently can be observed with the competition between oil palm and rubber in Indonesia as well as in Malaysia and the Banana rush in our study area in SW China. To what extend government subsidies, incentives through the REDD+ mechanism, or certification schemes can contribute to a change of practices needs to be seen, but the challenges of implementing such schemes and to acquire the necessary funding are considerable (Fox et al. 2011; Yi et al. 2014). There will definitely be no silver bullet or one-fits all solution. Any concept will need to be site-specific, adapted to the local socio-economic, but also political framework conditions. But considering the integration of socio-economic, ecological and ESS aspects, intercropping with native, long-living tree or shrub species together with the abandonment of clean-weeding currently seems to be the most integrative and promising approach.

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