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Economic outcomes of rubber-based agroforestry systems: a systematic review and narrative synthesis

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Abstract A systematic review was conducted to examine expected economic outcomes of rubber-based agroforestry systems during mature rubber stage in comparison with monoculture rubber farming. Twelve studies were identified for a narrative synthesis of economic outcomes of the mature rubber production systems. The review found that whilst monoculture rubber production may produce higher income in some cases, particularly when rubber prices are high, profitable diversified rubber agroforestry systems were reported in all but one study. Rubber agroforestry has the potential to reduce the vulnerability of smallholders to volatile markets for rubber, particularly if the share of income from secondary species is substantial. Shade-tolerant crops with small canopies (e.g. coffee, bamboo and tea) are reported as ideal intercrops for rubber. Economically advantageous systems reported appeared to be rubber combined with species which provide additional income in the medium to long term (e.g. sheep and high value timber) and/or enhance ongoing cash flow with a lengthy productive lifespan and regular harvests (e.g. durian and gnetum). However, these systems are subject to many constraints such as labour availability, investment and management capacity and market conditions for secondary products. The review showed an absence of farm portfolio studies aimed at finding risk reducing enterprise combinations. Future research on economic outcomes of rubber agroforestry systems should firstly distinguish traditional jungle rubber from rubber agroforestry systems which use clonal rubber similar to those used in monoculture rubber, and secondly consider the full value of secondary products even if they are grown for own consumption.

Keywords Economic · Smallholder · Rubber-based farming diversification · Intercropping · Rubber agroforestry · Narrative synthesis

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Introduction

Rubber is grown in nearly 30 countries. In 2019, 88% (12.9 out of 14.6 million tonnes) of total world natural rubber was produced in Asia (including nearly 11 million tonnes or 75% from South-Eastern Asia) (FAOSTAT 2021). Rubber plantations have expanded rapidly over the last half century from 4.6 million

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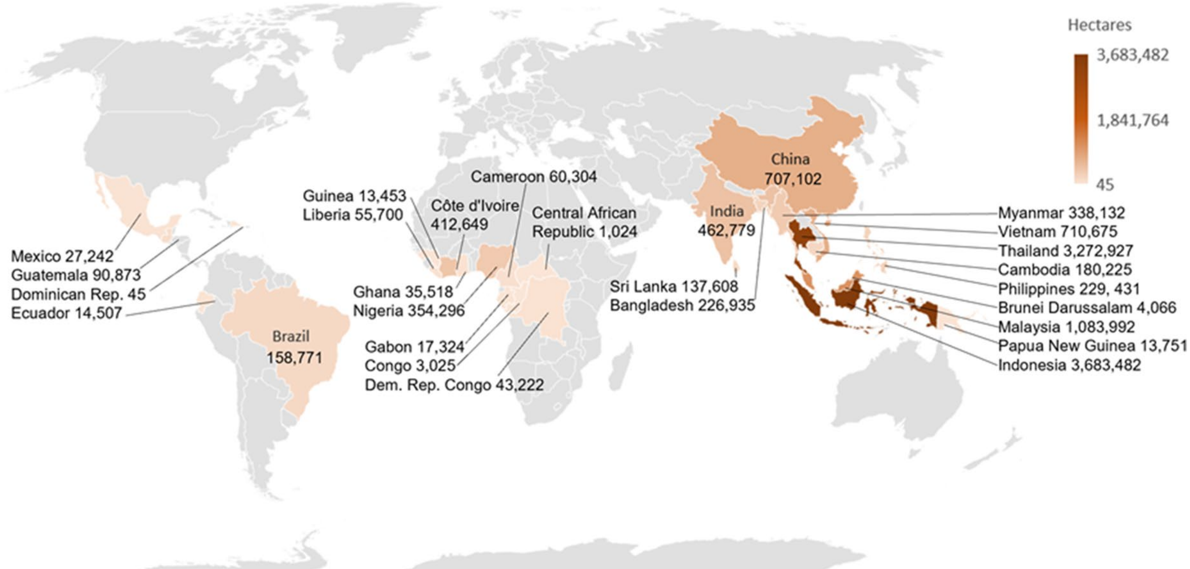

Fig. 1 Area harvested for natural rubber in each producing country in 2019 (Source: FAOSTAT 2021)

ha of global area harvested in 1969 to 12.3 million ha in 2019, of which 11 million ha were in Asia (FAOSTAT 2021) (Fig. 1). Outside Asia the most important producing countries are Côte d'Ivoire, Guatemala, Brazil and Nigeria but together these represent only 8% (1.02 million ha) of global area harvested in 2019 (FAOSTAT 2021). In the top rubber producing countries, natural rubber is largely produced on small holdings[1] constituting around 90% in Thailand and Myanmar, 88% in India and 85% of rubber production in Indonesia (Fox and Castella 2013; Penot et al. 2019).

Rubber is an important cash crop with two types of products for markets, namely latex and rubber wood at the end of rubber lifecycle. The market for latex which is used to make natural rubber products is mainly determined by industrial uses in the automotive and other industries. In many uses natural rubber and synthetic rubber are complements with both used to make the final products. The price of latex which is key to economic analysis is determined largely by the industrial business cycle. When automobile and other manufacturing output is down, natural rubber price and latex prices are down. Rubber wood is a useful by product of natural rubber production, but relatively small part of the overall cashflow, so research on the economics of natural rubber production focus on the latex. Also, rubber wood prices are correlated with latex prices, so rubber wood sales are not very useful in managing production risk. Rubber trees have a certain life span with a long pre-production period before becoming productive. Tapping of rubber trees for latex usually starts from the fifth year for modern clonal varieties (Winarni et al. 2018) to tenth year after planting for traditional unselected rubber trees (Lehébel-Péron et al. 2010). After approximately 30 years a decline in latex production makes further tapping of the trees uneconomic (Manivong and Cramb 2007). Planting density affects rubber productivity in that sparsely planted rubber plantations often suffer from higher wind damage and densely planted rubber trees may produce less latex as the growth of trees would be affected by lack of sunlight. Therefore, apart from market conditions and natural environment such as topology, climate and soil type, profitability of rubber farming is closely related to management decisions such as the selection of rubber varieties and rubber planting density which affect when rubber tree can first be tapped (i.e. producing latex) and how long the rubber trees can remain productive. Another interrelated decision is the rubber farming system which largely falls into two categories: monoculture

[1] For the definitions of small holder rubber farm for each country, see Table 3 in Fox and Castella (2013, p. 6).

and polyculture. Monoculture rubber production is a system where the entire farming field is planted with rubber, mostly with high yielding clonal seedlings at a density of between 400 to 600 trees per ha. Polyculture rubber system, also known as rubber-based agroforestry, involves integration of one or more other species of annual or perennial crops and/or animals alongside rubber trees.

Different forms of rubber-based agroforestry have been practiced. The first type is the jungle rubber system in which rubber trees are planted into secondary forest while retaining some naturally occurring trees and plants. This has been predominantly practiced in Indonesia and also in some small areas of other South and Southeast Asian countries. This system tends to use unselected rubber seedlings with mature rubber tree density of around 200 per ha due to high mortality rate (Lehébel-Péron et al. 2010). Although jungle rubber was found to have a similar return to labour as monoculture rubber in the 1930's (before the apparition of clonal planting material), return to jungle rubber was significantly lower than that of rubber monoculture (after apparition of clones) (Drescher et al. 2016). Jungle rubber has been seen as a low input and low output system which has become economically marginal in Indonesia (Grass et al. 2020) and has "almost entirely disappeared" in Thailand (Stroesser et al. 2018).

The second type is modern rubber agroforestry which is often known as intercropping, i.e. planting or growing other trees or crops with rubber trees (mainly clonal rubber seedlings). Langenberger et al. (2017) highlighted two types of intercropping: initial intercropping (e.g. planting other crops with rubber during the initial establishment period) and permanent intercropping (e.g. planting other crops or trees throughout the lifespan of rubber trees). From both biological and economic perspectives, intercropping young rubber trees is quite different from intercropping mature rubber trees. For the first few years after planting, the rubber trees are small and competition in the inter-row space is minimal. The young rubber trees do not greatly interfere with field operations. Crops interplanted between rubber rows in the first few years tend to be annual crops such as rice and pineapple. In this situation, rubber tree density may be the same as monoculture rubber plantation. In contrast, conventional planting densities needed to maximise latex yields and reduce wind damage can make intercropping in mature rubber trees difficult. Intercropping of rubber trees during the period when latex is being produced occurs in two circumstances: (1) Using the same planting density as monoculture rubber system (Warren-Thomas et al. 2020) or (2) Rubber tree density is reduced to make space for other species (Snoeck et al. 2013).

While great ecological and biophysical benefits of rubber agroforestry are well established (Drescher et al. 2016; Clermont-Dauphin et al. 2018; Warren-Thomas et al. 2015), worldwide production of natural rubber is increasingly in monoculture systems (Langenberger et al. 2017). This trend toward monoculture rubber is especially noted in Asia (Drescher et al. 2016). In Thailand, Delarue and Chambon 2012 reported that only 10% of the overall plantation area in Thailand is intercropped. In Xishuangbanna, southern China, a household survey indicated that only 14% of the assessed rubber plantation area was intercropped (Min et al. 2017). The preference for intensively managed monocrop rubber is often attributed to the greater income generated during periods of high rubber prices, especially when compared with traditional low yield jungle rubber (Clough et al. 2016) and where agricultural land use is intense.

Where smallholders rely primarily on income from monoculture rubber they are particularly vulnerable to fluctuations in price (Goh et al. 2016; Andriesse and Tanwattana 2018). Smallholders wishing to grow intensive monoculture rubber face several other challenges. Firstly, the long immature period and the decline of productivity in aging trees means that monoculture rubber represents a lengthy period of lack or reduction of income from rubber plots for smallholders. Secondly, intensive monoculture rubber planting often requires much higher establishment capital and input costs for fertilisers and herbicides which may be beyond the means of most smallholders (Wulan et al. 2006). Although in some countries such as Thailand (Stroesser et al. 2018) and China (Fox and Castella 2013) smallholders may receive subsidies in the form of new planting or replanting grants, such support has been mainly to cover the operational costs, insufficient to compensate for income from other crops forgone.

There is consensus in the literature that intercropping during immature rubber years is a way of enhancing an early return on investment or providing income before rubber production starts (Hougni et al.

2018; Snoeck et al. 2013). However, studies involving farming diversification during mature rubber stage have produced mixed results depending on the exact system being studied (Stroesser et al. 2016; Winarni et al. 2018).

Therefore, the general objective of this study is to compare systematically the economic outcomes of rubber agroforestry systems with that of monoculture rubber farming during mature rubber stage. The secondary objective is to identify which combinations of farming activities produce positive outcomes and in what context. A deeper and comprehensive understanding of the economic impact of rubber-based diversification will enable policy makers to tailor their intervention strategies to support smallholding rubber farmers, particularly in the top rubber producing countries where smallholdings dominate (Fox and Castella 2013). This also has great relevance to other tree cropping systems. It will also help agricultural extension advisers and individual farmers to make more informed advice or decision.

Methods

To provide the best possible evidence for informing policy and practice in rubber-based agroforestry, this study used systematic review, a tool to develop the evidence base from existing research studies. Systematic review has been used widely in health research since the 1970s (Cochran), more recently in environmental sciences and conservation studies (Centre for Environmental Evidence 2018) and increasingly used in the management and development studies (Denyer and Tranfield 2009).

The review was conducted in line with the widely accepted broad principles of rigour, transparency replicability, and inclusivity (Denyer and Tranfield 2009). A pre-review protocol detailing the scope of the review, the search strategy, the screening process, the pre-defined inclusion and exclusion criteria, and data extraction strategies and data management mechanisms was developed. The protocol was thoroughly discussed within the multidisciplinary international research team.

Scope of the review and inclusion criteria

The scope of literature was restricted to articles published in English. Articles published in Thai language with extended abstract in English were also considered. Articles had to provide primary evidence of economic outcomes of both monoculture rubber and intercropped rubber production systems during mature rubber stage. Any rubber-based farming diversification practice undertaken (i.e. intercropping and/or livestock reared within rubber plantation) and any measures of financial outcomes (e.g. net present values or land returns, benefit cost ratios, costs, margins, profit, income or labour returns etc.) were eligible. Jungle rubber with no secondary product counted for in economic analysis (Drescher et al. 2016; Clough et al. 2016) was excluded. Rubber farming systems at all farm sizes and ownership were considered. Articles were not restricted by publication date. All study designs were considered for inclusion.

Sources of literature

A comprehensive search of literature was undertaken using multiple information sources including: (i) Bibliographic databases (ii) Grey literature sources including websites of relevant organisations as listed below:

Bibliographic databases

- Access to research
- Agecon
- Agris
- Digital Access to Research Theses
- EBSCOHost including: Business Source Complete, CAB Abstracts, GreenFILE, Library, Information Science and Technology Abstracts
- Econlit
- Electronic Theses Online Service
- Emerald
- Open Dissertations
- Proquest
- PROQUEST Dissertations and Theses Global
- Scopus
- Web of Science (core collection)

Other databases

- Association of Natural Rubber Producing Countries
- Centre for International Forestry Research
- CIRAD Agricultural Research for Development
- Food and Agriculture Organization
- International Rubber Consortium Limited
- International Rubber Study Group
- The Consultative Group for International Agricultural Research
- The World Agroforestry Centre (ICRAF)
- Tropical Agricultural Research and Higher Education Centre

Search terms and searches

Search terms were formulated by the review team and a scoping search was performed to validate the methodology. Keywords were tested for specificity and sensitivity using the online database ISI Web of Knowledge (core collection). Search terms were developed based on the key elements of the research question as below:

- Rubber farming: (rubber NOT (tyre OR tire OR synthetic* OR man*made)) AND (agro*forest* OR farm* OR plantation* OR rural OR smallhold*OR small*scale OR tapp*) AND
- Rubber-based farming diversification: (agro*forest* OR "best practice*" OR diversif* OR innovat* OR inter*crop* OR mixed OR multi*crop* OR technolo* OR variabilit*) OR
- Economic outcomes: (benefit* OR economic OR efficien* OR financ* OR gain* OR income* OR inequal* OR livelihood* OR "gross margin" OR maximi*ation OR optimi*ation* OR "net present value" OR poor OR poverty OR portfolio* OR profit* OR return* OR risk* OR productivity OR stability OR sustain* OR variabilit* OR yield* OR wealth)

Searches were restricted to the field of Abstract (e.g. EBSCO) or Title-Abstract-Keywords (e.g. Scopus) or Topic (e.g. Web of Knowledge). The final search string was adapted to the syntax of each source searched. Literature was searched for and captured between February and April 2019.Where the search string could not be used, websites were 'hand-searched' for relevant literature. "Hand-searching" involves looking at all items in a source or using simple search term(s) to search and then screen through all items if search strings cannot be used (Collaboration for Environmental Evidence 2018).

Screening

All retrieved studies were imported to EPPI-Reviewer 4, an online specialised systematic review software appropriate for multi-site teamwork. Screening of articles was based on pre-defined inclusion criteria as explained in Sect. 2.1. The screening was conducted in two stages: (i) Title and abstract (screened concurrently for efficiency) and (ii) Full text. All articles appearing to meet the pre-defined criteria by screening title and abstract were recorded for full text screening. If in doubt, the article would be labelled for full-text downloading. However, 17 titles were not available for retrieval despite great efforts being made to obtain the articles including inter-library loan and extra paid services [Online resource 1, part 1]. Following full text screening, 12 studies met all inclusion criteria, but five of which also included ineligible systems (i.e., immature rubber stage only or non-intercropping farm enterprise). Details of reasons for exclusion of those ineligible systems from the five studies can be found from the Supplementary Material online resource 1, part 2. The narrative synthesis was therefore based on 12 studies which reported economic outcomes for both monoculture rubber system and rubber-based agroforestry system during mature productive rubber stage. One study was based on experimental data and the rest on data from commercial farms. The screening process and the number of inclusions and exclusions at each stage is summarised in Fig. 2.

Screening by title and abstract was completed by the full team. Prior to commencing screening, consistency checking and a Cohen's Kappa analysis was calculated for a random subset (10%) of articles at title and abstract level to ensure that bias was reduced, and inclusion criteria were being applied consistently between reviewers. A Cohen's Kappa statistic of 0.6 or higher was considered acceptable indicating substantial agreement (Landis and Koch 1977). Where

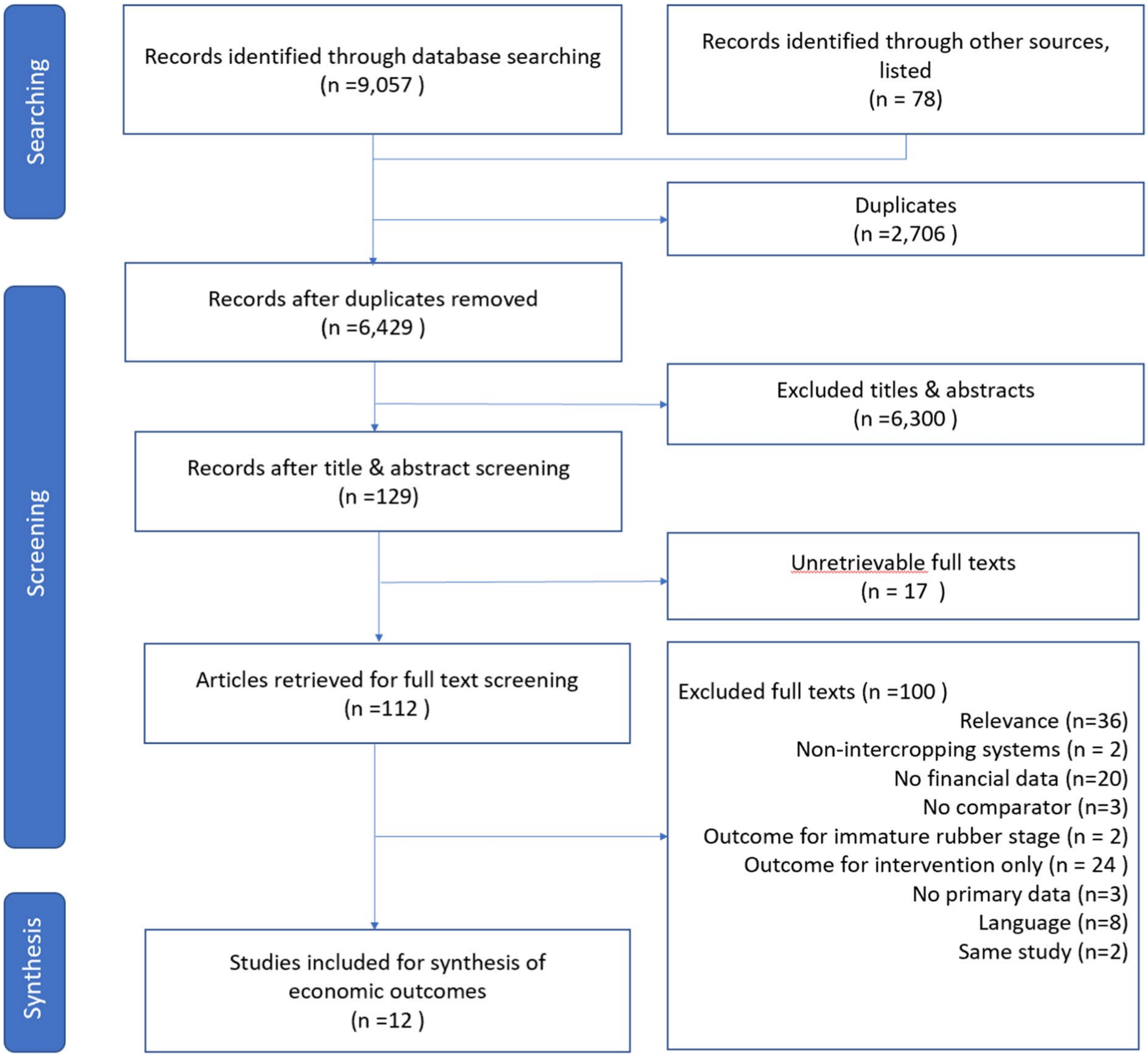

Fig. 2 Flow chart illustrating the number of articles in the process of retrieving, screening and synthesis (diagram adapted from Haddaway et al. 2017)

the level of agreement was low (below c. 0.6 agreement), in depth discussions about disagreements for inclusion and further consistency checking was performed. Each of the full text articles was screened and coded by at least two team members. The first two authors also sample-checked all categories of screening results. Where there was uncertainty or disagreement about inclusion or exclusion of an article, another team member examined the text and a consensus agreement was made.

Data extraction, appraisal and analysis

All eligible studies included for full text coding were coded and the data were extracted using the online software EPPI Reviewer 4. This enabled the review team to check data consistency following pre-defined coding categories. Bibliographic information (e.g. author, title, year, publication type) and information about intervention (i.e. rubber-based farming diversification practices such as crops intercropped with rubber, plant density of both rubber and intercrops), sample profile and country of study were extracted. Each intervention activity was recorded as a unique instance.

Appraisal of a study's risk of bias was based on a bespoke list of quality criteria. The criteria and the detailed scoring of risk of bias can be found in *Online Resource 2* (Supplementary materials).

Economic outcomes used by the studies vary greatly. To maximise the consistency of comparison, only one indicator of expected outcome was chosen from each study for synthesis. Net present value (NPV), if available, was the preferred option because it incorporated value over time of perennial crops. This was followed by cumulative return, net farm income, return to labour, gross margin and income.

A major concern is the completeness of data reporting in relation to the main economic outcome. Only three studies (Charernjiratragul et al. 2014; Snoeck et al. 2013; Somboonsuke 2001) presented complete appropriate financial details. No study conducted any statistical test of difference between the economic outcomes of the diversified activities and monoculture rubber farming. No study provided standard deviation, standard error, upper or lower quartile, minimum or maximum level for the economic outcomes.

Due to the missing information, heterogeneity of reporting and study context, it was impossible to conduct a conventional meta-analysis on the economic outcomes. Synthesis of the research findings was carried out in a narrative and descriptive approach. Only data for the productive stage of rubber plantation were used. Where multiple diversification systems were reported, each system was presented as an instance. Percentage of changes of economic outcomes (EO) was calculated with this formula:

% change of EO = (EO of rubber-based diversification – EO of monoculture rubber)/EO of monoculture rubber × 100.

This transformation provided a common rubric across studies (Popay et al. 2006), hence a basis for comparison of the economic outcomes in the narrative synthesis. Like most studies in international development, there is a substantive heterogeneity in study settings, measures and sources of data (Waddington et al. 2012). This narrative approach has been taken to ensure as much rigour as possible whilst making sure the interpretation of the results meaningful for different social and economic context.

Results

Profiles of studies selected

After applying criteria for economic outcomes as explained in the methods sections, 12 studies from five countries were eligible for narrative synthesis. Ten were published in peer-reviewed journals, one was presented to a conference (Wulan et al. 2006) and one was unpublished report (Charernjiratragul et al. 2014). Eleven articles were in English and one was in Thai but with detailed abstracts in English (Charernjiratragul et al. 2014) (with methods and results translated by Thai co-authors).

The majority of the farms studied were commercial private-owned small-scale farms with the modal size being less than five ha. Data were largely collected through cross-sectional survey interviews. Exceptionally, Guo et al. (2006) used data from a state-owned large commercial farm with 1333 ha for monoculture rubber plantation and 250 ha for rubber-tea intercropping. The Majid et al. (1990) study used smallholder data from the Federal Land Development Authority (FELDA). Snoeck et al. (2013) used data collected over 17 years on a 6-hectare experimental farm which was divided into 24 plots. Wulan et al.'s study (2006) obtained commercial on-farm demonstration/trial data from participants of a network of improved Rubber Agroforestry Systems (RAS) established jointly by the World Agroforestry Centre and CIRAD-France and normal commercial farm data from non-participant smallholder rubber farmers.

A total of 43 secondary species associated with mature rubber were reported in the 12 eligible studies (Table 1). The majority of the secondary species were food crops including: 19 tree types grown for fruits, nuts and legume pods, 5 non-tree legume crops and 3 other non-tree food crops. These were followed by 11 timber tree species including eight species of fast-growing trees and three slow-growing trees. Of all the crops, durian was reported in most studies (n = 7). Livestock reared within mature rubber plantations were sheep, goat, cattle or mixed.

Table 1 Species integrated with rubber as reported in eligible studies

Category	Species integrated with rubber Name used in study	1 Charernjiratragul et al. 2014	2 Guo et al. 2006	3 Majid et al. 1990	4 San & Deaton, 1999	5 Somboonsuke, 2001	6 Lehébel–Péron et al. 2010	7 Simien & Penot, 2011	8 Snoeck et al. 2013	9 Somboonsuke, 2011	AFTb 10 Stroesser et al. 2016	AFMx 10 Stroesser et al. 2016	AFLvA 10 Stroesser et al. 2016	AFLvB 10 Stroesser et al. 2016	AFFr 10 Stroesser et al. 2016	AFVg 10 Stroesser et al. 2016	11 Winarni et al. 2018	RAS1 12 Wulan et al. 2006	RAS2 12 Wulan et al. 2006	RAS3 12 Wulan et al. 2006
Non-tree food Legume crop	Flemingia																			-
Non-tree food Legume crop	Macuna																			-
Non-tree food Legume crop	Manau						-													
Non-tree food Legume crop	Pueraria																			-
Non-tree food Legume crop	Soybean				+															
non-tree food	Pak mieng							+												
non-tree food	Rice							-												
non-tree food (S)	Tea		+																	
Other crop	Cape marigold									-										
Other crop	Cotton									-										
Timber trees	Camphor																-			
Timber trees	Eaglewood	+																		
Timber trees	Ironwood	+									-	-		+						
Timber trees	unspecified																	+		
Timber trees - FGT	Acacia Mangium										-									-
Timber trees - FGT	Bamboo	+																		
Timber trees - FGT	Champak	+									-	-								
Timber trees - FGT	Gmelina arborea																			-
Timber trees - FGT	Moluccan albizzia																			-
Timber trees - FGT	Neem										-	-		+						
Timber trees - FGT	Tung										-	-		+						
Timber trees - FGT	White Meranti						-							+						
Tree food crop - Fruit	Bedaro (Longan)						-													
Tree food crop - Fruit	Custard apple									+										
Tree food crop - Fruit	Durian					+	-	+		-			+				+		+	
Tree food crop - Fruit	Jack fruit (Champada / Cempedak)					+	-			-										
Tree food crop - Fruit	Lemon								-											
Tree food crop - Fruit	Longkong					+		+				-	+							
Tree food crop - Fruit	Mango									-										
Tree food crop - Fruit	Mangosteen							+		-		-			+					
Tree food crop - Fruit	Rambutan					+							+						+	
Tree food crop - Fruit	Salaccca							+		+					+					
Tree food crop - Fruit	unspecified																+			
Tree food crop - Legume	Jengkol						-												+	
Tree food crop - Legume	Kabau						-													
Tree food crop - Legume	Petai / Stink bean						-						+		+				+	
Tree food crop - Nut	Cashew									-										
Tree food crop - Nut	Cola								-											
Tree food crop - Nut	Tenkawang																		+	
Tree food crop - Nut (S)	Cocao								+											
Tree food crop - Nut (S)	Coffee								+											
Tree food crop - Nut (S)	Gnetum											-			+	+				
Livestock	Cattle									-										
Livestock	Sheep/Goat			+	+								+	+						
Livestock	Mixed					+														

S: Shade tolerant
FGT: Fast growing tree

\+ Economic outcome is better than that of monculture rubber
\- Economic outcome is worse than that of monculture rubber
For specific percentage of changes, see Tables 2 and 3.

Table 1 provides an overview of whether rubber-based diversification system produces better or worse economic expected outcomes in terms of NPV or net farm income or gross margin (indicated by "+" or " – ") compared with monoculture rubber. The table shows that five studies (number 1–5 in Table 1) found that intercropped systems outperformed monoculture rubber. One study (number 6) found the opposite. Studies 7–12 in Table 1 had mixed results within each study, i.e. some system outperformed and some underperformed monoculture rubber. Details will be examined in Sect. 3.2.

Due to the heterogeneity of farming context and methods used across different studies, it is important to look into the details of the findings of each study. Two summary tables (Tables 2 and 3) provide specific percentages of changes in economic outcomes and key contextual details (if available) including rubber age, rubber planting density, intercrop planting density or animal stocking rate, rubber tapping start year, rubber lifespan and research details including average farm size, sample size and data type. Not all studies provided complete information and the bias risk was presented in the last column of the two tables. The next part will examine the details of the findings.

Economic performance of rubber-based diversification systems in comparison with monoculture rubber system

Seven studies reported net present value (NPV) for both rubber-based diversified systems and monoculture rubber (Table 2). These include four studies based in Indonesia (Lehébel-Péron et al. 2010; San and Deaton 1999; Winarni et al. 2018 and Wulan et al. 2006), one in Thailand (Charernjiratragul et al. 2014), one in China (Guo et al. 2006) and one in Malaysia (Majid et al. 1990). Table 3 shows the four studies which reported net farm income based on cross-sectional survey data from Thailand (Simien and Penot, 2011; Somboonsuke, 2001; Somboonsuke et al. 2011 and Stroesser et al. 2016) and one other study (Snoeck et al. 2013) which reported cumulative gross margin using longitudinal experimental data from Cote d'Ivoire.

Table 2 Percentage of changes of economic outcomes of rubber-based agroforestry systems compared to monocrop rubber farming and key characteristics of studies based on net present value (NPV)

Author, year, country / Crops intercropped with rubber	Rubber stage	Percentage of NPV change compared with monoculture rubber	Discount rate (%)	Rubber planting density	Intercrops density	Tapping start year	Rubber lifespan	Average farm size (Sample size) (Data type and data collection period) Risk of bias****
Charernjiratragul et al. 2014, Thailand								3.2 ha
Bamboo (S3)	Full cycle	↑ 71.5%	9.25*	7 x 3m (72/rai)	72	6.6	28	(21 RBIS and 31 monoculture farms)
Ironwood and eaglewood (S1)	Full cycle	↑ 70.4%	9.25*	7 x 3m (72/rai)	18	6.6	28	(Interviews and secondary data
Ironwood and champak (S2)	Full cycle	↑ 46.3%	9.25*	7 x 3m (72/rai)	18	6.6	28	Data collected in 2011)
Monoculture rubber	Full cycle	n/a	9.25*	7 x 3m (72/rai)	n/a	7.2	28	Risk of bias: Low
Guo et al. 2006, China								12,250 ha (1,333 ha for monoculture rubber
Tea	Mature	↑ 29.1%	5.76*	12 x 2m (405/ha)	1.6 x 0.3 (14,400/ha)	7	34 (26**)	and 250 for rubber-tea intercropping)
Tea	Mature	↑ 17.4%	2	12 x 2m (405/ha)	1.6 x 0.3 (14,400/ha)	7	34 (30**)	(1 state farm's farm records collected in 2001-2004)
Monoculture rubber	Mature	n/a	5.76* & 2	7 x 3m (480/ha)	n/a	8	33 (29**)	(Economic data beyond Yr 10 estimated)
								Risk of bias: Moderate
Lehébel-Péron et al. 2010, Indonesia								2 ha
Petai dominated (Petai model)	55 years average	↓ -45.6%	0	500/ha (200 tapping)	26 (20 petai, 4 durian and 2 others)	10	55	(26 farms with additional 35 plots)
Agroforest (petai, durian & others)	55 years average	↓ -62.5%	0	500/ha (200 tapping)	28 (7 petai, 4 durian and 15 others)	10	55	(Cross-sectional survey interviews,
Petai dominated (Petai model)	21st - 55th year	↓ -23.0%	0	500/ha (200 tapping)	26 (20 petai, 4 durian and 2 others)	10	55	Olympe simulation modelling,
Agroforest (petai, durian & others) (Potential model)	21st - 40th year	↓ -48.3%	0	500/ha (200 tapping)	26 (7 petai, 4 durian and 15 others)	10	55	Data collected in 2008)
Agroforest (petai, durian & others) (Real model)	21st - 40th year	↓ -55.3%	0	500/ha (200 tapping)	27 (7 petai, 4 durian and 15 others)	10	55	Risk of bias: Moderate
Monoculture rubber	21st - 30th year	n/a	0	550 (assumed)	n/a	5	30	
Majid et al. 1990, Malaysia								28 ha
Sheep grazing in rubber area between year 3 to 25 (S3)	Mature	↑ 11.9%	0	550 (assumed)	50 female and 1 male sheep	7	25	(51 farms)
Monoculture rubber (S2)	Mature	n/a	0	550 (assumed)	n/a	7	25	(Interviews and secondary data,
								Data collected in 1987-88)
								Risk of bias: High
San and Deaton 1999, Indonesia								3 ha
Sheep + soybean	Mature	↑ 38.0%	10	593/ha (optimal)	8 ewes plus soybeans	6	20-30	(85 farms)
Sheep	Mature	↑ 20.0%	10	593/ha (optimal)	8 ewes	6	20-30	(Cross-sectional survey interviews collected in 1993
Monoculture rubber	Mature	n/a	10	550 (assumed)	n/a	6	20-30	Linear Programming modelling)
								Risk of bias: Low
Winarni et al. 2018, Indonesia								5.6 ha -14.7 ha
Durian (fruit) price increased by 5%	60 years plant cycle	↑ 144.4%	6	7 x 3m	220 in year 3 (210 in year 25)	5	25	(Sample size NS)
Camphor (timber) price increased by 3%	50 years plant cycle	↓ -10.6%	6	7 x 3m	400 in year 3 (200 in year 30)	5	25	(Structured interviews and observations
Monoculture rubber price decreased by 4%		n/a	6	7 x 3m	n/a	5	25	and estimated economic data during 2000-2016)
								Risk of bias: Moderate
Wulan et al. 2006, Indonesia								4.8 ha
RAS-2 associated trees (rambutan, durian, petai, tenkawang)	Full cycle***	↑ 127.7%	11	550	92-270	6	28	(80 farms)
RAS-1 (naturally regrown timber + fruit trees) high density	Full cycle***	↑ 67.8%	11	750	NS	7	28	(Ten-year on-farm trial/demonstration plots
RAS-1 normal density medium weeding	Full cycle***	↑ 39.2%	11	550	NS	7	28	and interviews with non-participants,
RAS-1 normal density low weeding	Full cycle***	↑ 25.4%	11	550	NS			yield data beyond year 3 estimated,
RAS-3 timber fast growing trees e.g. acacia (degraded land)	Full cycle***	↓ -11.4%	11	550	NS	7	28	Data collected in 2005-2006)
Monoculture rubber SRDP 90	Full cycle***	n/a	11	550	n/a	5	30	Risk of bias: Moderate

Notes: NS: Not specified   * actual interest rate   ** modelled optimal rotation age

*** First ten years of latext yield and over 20 years profit margin were estimated   **** Full risk of bias appraisal is available in Supplementary materiials (online resource 2)

Table 3 Percentage of changes of economic outcomes of rubber-based agroforestry systems compared to monocrop rubber farming and key characteristics of studies based on net farm income/net profit/income/gross margin

Author, year, country	Crops intercropped with rubber	Rubber stage (year)		Percentage of change compared with monoculture rubber	Rubber planting density**	Intercrops density	Average farm size (Sample size) (Data type and data collection period)	Risk of bias****
Snoeck et al. 2013, Cote d'Ivoire				Cumulative Gross Margin/ha			6 ha	Low
	Coffee	Year 1-10*	↑	98.5%	16 x 2.8m (420/ha)	682/ha	(24 plots within the 6 ha)	
	Cacao	Year 1-10*	↑	65.4%	16 x 2.8m (420/ha)	682/ha	(Experimental data over 17 years)	
	Cola	Year 1-10*	↑	22.4%	16 x 2.8m (420/ha)	55/ha	Data collected during 1989 to 2005	
	Lemon	Year 1-10*	↓	-0.2%	16 x 2.8m (420/ha)	55/ha		
	Coffee	Year 1-17	↑	11.2%	16 x 2.8m (420/ha)	682/ha		
	Cacao	Year 1-17	↑	6.2%	16 x 2.8m (420/ha)	682/ha		
	Cola	Year 1-17	↓	-4.4%	16 x 2.8m (420/ha)	55/ha		
	Lemon	Year 1-17	↓	-7.6%	16 x 2.8m (420/ha)	55/ha		
	Monoculture rubber	Year 1-17		n/a	7 x 2.8m (510/ha)	n/a		
Simien and Penot 2011, Thailand				Net farm income/ha/year			1.5 ha - 17 ha	High
	Vegetable and fruit trees (incl. pak mieng, longkong, rambutan and salacca) in 2005 actual price	Mature***	↑	199.2%	NS	NS	(20 farms)	
	Fruit trees - durian in 2005 actual price	Mature***	↑	93.2%	NS	NS	(Cross-sectional survey interviews	
	Upland rice in 2005 actual price	Mature***	↓	-68.4%	NS	NS	and Olympe simulation modelling)	
	Monoculture rubber	Mature***		n/a	NS	n/a	Data collected in 2005	
	Vegetable and fruit trees in 2009 with no change of price	Mature***	↑	359.1%				
	Fruit trees - durian in 2009 with no change of price	Mature***	↑	222.1%				
	Upland rice in 2009 with no change of price	Mature***	↓	-73.6%				
	Vegetable and fruit treein 2009 with rubber price decrease to US$1/kg	Mature***	↑	161.9%				
	Fruit trees - durian in 2009 with rubber price decrease to US$1/kg	Mature***	↑	333.6%				
	Upland rice in 2009 with rubber price decrease to US$1/kg	Mature***	↓	-84.1%				
Somboonsuke 2001, Thailand		Mature		Net farm income/ha/year			1.92 ha	High
	Fruit trees - durian, rambutan, longkong, champada (R4)	Mature	↑	1451.0%	NS	NS	(26 farms)	
	Integrated system (R6)	Mature	↑	770.1%	NS	NS	(Cross-sectional survey interviews)	
	Livestock unspecified (R5)	Mature	↑	413.6%	NS	6-8 animals/ha	Data ccollected in 1999-2001	
	Monoculture rubber	Mature		n/a	NS	n/a	Risk of bias: High	
Somboonsuke et al. 2011, Thailand				Net farm income/ha/year			2.5 ha	High
	Fruit trees - custard apple	Mature	↑	199.7%	NS	NS	(300 farms)	
	Fruit trees - salacca	Mature	↑	163.7%	NS	NS	(Cross-sectional survey interviews)	
	Fruit trees - mangosteen	Mature	↓	-2.1%	NS	NS	No information on time for data collection	
	Fruit trees - cashew	Mature	↓	-4.1%	NS	NS		
	Fruit trees - durian	Mature	↓	-40.1%	NS	NS		
	Cotton	Mature	↓	-53.3%	NS	NS		
	Cape marigold	Mature	↓	-63.7%	NS	NS		
	Cattle	Mature	↓	-64.0%	NS	NS		
	Fruit trees - mango	Mature	↓	-65.2%	NS	NS		
	Fruit trees - jackfruit	Mature	↓	-92.8%	NS	NS		
	Monoculture rubber	Mature		n/a	NS	n/a		
Stroesser et al. 2016, Thailand				Gross margin/ha/year	Average (min-max)	Average (min-max)	3.48 ha	Moderate
	Goats + fruit trees (longkong, durian, petai, rambutan) AFLvA	Mature	↑	105.7%	479/ha	59/ha plus 60 goats	(32 farms with a total of 59 plots)	
	Gnetum AFVg	Mature	↑	43.2%	446/ha (347-550)	NS	(Cross-sectional survey interviews)	
	Goats + timber (neem, tiam, ironwood and shorea long-term) AFLvB	Mature	↑	42.0%	469/ha	125/ha plus 12 goats	Data collected in 2014-15	
	Fruit trees (mangosteen, petai, salacca) + gnetum + vegetables AFFr	Mature	↑	31.8%	456/ha (141-625)	280/ha (30-1,000)		
	Fruit trees (mangosteen, longkong) + gnetum + timber (neem, tung, and champaka) AFMx	14	↓	-12.3%	456/ha (256-833)	310/ha (35-1,240)		
	Timber trees collected at the end of the rubber trees lifespan AFTb	15	↓	-28.7%	429/ha (313-625)	180/ha (40-470)		
	Monoculture rubber	18		n/a	NS	n/a		

* Tapping starts in the 7th year. Tapping start year not specified in other studies. NS: Not Specified **No studies in this group provided rubber lifespan

*** Rubber productivity decreases by 34% from 2008 onwards and by 2014 rubber trees would bave to be felled (Simien and Penot, 2011, p.255).

**** Full risk of bias appraisal is available in Supplementary materiials (online resource 2)

Based on direct comparison of NPV or net farm income or cumulative gross margin of rubber-based diversified systems with those of monoculture rubber system within each study, five studies found that diversified systems performed better than monoculture rubber system. They are associations of rubber with timber trees in Thailand from Charernjiratragul et al. (2014), with tea in China (Guo et al. 2006), with fruit trees such as durian, rambutan, longkong and champada or other integrated crops in Thailand (Somboonsuke 2001) and with sheep in Malaysia (Majid et al. 1990) and Indonesia (San and Deaton 1999) or mixed livestock in Thailand (Somboonsuke 2001).

Based on samples in Thailand, Charenjiratragul et al. (2014) compared monoculture rubber system with three rubber agroforestry systems namely: rubber combined with ironwood and eaglewood (S1), or with ironwood and champak (S2) or with bamboo (S3). All systems adopted the same rubber density (7×3 m) with S1 and S2 adding 18 other trees per rai (112 trees per ha) and S3 adding 72 bamboos per rai (448 bamboos per ha) within the rubber plantations. Tapping started slightly earlier in the intercropped systems with first tapping at 6.6 years after planting and monoculture rubber at 7.2 years. With a rubber lifespan of 28 years for all four systems and the current interest rate of 9.25%, they found that rubber combined with bamboo (S3) was the most profitable, followed by S1 and S2 (71.5, 70.4 and 46.3% increase of NPV against monoculture rubber respectively). The enhanced NPV of the diversified systems was mainly due to the additional income from secondary products. Two species found to be particularly valuable are bamboo and ironwood. Bamboo were introduced into rubber area in year 7 and harvested in the 9th year of rubber plantation. This brought in extra income all the way to year 28 (the end of rubber lifespan). Income from ironwood, eaglewood and champak were realised only in year 28. The difference between S1 and S2 was due to the higher value of ironwood and eaglewood. The three systems adopted much higher planting density than monoculture rubber. However, this actually increased the rubber yield by 2.3%. One key reason given was that the intercropped systems provided shade which preserved moisture and prevented soil erosion for rubber area, a benefit also found in Chen et al. (2019). Although the density of bamboo was higher than S1 and S2, bamboos are shade tolerant, fast growing and straight growing with a small canopy that does not normally obstruct rubber growth and rubber tapping.

Guo et al. (2006) conducted an economic analysis of monoculture rubber and rubber intercropped with tea based on one case study of a large state-owned farm in Hainan, China. Whilst monoculture rubber adopted the normal density of 7 × 3 m spacing, the intercropped system used 12 × 2 m spacing between rubber trees to accommodate 14,400 tea plants/ha (at 1.6 × 0.3 m spacing between tea plants). Due to typhoon and temperature change, the loss rate of rubber plants was 15% for both systems. Rubber production cycle of monoculture rubber and intercropped rubber was 33 and 34 years with first tapping in the 8th and 7th year respectively. Tea can normally be harvested from year 2. Using the interest rate of 5.76% as discount rate and costing and pricing record from the company, they calculated the NPV of the two systems and found that the rubber-tea intercropping system was consistently more profitable than monoculture rubber and the optimal rotation age was 29 years for monoculture rubber and 26 years for rubber-tea intercropping system. Guo et al. (2006) also conducted some sensitivity tests with different discount rates and price fluctuations of tea or rubber. They found that monoculture rubber would only outperform rubber-tea intercropping system if tea price decreased by 30%. Rubber-tea combination was more profitable because tea is a high value secondary plant and grows well under 30–40% of shade. This also benefited rubber growth so that rubber tapping started one year earlier but ended one year later than monoculture rubber.

Integrating animals into rubber plantations was found to be more profitable than monoculture rubber by both Majid et al. (1990) and San and Deaton (1999). Based on data collected from 51 farms and FELDA, Majid et al. (1990) found that the system with 50 female and one male sheep grazing within rubber plantations for year 3 to year 25 was more profitable than monoculture rubber and the NPV was 11.9% higher than monoculture rubber with a payback period reduced by one year to 8–9 years. San and Deaton (1999) looked at the feasibility of integrating sheep and soybeans into rubber plantations based on data collected from 85 farms participating in the Nucleus Estate smallholder (NES) development projects in North Sumatra of Indonesia. Using linear programming modelling, they found that the optimal combination of rubber trees and sheep for a smallholder rubber farmer was 593 rubber trees and eight ewes plus annual soybean production. The addition of soybean produced higher profit than monoculture rubber or integrating sheep alone within the rubber trees. This applies to the high exploitation model with 16 rubber productive years. If a low exploitation model is used, the optimal number of trees would be 529 with eight years longer productive life. Whilst no details about rubber density and yield were provided, it could be assumed that rubber density for both monoculture and intercropped systems were the same. Addition of sheep into rubber plantations would benefit rubber growth by adding nutrient to the soil and reduce costs for weeding. Family spare labour may be relied upon to herd the sheep. Therefore, the rubber-sheep combination would bring in extra income and reduce costs. However, this finding is based on studies conducted in the last century and may not reflect the present-day situation.

Somboonsuke (2001) reported the economic performance of five types of rubber-based farming systems in comparison with monoculture rubber (R1). Two systems (R2 and R3) are excluded from this synthesis as intercropping mainly take place during immature rubber stage. The three systems looked at in this review are: rubber combined with fruit trees (R4), rubber combined with livestock (R5) and rubber combined with two other species (R6 rubber-integrated system). Fruit trees in R4 system are normally mixed, but often include durian, rambutan, longkong and champada. They may be interplanted with rubber or grown in a separate plot. The author did not separate the two patterns in reporting the financial performance. R5 normally involves 6–8 animals (e.g. cows, poultry, swine, goat and sheep) reared within one hectare of rubber plantation of at least 18 months old. R6 is an integrated system with mixing of more than two activities with four common patterns: rubber-fruit trees-livestock, rubber-rice-livestock, rubber-rice-fruit trees and rubber-fruit tree-fish. Based on data from 26 farms in Songkhla province, Thailand, Somboonsuke (2001) found that all three diversified systems are more profitable than monoculture rubber system with the net farm income of rubber-fruit tree combination (R4) being the highest (1451% higher), followed by rubber-integrated system (R6) (770% higher) and rubber-livestock (413% higher). However, the results of this study should be treated with caution because the study did not separate intercropping systems from non-intercropping systems.

Whilst the above five studies showed positive outcomes achieved by rubber-based agroforestry systems, not all diversified systems are more profitable than monoculture systems. One study (Lehébel-Péron et al. 2010) found that the monoculture rubber system outperformed diversified systems and the other six studies have mixed results. Both positive and negative changes due to diversification were reported within each study.

Lehébel-Péron et al.'s (2010) study looked at three types of rubber-based diversification systems compared with monoculture rubber based on samples in Lubuk Beringin of Jambi Province, Indonesia. One diversified system was labelled 'petai model' which included 20 petai trees, four durian trees and two other trees grown in rubber area. The other two diversified systems were the "real performance model" and the "potential performance model", both included seven petai, four durian and 15 other trees. The real model involves selling "the secondary products of highest value" (p. 80) and the potential model assumes that all secondary products were harvested and sold. All three diversified models planted 500 rubber trees initially but assumed a loss of 60% due to a high incidence of pests and wild boars which means only 200 rubber trees remained when tapping began about 10 years after planting. A full planting cycle was 55 years with 21st to 40th year being the "cruising stage" (full production period) in their analysis (p.72 and p.76). Monoculture rubber has a lifespan of 30 years with tapping starting in the fifth year. Direct comparison of the systems during rubber stage during 21st to 40th year (21st to 30th year for monoculture rubber) shows that the monoculture rubber system was the most profitable of all with the NPV for the "real performance model" (diversified system) being -55.3% of that of monoculture rubber (i.e. less than half of the NPV of monoculture rubber). The petai model's NPV was slightly better than the real model, but still 23% lower than that of monoculture rubber. A key reason for such low financial performance of the agroforest systems analysed in this study was the low-quality rubber varieties and high loss rate of rubber seedlings (with 200 productive trees per hectare only). The average yield dry rubber content (DRC) (50%) was 1,860 kg/ha or 930 kg (DRC 100)/ha from year 21 to 40 (p. 74). The authors did not provide specific average yield for monoculture rubber, but Wulan et al. (2006) showed that the average yield of DRC 100 for monoculture rubber for smallholder project were 1,174 kg/ha with over 500 productive rubber trees. Therefore, it is not surprising that the authors found that monoculture rubber system was more profitable.

Nevertheless, even when modern rubber seedlings and management practices were used in both monoculture and intercropped rubber-based systems, six studies (Snoeck et al. 2013; Simien and Penot, 2011; Somboonsuke et al. 2011; Stroesser et al. 2016; Winarni et al. 2018 and Wulan et al. 2006) found that some rubber-based diversification systems are more profitable and some are less profitable than monoculture rubber production system.

Snoeck et al. (2013) conducted a comparative study of monoculture rubber with four rubber-based diversifications, i.e. rubber intercropped with coffee or cacao or cola or lemon using actual data from a 17-year field trial in South-Western Cote d'Ivoire. Rubber density for monoculture rubber was 510/ha whilst the intercropped systems planted 420 rubber trees per ha. The density for the intercrops was 682 trees/ha for coffee and cacao (small and shade tolerant trees), 55 trees/ha for cola and lemon (larger and need more sunlight). Rubber tapping started in the 7th year. They calculated year-on-year cumulative return defined as the sum of each year's gross margin [income-variable cost]. Snoeck et al. (2013) found that three diversified systems (i.e. rubber intercropped with coffee, cacao and cola) were statistically significantly more profitable than monoculture rubber from year 3 to year 12. The biggest difference was in year 10 when the cumulative return of rubber-coffee, rubber-cacao and rubber-cola combination was 98.5, 65.4 and 22.4% higher than that of monoculture rubber respectively. From the 11th year onwards, the difference between the intercropping systems and monoculture rubber became less and from the 13th year, rubber-cola combination became less profitable, but rubber-coffee and rubber-cacao combinations remained more profitable than monoculture although the difference was less significant. Intercropping rubber with lemon was less profitable from the 8th year onwards due to the sharp drop of lemon yield from year 6. Cola can be harvested between year 7 and 13 with the yield peaking in year 10. This study showed that rubber latex yield actually benefited from having intercrops with yield per tree slightly higher than monoculture rubber. However, the reduction of rubber trees by 17.6% in the diversified systems has to be compensated by sufficient profit from secondary products. In this study, it was found that the growth of lemon and cola (both need more sunlight) was more adversely affected by shade from rubber and stopped producing from year 13 whilst coffee and cacao remained productive until year 17 although the yields peaked in year 7 and year 8 respectively. This explains why cola and lemon were less profitable than monoculture rubber, rubber-coffee or rubber-cacao combinations. However, it is possible that in the full lifespan of rubber, cumulative return of monoculture rubber might be higher than coffee and cacao intercropped systems.

Simien and Penot (2011) studied four rubber-based diversification systems in Phatthalung and Songkhla provinces of Thailand: rubber intercropped with durian, with rice, and with other vegetable and fruit crops (including pak mieng, longkong, rambutan and salacca) in comparison with monoculture rubber systems. No information was available regarding the planting density for each system. Based on data collected in 2005 from 20 commercial farms ranging from 1.5 to 17 ha in size, the authors found that rubber-rice intercropping system was less profitable (68.4% lower net farm income as of 2005) than monoculture rubber. On the contrary, the other two systems, i.e. rubber intercropped with vegetables and fruit crops and rubber with durian, were more profitable with net farm income 199.2 and 93.2% higher than that of monoculture rubber. Based on the assumption that rubber latex would decrease by 34% from 2008 to 2014 when rubber trees would have to be felled, they modelled three scenarios of rubber price fluctuations which were: (1) No change of price, (2) Increase by 5% per annum, and (3) Gradual decrease to US$1/kg in 2009. As shown in Table 3, in 2009 when the rubber price was assumed to be the lowest and rubber income would fall by 34% compared to 2005, rubber-durian combination became the most profitable (333.6% higher than monoculture rubber). If rubber price increases by 5% pa, the net farm income of rubber-mixed system and rubber-durian system would be 400% and 198% higher than that of monoculture rubber respectively. Rubber-rice combination would be consistently less profitable than monoculture rubber system regardless of rubber price fluctuations. This is mainly because rice is less profitable and upland rice has a low yield. In addition, 40% of rice was for own consumption, hence the real value of rice may not be included in the calculation of net farm income.

Somboonsuke et al. (2011) collected data from 300 rubber farms from the three main rubber production regions in Thailand and identified 21 rubber-based production systems. Ten combinations typically grown throughout the rubber plant cycle include seven species of fruit trees (custard apple, salacca, mangosteen, cashew, durian, mango, and jackfruit) plus cotton, cape marigold and cattle. It was found that only rubber-custard apple and rubber-salacca systems generated higher net farm income than monoculture rubber (199.7% and 163.7% higher respectively). No contextual details and cost structure for each system was provided in either of the two studies. Therefore, it is difficult to understand what specific components contributed to the differences. For example, if the plantations were still young and fruit trees (e.g. durian and jackfruit) had not reached high yielding stage, the income of such trees combined with rubber would undoubtedly be lower than monoculture rubber, but in the long term, the performance would be different.

Stroesser et al. (2016) compared economic performance of monoculture rubber system with that of six rubber-based agroforestry systems (see Table 3) based on data collected from 32 farms (59 plots) in Phatthalung province in Southern Thailand. The average rubber planting density was all above 420 for the diversified systems and but no information was provided for monoculture. Measured by gross margin per ha of land used, four systems found to be more profitable than monoculture rubber were: rubber-goats-fruit trees (AFLvA) (105.7% higher), rubber-gnetum (AFVg) (43.2% higher), rubber-goats-timber (AFLvB) (42% higher), and rubber-fruit trees-gnetum-vegetables (AFFr) (31.8% higher). Both rubber-fruit trees-gnetum-timber mix (AFMx) and rubber-timber (AFTb) were less profitable than monoculture rubber. Rubber-livestock combinations (AFLvA and AFLvB) reduces costs in weeding, rubber tree fertilization and goat feed. AFVg is profitable because gnetum requires little care and grows well under shade.

At the time of study, the price for gnetum was also high. The reason that AFMx and AFTb systems were less profitable was because fewer fruit trees in the AFMx system were productive at the time and timber trees were not cut and sold on a regular basis for the AFTb system. However, the timber trees will produce significant income in the end.

Winarni et al. (2018) produced financial analysis results of three rubber-based systems: monoculture rubber (model 1), rubber and camphor (model 2), and rubber and durian (model 3) based on data from Dusun Sanjan, Sanggau District, West Kalimantan, one of the areas also included in Wulan et al.'s (2006) study. In the three systems, rubber trees were planted with the same density (7 × 3 m) and first tapping all started in the fifth year and remain productive until year 25. 400 camphor trees and 220 durian trees were planted between rubber rows initially. Durian fruits can be harvested from year three, peaking in year 55. Camphor timber is harvested from 30th year and durian timber from the 25th year although the maximum timber production potential would be after 40 years. With income component from the sale of durian fruit, sap, firewood, and timber for construction and medicines in addition to latex, NPV at 6% interest rate was calculated for the three systems. They found that rubber combined with durian with 60 years plant cycle was the most profitable (144.4% higher than monoculture rubber), but rubber combined with camphor was the least profitable (10.6% lower than monoculture rubber). To generate profit, monoculture rubber system requires 10.1 ha of land, rubber-camphor system, 14.7 ha and rubber-durian system only requires 5.6 ha. Although this study also adopted the same rubber planting density for both monoculture rubber and diversified systems, the density of secondary plants actually affected rubber productivity with rubber yield decreased by 42% for rubber-camphor system and 57% for rubber-durian system. Such decrease would have to be compensated by the income from secondary products. This fared well with durian which remains productive from year 3 to year 60 with a peak in year 55. Durian is also a high value product. However, income from camphor was not sufficient as camphor trees reach the highest growth by year 40 when camphor timber starts getting harvested. The delayed one-off income from camphor (even if the price is high) combined with the reduction of rubber yield explains why rubber-camphor system was less profitable than monoculture rubber system.

Wulan et al.'s (2006) study looked at three main types of rubber agroforestry systems (RAS) with some variations within each system. All RAS systems used clonal rubber seedlings (PB260, RRIC100, BPM1, or RRIM600 as reported in Joshi et al. 2006). RAS-1 was described as a system like traditional jungle rubber, but used clonal rubber. It differs from RAS-2 in that RAS-1 combines rubber with natural regrowth of timber and fruit trees whilst RAS-2 used high value timber and fruit trees (e.g. rambutan, durian, petai and tengkawang). RAS-3 differs from RAS-2 in that the plots were on degraded land and rubber was combined with annual crops in first year and then fast-growing trees which can be harvested 7–8 years after planting (Joshi et al. 2006). Most RAS systems used rubber planting density of 550 rubber trees/ha. 'RAS-1 high density' planted 750 rubber seedlings instead. 'RAS-1 low weeding' involves weeding twice a year whilst 'RAS-1 medium weeding' about four times a year (Wulan, et al. 2006, p. 438), but both planted 550 rubber seedlings/ha. Calculation of NPV at a discount rate of 11% showed that RAS-1 and RAS-2 systems performed better and RAS-3 with fast growing trees was worse than SRDP monoculture rubber system. In particular, RAS-2 with high value timber (e.g. terindak and nyatu) and fruit trees (e.g. durian, pekawai, petai, jengkol and tengkawang) seemed to provide the highest land return (i.e. 127.7% of NPV for SRDP monoculture rubber). RAS-3 with fast growing trees produced the lowest NPV (11.4% worse than monoculture rubber). Whilst planted on degraded land, rubber yield was actually better than all RAS-1variants due to extra moisture created by the shade from secondary trees. However, RAS-3 requires harvesting and replanting timber trees every seven or eight years. It is not surprising that the establishment cost was the highest and labour return for the full cycle was the lowest of all systems compared. RAS-2 system where rubber was intercropped with high value fruit trees incurred the 2nd highest establishment costs but produced the highest land return. This is because the rubber yields only decreased by 3.6% (from 1,174 kg to 1,131 kg per ha per year) in spite of the much higher overall planting density, but the extra profit from secondary products was much higher than the loss value of rubber yield.

Limitations of this review

The results presented in this study come with the caveat that only a narrative synthesis of study results was possible in this review because of differences in methodologies used in the studies. The variability of results of the narrative synthesis was exacerbated by the wide range of variables that can affect the sustainability of rubber-based systems and their resilience, which vary not only between but also within countries. The strategy developed and used to conduct this systematic review was designed to be comprehensive but not exhaustive. The search was limited to English language terms, which meant that literature published in other languages has not been searched for. It may therefore be possible that considerably more research is done, for example in South America, West Africa and China than the identified literature suggests. Other limitations of this review include: (1) The number of studies eligible for inclusion for this review was small; (2) The rubber-based diversification activities explored in the studies were highly context specific; (3) The outcomes of diversifications were measured differently; (4) Some studies showed a moderate to high risk of bias due to incomplete reporting, small sample size, or unspecified settings such as yield and cost structure for each cropping activity; rubber planting density and rubber life span. It is also worth noting that the majority of studies are based on data from Thailand and Indonesia although this may reflect the dominance of rubber production in the two countries which together accounted for 58.4% of the global supply in 2019 (FAOSTAT 2021).

Discussion

This study adopted a narrative synthesis approach to understand the differences of economic outcomes of rubber-based agroforestry systems during mature rubber stage and their underlying reasons. Despite the limited evidence base and heterogeneous study design and context, some common themes have emerged.

First of all, there is an important distinction to be made between traditional low input low output jungle rubber and modern rubber agroforestry when assessing economic outcomes. As shown in Lehébel-Péron et al.'s (2010) study, the high mortality rate of traditional jungle rubber coupled with low yielding rubber breed and low level of management meant that this type of jungle rubber, even if with incomes from secondary products being considered, would always be less profitable than intensive monoculture rubber plantations (Grass et al. 2020). However, Wulan et al. (2006), also based on data from Indonesia, found that clonal rubber combined with naturally regrown timber and fruit trees and low weeding (RAS-1) was more profitable than monoculture rubber system.

Secondly, majority of the studies reviewed in this study show that modern rubber agroforestry can be more profitable than monoculture rubber and can enhance the long-term resilience of smallholders' livelihood. One of the systems identified is integrating sheep or goat with rubber (Majid et al. 1990; San and Deaton 1999) which generates three types of symbiotic benefits: enriching the soil nutrients for rubber plants, reducing cost for fertiliser, herbicides and weeding, and providing shelter and feed for animals (Stroesser et al. 2016). This system does not require adjustment of rubber planting density. Therefore, any output from the animals would be additional income. There is also potential to make better use of family spare labour such as children's help in rearing sheep. However, there are a number of practical issues regards integrating some species of livestock into rubber, including damage to the bark of young rubber (e.g. from goats), and livestock drinking and spilling latex from cups and causing root damage and soil compaction due to trampling (e.g. from cattle) (Tajuddin 1986).

In additional to the rubber-livestock systems, this review identified over 40 intercropping species associated with mature rubber, with more than half of the diversified systems studied being found to be more profitable than monoculture rubber production system. For rubber-based intercropping systems, the profitability is closely related to the following biophysical and economic factors:

- Biophysical interactions between rubber and secondary crops interplanted – Some species may benefit from rubber tree shade, for example in some parts of Asia, tea quality is improved by being grown in partial shade of rubber trees (e.g. Guo et al. 2006). Other shade tolerant secondary species are coffee and cacao (Snoeck et al. 2013), bamboo (Charernjiratragul et al. 2014) and pak mieng (Simien and Penot, 2011). Species to avoid in particular are those which need a lot of sunlight e.g. lemon (Snoeck et al. 2013) or those growing too tall to affect rubber growth (e.g. camphor in Winarni et al. 2018).

- Lifespan of secondary species – Species found to perform well are those with longer lifespan. Food trees such as durian and petai belong to this category; both can be harvested for over 50 years. Examples of profitable combinations of rubber with durian and/or petai can be seen in studies of Somboonsuke (2001), Simien and Penot (2011), Stroesser et al. (2016), Winarni et al. (2018) and Wulan et al. (2006). This also applies to timber trees. Fast growing timber trees in general were found to be less profitable as they have to be cut and replanted two or three times during one rubber lifecycle (e.g. Wulan et al. 2006).
- Regularity of harvesting of secondary species – Patterns of harvesting vary greatly from those requiring daily harvesting (e.g. pak mieng), two or more harvestings per year (e.g. rice), perennial harvesting (e.g. most fruits and nuts) to one-off harvesting at the end of lifespan (e.g. timber trees). Regular harvesting normally incurs higher labour costs, hence low labour return, but can improve cashflow, particularly for smallholder farmers with limited land resources. Timber trees harvested at the end of lifespan may provide high land return in the long-term, but may not be suitable for rubber farmers who need regular income. This may also affect the findings of studies which were based on data collected at one point of time when additional income from secondary species were not realised (excluded in the financial analysis), the diversified system may appear to be less profitable (Stroesser et al. 2016).
- Planting density design for both rubber and secondary species – whilst there seems to be a fairly standard planting density for monoculture rubber (normally with a 7×3 m spacing), density for secondary species depends very much on the ultimate size and height of the crop. Example of appropriate density which did not adversely affect rubber yield can be found in Charernjiratragul et al. (2014) with standard rubber density combined with 112 ironwood and eaglewood trees per ha. The optimal density of different species in a rubber agroforestry system needs to consider individual farming households' multiple goals (Gosling et al. 2020) and the wider socio-economic-ecological environment.
- Market value of rubber and secondary species – In general, it is advisable to combine rubber with high value timber and fruit trees which have better market stability to hedge the price fluctuation of rubber. Durian (Simien and Penot, 2011) and tea (Guo et al. 2006) are found to withstand price changes. Durian has been highlighted as a desirable plant complementing rubber in both Thailand (Simien and Penot, 2011) and Indonesia (Winarni et al. 2018) where the markets for durian are well developed.

However, what works in one region or country may differ considerably from that in another region country due to environmental, political and socio-economic factors. Despite the positive ecological benefits (Drescher et al. 2016), rubber agroforestry is still not widely adopted, particularly not beyond initial integration of crops in the first 2 years (Langenberger et al. 2017). Apart from the aforementioned factors to consider, a range of other constraints to intercropping have been reported in the literature, including the additional labour requirements and local labour shortage (e.g. Guo et al. 2006; Snoeck et al. 2013; Stroesser et al. 2016), skills and knowledge to implement diversification, investment capacity (e.g. Somboonsuke 2001), government policies (e.g. Penot et al. 2019) and concerns about pest and diseases associated with the intercrop (Somboonsuke 2001; Langenberger et al. 2017). Early and frequent returns from secondary species to better satisfy smallholder farmers cash flow and household consumption needs have been suggested by Gosling et al. (2020) as key requirements to increase agroforestry adoption. Some of the findings of this review provide promising outlook as the positive systems largely align with those requirements.

The rubber agroforestry studies included both indigenous and native trees, as well as a range of livestock species. All of the twelve studies use deterministic (non-stochastic) models to identify biological and physical interactions among various rubber-based diversification alternatives. They focus on the expected value of returns at current or representative prices.

Those studies which conducted price sensitivity testing report that diversified farms have higher returns when rubber prices are low, but none of the twelve studies consider the variability over time and covariance of returns from different activities in developing portfolios of activities. Resilience is subject to a wide variety of other variables (e.g. availability of labour, off-farm income, input costs, local markets for intercrop products, quantities, species, age and productivity of intercrops, efficiency and 'know-how' in management to increase yields, and adaption of other kinds of products from intercrops).

This study focuses on the economics of mature rubber intercropping and monoculture. There is a parallel literature on financial and policy tools to deal with fluctuations in the rubber price and includes: (1) Hedging – for example smallholder rubber producers might access forward pricing contracts based on futures markets for natural rubber (e.g. Goh et al. 2016; Nair 2018); (2) Price insurance—designed to provide financial assistance for the adjustment to a price rather than provide a tool for ex-ante price risk management (e.g. Page and Hewitt 2001; Somboonsuke and Shivakoti 2001); and (3) Government Price Stabilisation Funds – for example the Price Stabilisation Fund in India (e.g. Varkey and Kumar 2013). The financial and policy tools for rubber price risk management are potentially useful for smallholder rubber farmers but are beyond the scope of this review.

Economists have outlined various theories and mechanisms to guide development of portfolios in which the variability of some activities offsets the variability of others (e.g. Markowitz 2008). Those same risk management methodologies have long been used to guide risk management in agriculture (e.g. Anderson et al. 1977; Robison and Barry 1987). Most business and stock market diversification in industrialised countries is at least partially driven formally or informally by portfolio balancing concepts and those portfolio concepts are also applied to understand diversification by smallholder farmers (e.g. Barrett et al. 2001) and producers of tropical tree crops (e.g. Schrott and Ruf 2014). None of the rubber diversification studies used portfolio analysis to identify enterprises that would offset the production and price variability of natural rubber. There is an opportunity to apply those portfolio concepts and tools to rubber farm diversification. The rubber farm activities would be sought that balance risk by identifying enterprises with distributions that offset low returns to rubber production (i.e. when rubber profitability is down, the rubber-based diversification enterprise profitability would tend to be up).

Conclusion and implications for future research

Overall, the twelve studies with economic results for both monoculture rubber system and diversified system suggested that rubber-based agroforestry can provide smallholder rubber farmers with an opportunity to improve the economic outcomes of their farms, but this is dependent on the choice of crops and livestock enterprises that provide good returns for the land and labour use. Rubber-based agroforestry has the potential to reduce the vulnerability of smallholders to volatile markets for rubber, particularly if the share of income from secondary species is substantial. While income of intense monoculture rubber may be greater in some cases than that of diversified rubber production systems particularly when rubber prices are high, profitable diversified rubber farming systems have been reported in all but one study which involved comparison of traditional jungle rubber with high loss rate with conventional monoculture rubber system. Shade-tolerant crops with small canopies (e.g. coffee, bamboo and tea) are reported as ideal intercrops for rubber. Economically advantageous systems reported appeared to be rubber combined with species which provide additional income in the medium to long term (e.g. sheep and high value timber) and/or enhance ongoing cash flow with a lengthy productive lifespan and regular harvests (e.g. durian and gnetum). However, these systems are subject to many constraints such as labour availability, investment and management capacity and market conditions for secondary products. Optimisation of land resources is especially important for smallholders. More research could be done on optimal density and share of different species of secondary crop combined with rubber.

The fact that there are only 12 articles with data to compare the economics of rubber monoculture and rubber-based agroforestry systems suggests a need for more studies of this kind. Economic analysis should be incorporated in studies of rubber production systems and studies on the returns of intercropping rubber should provide a control group of monoculture rubber (either before and after or cross-sectional comparison). Clarity of reporting to facilitate synthesis/analysis of studies and repeatability of experiments is an issue encountered in this review. There was also an issue with the way studies reported and defined financial outcomes. Better standardisation of reporting financial outcomes is needed in all studies of economic impact of any intervention activities.

There are several studies involving economic analysis of jungle rubber. The economic and ecological benefits of jungle rubber require more detailed understanding or analysis. In jungle rubber, many species with economic interests are grown, but are not often taken into consideration in economic analysis. Future research comparing economic outcomes of rubber agroforestry with monoculture rubber should firstly distinguish traditional jungle rubber from rubber agroforestry systems which use rubber breeds similar to those used in monoculture rubber, and secondly consider the full value of secondary products even if they are grown for own consumption.

This review identified a number of understudied subtopics which may benefit from further primary research. There is an absence of portfolio balancing studies that seek to identify crop and livestock enterprises with variability patterns that offset the variability of rubber returns. Studies of historical price series would show which potential intercrop species have price patterns with low correlation, or ideally negatively correlated, with rubber prices.

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Data availability Supplementary materials are provided as online resource 1 and online resource 2.

Code availability Screening and coding of this review were conducted using EPPI-Reviewer 4 which is available online http://eppi.ioe.ac.uk/cms/Default.aspx?alias=eppi.ioe.ac.uk/cms/er4.

Declarations

Conflicts of interest The authors declare that they have no known competing interests that could have appeared to influence the work reported in this report.

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