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Understanding adoption risks of peat-adapted agroforestry options in South Sumatra through decision analysis

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Abstract Peatlands in South Sumatra, Indonesia, covering 24% of the region, are vital for local livelihoods and ecosystem services. Unsustainable cultivation practices threaten their sustainability through irreversible drying of the peat, increased greenhouse gas emissions and fire risks. Agroforestry practices, when adapted to peatlands, may offer multiple socio-economic and environmental benefits. This study evaluated the economic viability of two rice-based and three rubber-based agroforestry systems, designed by World Agroforestry for cultivated peatlands in South Sumatra, comparing them to monoculture baselines. Using decision analysis and probabilistic modelling, including Monte Carlo simulations, we conducted probabilistic cost-benefits analyses, accounting for risks and uncertainties and incorporating expert knowledge. Our model simulated decision outcomes under two scenarios—with and without considering family labour in the costs—to assess the impact of family labour on the outcomes. We identified key uncertainties affecting model outcomes through sensitivity analysis and value of information calculations. Our results showed that rice-based agroforestry systems require substantial establishment costs, mainly for constructing dikes to enable dryland crop cultivation. Despite these upfront costs, the two designed rice-based agroforestry systems offer the potential for higher net returns compared to rice monoculture, especially when family labour costs are excluded from the calculation. All rubber-based agroforestry systems demonstrate higher net returns in the long term compared to rubber monoculture in both family labour scenarios. Narrowing knowledge gaps related to key variables, such as the discount rate, crop yields, crop prices, risk event probabilities and rice yield losses, is important for supporting the decision-making process for rice-based agroforestry systems.

Keywords Decision analysis · Uncertainty · Probabilistic modelling · Agroforestry · Peatlands

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Introduction

Peatland ecosystems provide ecological and socio-economic benefits to many nations and communities worldwide. In Indonesia, peatland ecosystems cover approximately 206,950 km^2, making up about 11% of the country's total land area (Osaki and Tsuji 2016). The integrity of Indonesian peatland ecosystems has been severely compromised by forest fires, logging and the conversion of forests to industrial plantations, alongside unsustainable plantation practices (Koh

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et al. 2011; Miettinen et al. 2012). These activities have led to profound changes in hydrological conditions (Thomas et al. 2014), increased greenhouse gas emissions (Wooster et al. 2018), economic losses (Glauber et al. 2016) and adverse impacts on human health (Hein et al. 2022).

In response to the severe threats posed by peatland degradation, the Indonesian government has implemented a range of plans and regulations to achieve targets in the protection and restoration of peatland ecosystems (Harrison et al. 2020). A key initiative was the establishment of the Indonesian Peatland Restoration Agency (BRG) in 2016, now renamed the Indonesian Peatland and Mangrove Restoration Agency (BRGM). BRGM's primary goal is to restore 1.2 million hectares of degraded peatlands by the end of 2024. To achieve this goal, the BRGM peatland restoration programs are centered around three core strategies: peat rewetting, revegetation, and livelihood revitalization (Peatland and Mangrove Restoration Agency 2021).

According to regulations issued by the Indonesian government,[1] peat areas in the country are classified into two functional categories: peat ecosystems with protection function and peat ecosystems with cultivation function. Peat ecosystems with protection function are only used for conservation purposes such as hydrological balance, carbon storage and biodiversity conservation, while in peat ecosystems with cultivation function, agricultural activities are allowed, subject to other relevant regulations. Unsustainable cultivation practices on peatlands often require drainage, which can cause irreversible peat drying, leading to the release of significant greenhouse gas emissions and an increased risk of fire (Page and Hooijer 2016). Agroforestry presents a viable solution for restoring degraded cultivated peatlands (Giesen and Nirmala 2018). When adapted to peatlands, agroforestry can reduce the risk of fire outbreaks (Dewi et al. 2015), alleviate poverty and enhance food security while simultaneously delivering a range of other ecosystem services (Duffy et al. 2021). However, implementing agroforestry on peatland requires intricate management due to its complex biophysical and institutional requirements. These include careful consideration of hydrological conditions, plant suitability, existing land use, peat typology, land tenure and relevant policies (Blackham et al. 2014; Widayati et al. 2016). Moreover, agroforestry requires long-term investment and sustained system management, which may be beyond the financial and technical capacities of farmers. In addition, the outcomes of agroforestry are difficult to predict due to the dynamic interactions and uncertainties inherent in agricultural systems, which are exacerbated by climate change impacts. These factors contribute to the high-risk nature of agroforestry, which should be considered as an important aspect in decision-making when designing agroforestry interventions for peatland areas.

In support of sustainable peat landscape restoration, World Agroforestry (CIFOR-ICRAF)'s Peat-IMPACTS project has trialed several agroforestry options in selected villages of South Sumatra (Fig. 1). The project focuses on peat ecosystems with cultivation function, which allow agricultural activities under specific management according to government regulations. The initiative involves integrating crops such as coconut (*Cocos nucifera*), areca palm (*Areca catechu*), maize (*Zea mays*), jengkol (*Archidendron jiringa*), petai (*Parkia speciosa*), sentul (*Sandoricum koetjape)* and durian (*Durio zibethinus*) into conventional rice (*Oryza sativa*) and rubber (*Hevea brasiliensis*) systems on cultivated peatlands. The project has designed and implemented agroforestry plots for demonstration. However, comprehensive assessments of economic profitability that incorporate uncertainties, which are crucial for farmers' decision-making processes, are still lacking.

Decision-makers and researchers often encounter challenges due to a lack of effective tools for incorporating uncertainties into assessments of intervention outcomes (Luedeling and Shepherd 2016). Traditional cost–benefit analysis methods, which assign best-bet estimates to uncertain variables, fail to capture the full range of possible outcomes and may thus inadequately reflect uncertainties and risks (Luedeling et al. 2015; Dudley et al. 2019). Decision analysis facilitates the active involvement of relevant stakeholders in defining impact pathways, thereby enhancing model comprehensiveness (Luedeling and Shepherd 2016). In addition, the knowledge and expertise of stakeholders such as farmers, land managers (Oliver et al. 2012) and scientists (Page et al.

[1] Government Regulation of the R.I. No. 57 of 2016 amending Government Regulation of the R.I. No. 71 of 2014 on Protection and Management of Ecosystem of Peat lands.

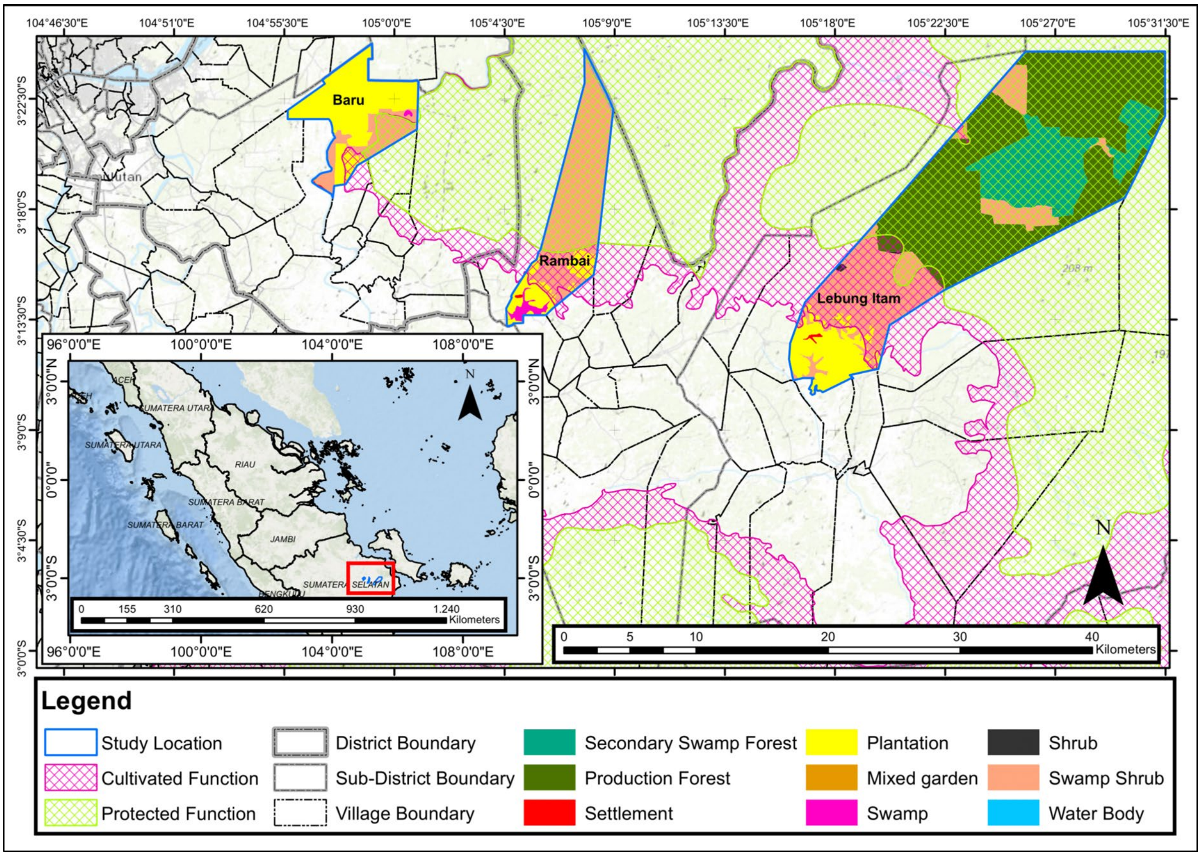


Fig. 1 Map of the study locations. Baru village (left) is located in Banyuasin Regency, while Rambai village (middle) and Lebung Itam village (right) are located in Ogan Komering Ilir Regency, South Sumatra. Based on the overlay with the National Peatland Ecosystem Function Map (MoEF 2017, 2022), areas with a pink striped pattern represent peatland ecosystems designated for cultivation, while areas with a green striped pattern represent peatland ecosystems designated for protection and conservation. Of the three villages, only a few peatlands are designated for cultivation, some of which have been used for plantation

2012) becomes invaluable in situations where data are scarce (Krueger et al. 2012; Shepherd et al. 2015). A hybrid participatory approach that combines a decision analysis with stakeholder inputs has been shown to improve the ability to address bias in decision-making by explicitly accounting for uncertainties and capturing diverse perspective in land-use planning (Uhde et al. 2015).

In typical decision analysis workflows, uncertainty is incorporated in the form of value ranges and associated probabilities (i.e. probability distributions), derived from various sources of information including expert estimates. This approach has also been applied in agroforestry research, where variability in farmers' knowledge was incorporated into multi-criteria optimization models to quantify trade-offs between ecological and economic goals (Gosling et al. 2020). While expert estimates are generally prone to inaccuracies caused by cognitive biases, such biases can be mitigated by subjecting experts to calibration training before eliciting estimates from them (Hardaker et al. 2004, Hubbard 2014).

In the pursuit of more robust analysis of agroforestry options designed for cultivated peatlands in South Sumatra, our study aims to provide comprehensive economic assessments, incorporating risks and uncertainties through applying a decision analysis approach (Luedeling and Shepherd 2016). The procedure of decision analysis allows the development of holistic decision models that integrate hard data with expert knowledge to appropriately present and quantify uncertainties associated with peat-adapted agroforestry interventions in the location.

Materials and methods

Study locations

Our study was conducted in South Sumatra province, which features an extensive peat ecosystem of 2.09 million hectares, as estimated in the Decree of the Minister of Environment and Forestry (MoEF) No 129/MENLHK/SETJEN/PKL.0/2/2017. During 1990–2017, the province experienced significant forest degradation, with approximately 277,000 hectares affected, 71% of which occurred on peatland areas (MoEF 2017). Since 2020, South Sumatra has been a priority location for peatland restoration programs.

Three villages, including Baru in Banyuasin Regency and Lebung Itam and Rambai in Ogan Komering Ilir Regency (Fig. 1), were selected for this study. These villages are part of the focus areas for CIFOR-ICRAF's Peat-IMPACTS project. Local livelihoods mainly rely on agricultural production within peatland ecosystems. The community's livelihoods are mainly derived from rubber, oil palm and timber plantations, animal husbandry, sawmill operation, swallow keeping and horticulture, along with minor areas devoted to aquaculture.

Agroforestry options for local peatlands

We assessed two rice-based agroforestry (AF) systems (Fig. 2) and three rubber-based AF systems (Fig. 3). One of the rice-based AF systems (Fig. 2a) is a combination of coconut, areca palm, maize and rice. The other rice-based AF system (Fig. 2b) consists of areca palm, maize and rice. In both systems, the rice field is surrounded by four 2-m-wide dikes, which are further protected by fences and barbed wires to prevent cows and buffaloes from entering the field. An area of 0.08 hectares on the dike is made available for cultivation of dryland crops. In the first setting, the planting density allows the integration of about 40–45 coconut trees at a spacing of 9 m between trees, and 36–40 areca palms, spaced 3 m apart. The second design accommodates 125–135 areca palm trees along 400 m on the dike. In both designs, maize is cultivated on the dike areas alongside the trees. Given the prevalence of free-grazing cows and buffaloes, establishing field protection is suggested for safeguarding the rice-based agroforestry systems.

The first rubber-based AF system (Fig. 3a) involves a combination of rubber, areca palm and durian. In this design, areca palms are typically planted along the border with a spacing of 3 m, accommodating between 230 and 250 trees. Durians and rubber are intercropped with a spacing of 6 m between trees, resulting in densities

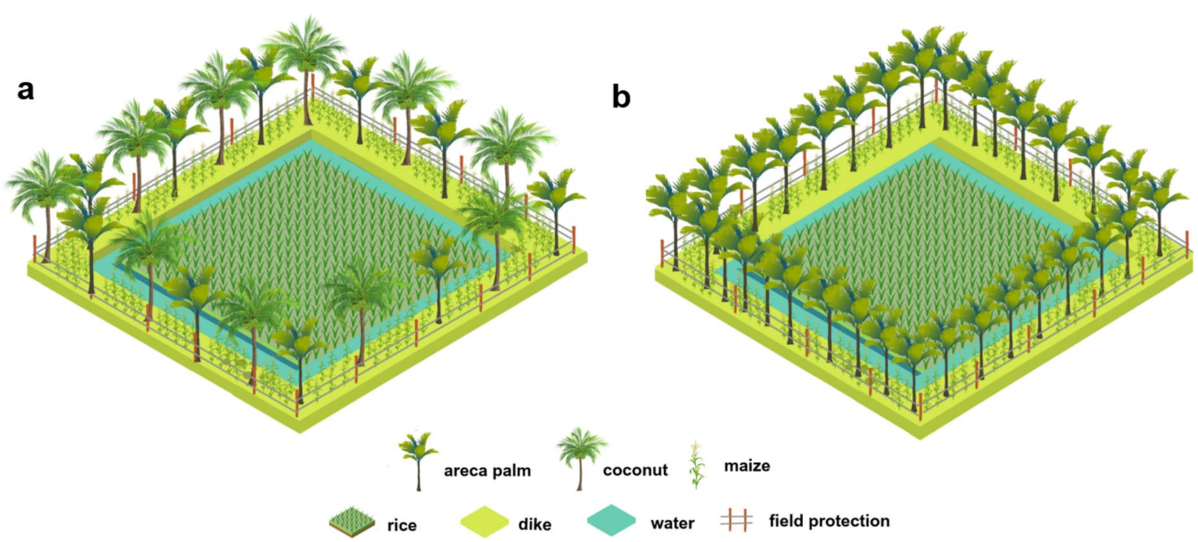


Fig. 2 Rice-based agroforestry farming systems are designed with a dike with a width of 2 m surrounding the rice field to enable crop cultivation, along with field protection. **a** rice-maize-coconut-areca palm system; and **b** rice-maize-areca palm system, as cultivated in Baru village at low altitude (< 20 m above sea level)

of 28 to 56 durian trees and 260–270 rubber trees per hectare.

In the second rubber-based AF system (Fig. 3b), rubber trees are integrated with jengkol and petai, two tropical fruits that belong to the Fabaceae family and are native to Southeast Asia, including Indonesia. Jengkol and petai fruits are commonly used in local cuisine and only available within the local market. Jengkol and petai seedlings are often cultivated from local seeds. The number of petai and jengkol trees per hectare typically ranges from 20 to 40 trees for each species depending on farmers' preferences. Farmers have observed that the cultivation of jengkol and petai does not affect the growth of rubber trees, which are planted at a density of 400 to 600 trees per hectare, as in typical rubber monoculture settings.

The third rubber-based AF system (Fig. 3c) combines rubber with jengkol and sentul. The sentul tree is a local species in the region. Its fruit has sweet and sour tastes and is commonly used for fresh consumption. The tree can be exploited for timber, which is widely used in construction, as well as for furniture-making and carving. In this system, jengkol and sentul trees are usually planted either on plot borders or interspersed among the rubber trees to provide shade during harvesting. The number of jengkol trees varies between 10 and 20 trees per hectare, while farmers typically grow between 10 and 50 sentul trees per hectare. Similar to the second setting, the integration of jengkol and sentul is considered to have no negative impact on rubber growth. Therefore, the rubber tree density is comparable to that of a rubber monoculture, ranging from 400 to 600 trees per hectare.

In all three rubber-based agroforestry systems, annual crops such as chili (*Capsicum annuum*), cassava (*Manihot esculenta*) and banana (*Musa spp.*) are integrated in the first two years to gain short-term income when trees are small. After that, increasing shade levels strongly compromise the growth of these annual crops, leading farmers to discontinue their cultivation.

Decision analysis of rice-based and rubber-based AF systems

We used a decision analysis approach (Hardaker and Lien 2010; Luedeling and Shepherd 2016) to develop cost–benefit models of the two rice-based agroforestry systems, three rubber-based agroforestry systems and monocultures of rice and rubber for comparison. In these models, we incorporated all relevant risks and uncertainties associated with agroforestry implementation. The procedure is outlined in Fig. 4.

The model development process was supported by 2 core experts of the Peat-IMPACTS project team and CIFOR-ICRAF's researchers, who have been responsible for agroforestry trials. The experts were consulted for their expertise and extensive field experience in agroforestry implementation, particularly with crops such as rice, durian and rubber. We conducted structured interviews with 30 farmers, either participants in agroforestry trials or farmers with experience in cultivating various trees and annual crops.

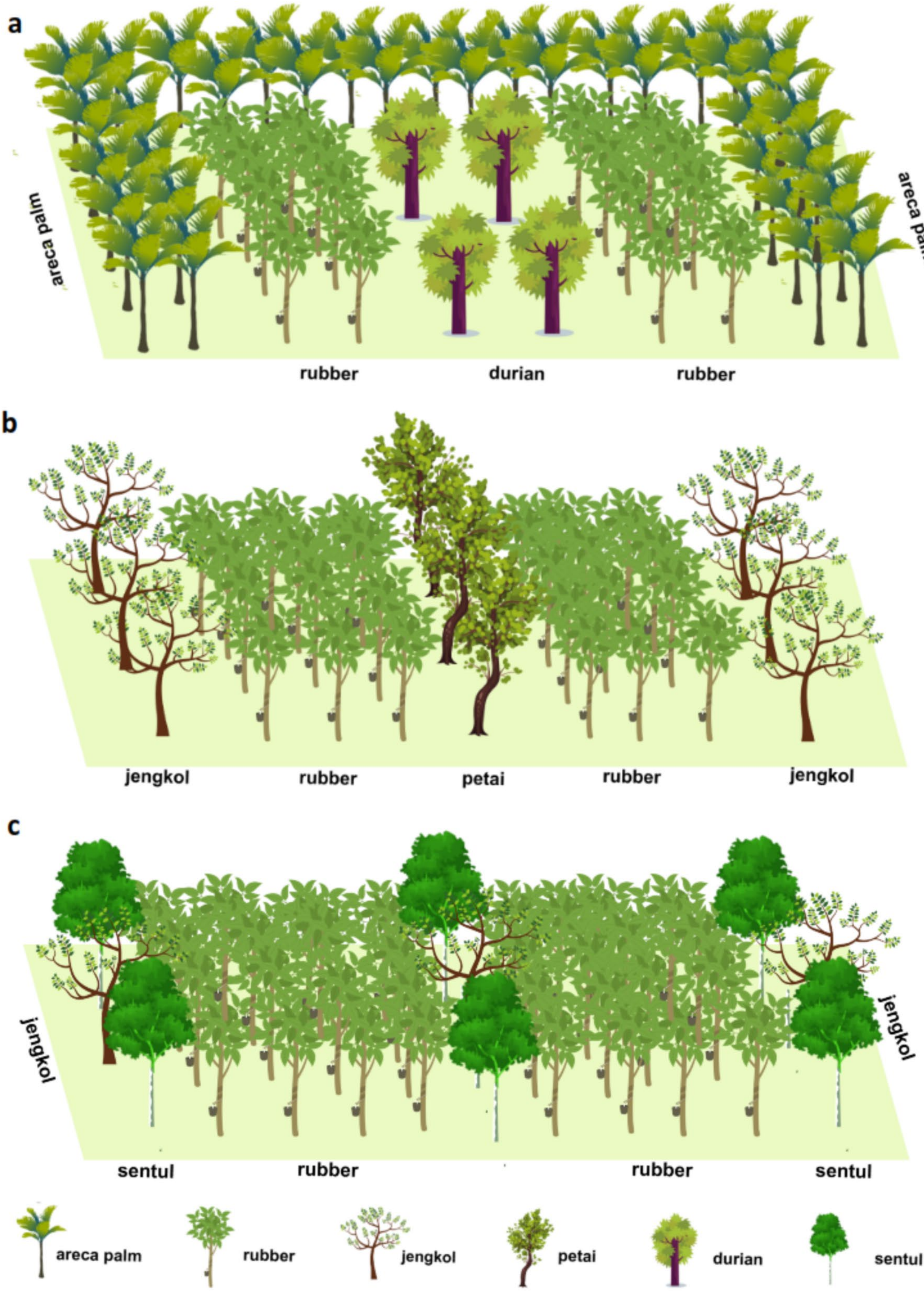
Cost- benefit models of agroforestry farming systems

The conceptual model incorporates cost, benefit and risk components, identified during farmer interviews and refined through expert consultation (Fig. 5). The costs were grouped into three main categories:

1. Establishment costs: These include expenses for land preparation, seedlings and farming equipment for rice monoculture, rubber monoculture, rice-based AF systems and rubber-based AF systems. Additional costs specific to rice-based systems, such as dike establishment and field protection, are also included.
2. Maintenance costs: These cover monitoring expenses, labour costs for ongoing maintenance, and other inputs such as fertiliser, herbicides and dolomite.
3. Harvesting costs: These include costs for transportation, labour for harvesting and the use of harvesting equipment.

The establishment costs were incurred only in the first year. In contrast, maintenance and harvesting costs recurred annually. These recurring costs were estimated by experts, who advised on the periodic costs for replacing or updating equipment as part of the maintenance cost.

Benefits were derived from the revenues of marketable products harvested from each system. These products, which varied by system, included fruits, annual crops, timber, latex, and rice. The revenues


a
areca palm
areca palm
rubber
durian
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b
jengkol
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c
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◀**Fig. 3** Rubber-based AF systems are designed with strip patterns to facilitate efficient harvesting: **a** rubber-areca palm-durian, **b** rubber-jengkol-petai, **c** rubber-jengkol-sentul system, as cultivated in Rambai and Lebung Itam villages at low altitudes (< 30 m above sea level)

were calculated based on product yields and market prices.

The model incorporated risks by simulating the likelihood and impact of risk events, mainly manifesting as yield reductions for trees and crops. Experts identified key risks for both rice-based systems and rubber-based systems. In South Sumatra, extreme weather conditions such as heavy rains, strong winds, and prolonged droughts associated with El Niño events significantly affect the productivity of both rice-based and rubber-based systems. For rice-based agroforestry, droughts can lead to an increase in rodent pests, while heavy rainfall and strong winds can lead rice to fall over. Heavy rains can cause excessive water levels, leading to rice mortality, exacerbated by poor drainage in the diked area. For rubber-based agroforestry, heavy rainfall and prolonged drought conditions reduce latex yields and increase the risk of fires, especially in swampy areas. Additionally, low soil fertility and the presence of free-ranging cows and buffaloes pose threats to rice production in both agroforestry and monoculture setups. The model also considered the spread of pests and diseases and the competition among crops within agroforestry systems.

We employed a Gompertz growth curve to model tree yields (Do et al. 2020; Luedeling et al. 2022). Trees typically require several years after planting before they begin to yield products. The yield then increases gradually until reaching maximum productive capacity, which is maintained throughout the rest of the trees' productive cycles. The Gompertz function requires parameters including maximum harvest (the maximum yield a tree can reach), time to first yield (when immature trees start producing), time to second yield (when trees reach maturity), and yield percentages (proportion of maximum yield at immature and mature stages). In our study, the Gompertz function was specifically applied to simulate yields of rubber, durian, jengkol, petai, coconut, sentul, and areca palm. Apart from its fruit, the sentul tree is harvested for timber and was modeled to be clear-cut every 25 years.

Maize yield was modeled using an exponential decay function to reflect a decline over time (Do et al. 2020). The expected long-term decline in maize yields is caused by competition and shading associated with coconut and areca trees growing in agroforestry systems:

$$Y = Y_f + (Y_0 - Y_f)e^{-rt}$$

In this formula, Y_0 represents the initial maize yield at the time a system is established. The minimum yield that maize can sustain is referred to as Y_f. The minimum yield serves as an indicator of the capability of agroforestry to maintain maize production over the duration of the simulation period. The coefficient k denotes the rate at which the maize yield will converge towards the Y_f value, while t denotes the production cycles.

In rice-based agroforestry systems, areca palm and coconut are integrated at low densities on dikes, providing sufficient space for maize to grow with minimal shading. Harvests from other annual crops such as chili, cassava and banana in rubber-based systems are limited to the first two years. Specifically, chili and cassava are planted in the first year, while bananas are introduced in the second year.

We used the conceptual framework to develop a mathematical model simulating two scenarios of labour costs: excluding and including family labour in the cost calculation. These scenarios reflect the diversity of existing farm operating practices, which range from complete reliance on hired labour to exclusive dependence on family labour for daily farming activities. The purpose of modelling both labour scenarios was to assess the impact of labour costs on projected cash flow and the net benefits to farmers, as well as to highlight the differences in variables most influential to the simulated systems' outcomes.

For each system, we calculated the net present value (NPV) over a 25-year period for one hectare. The 25-year period was based on the lifespan and productive cycles of areca palm (Ghimire and Dhungana 2020) and rubber trees (De Jesus Eufrade Junior et al. 2015; Qi et al. 2016; Yi et al. 2014). NPVs were calculated by discounting the net cash flows, which are the difference between annual benefits and annual costs. The calculation was

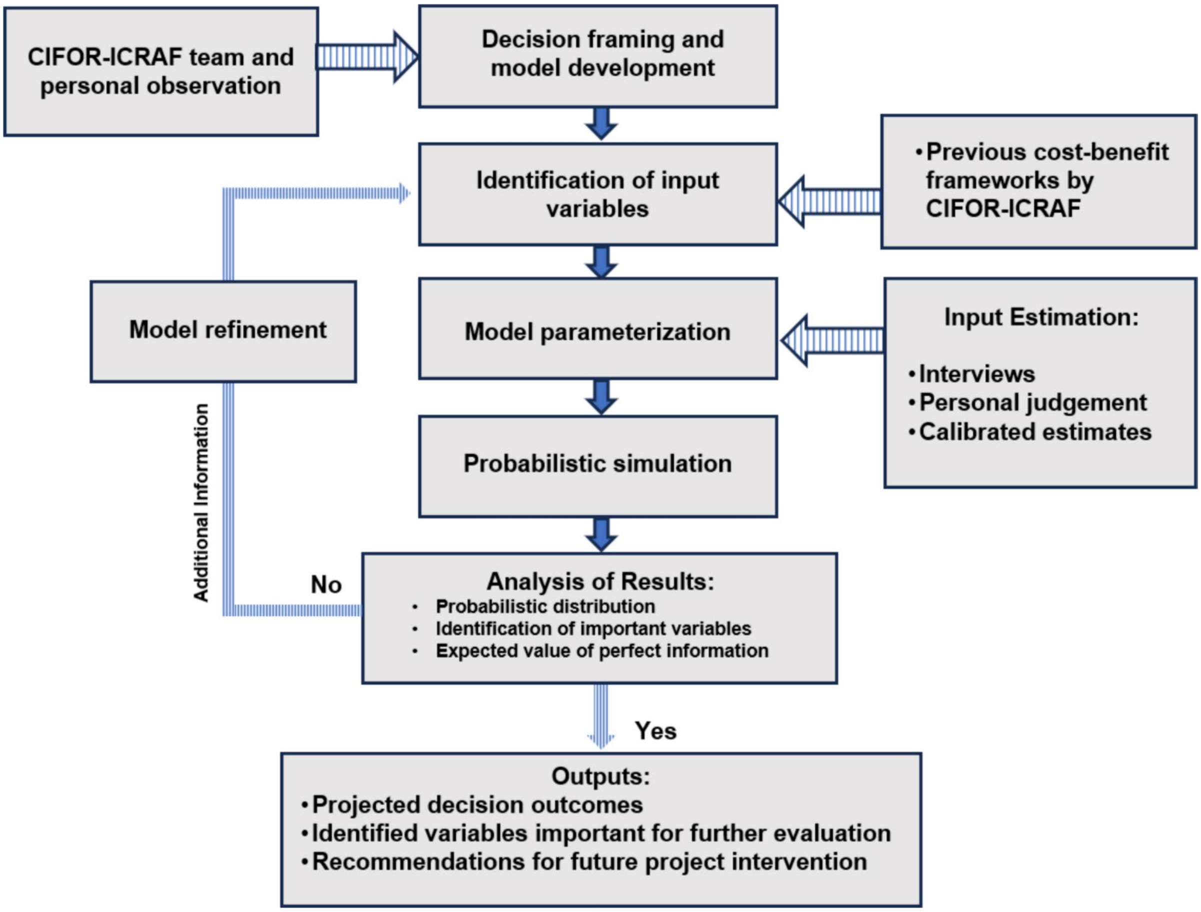


Fig. 4 Decision analysis procedure used to simulate the outcomes of the agroforestry options promoted in Baru, Rambai, and Lebung Itam villages, South Sumatra, Indonesia

performed using the following equation (Gittinger 1982):

$$NPV = \sum_{t=0}^{n} \frac{B_t - C_t}{(1+r)^t}$$

B_t = *Benefits of farming system in yeart*

C_t = *Costs of farming system in yeart*

n = *total simulation life span*

t = *year of simulation*

r = *discount rate*

Quantification of uncertainties in the model inputs

Uncertainty in the model inputs was quantified using 90% confidence intervals for all input variables, estimated based on expert assessments and farmer interviews. Experts, including CIFOR-ICRAF technical experts and the Peat-IMPACTS project team members, underwent calibration training to enhance the accuracy of their estimates (as described by Whitney et al. 2024). This training focused on recognizing and mitigating biases, particularly overconfidence, and introduced debiasing techniques. These techniques allowed assigning probabilities subjectively, equipping experts with skills needed to accurately estimate their uncertainty (as 90% confidence intervals for the actual values) on a certain quantity. The participants were trained and calibrated using a set of trivia

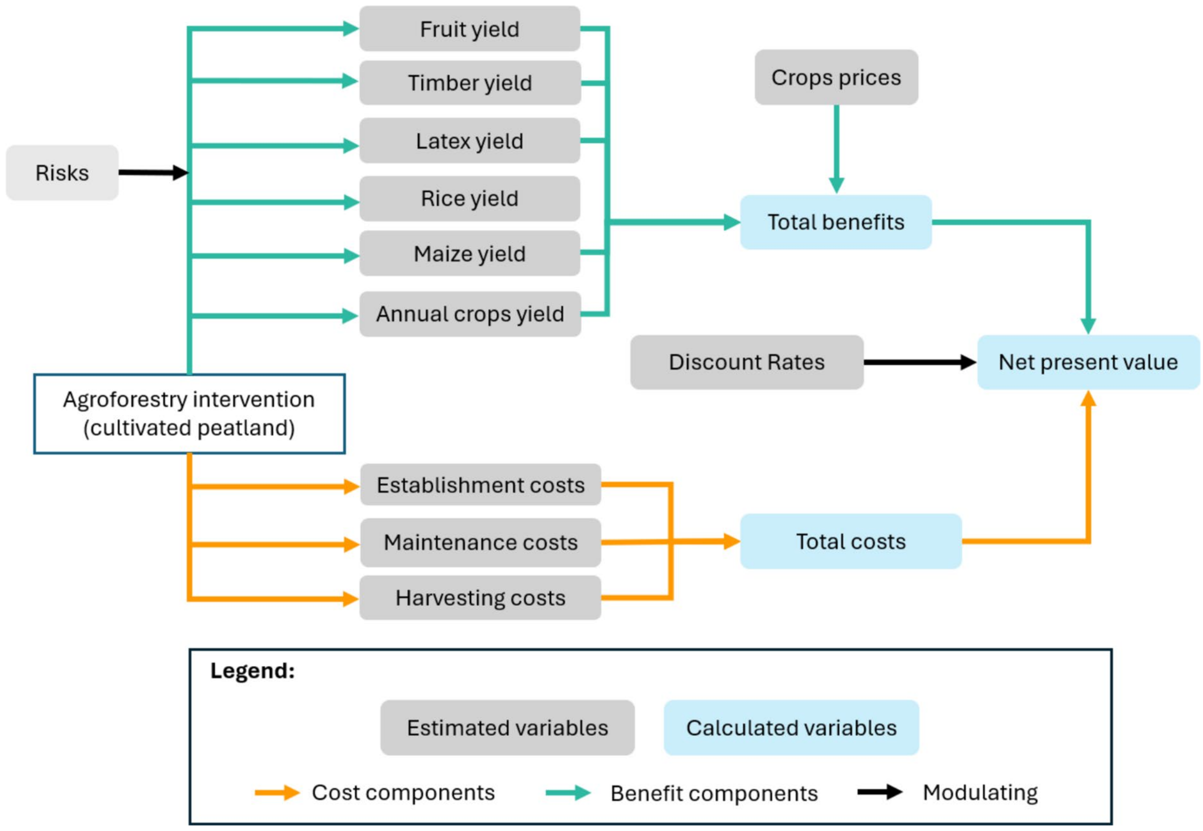


Fig. 5 Conceptual framework of a cost-benefit analysis of agroforestry interventions on cultivated peatlands in South Sumatra, incorporating various risk factors. "Fruit yield" refers to the harvest of areca nuts, durians, jengkol, petai, and sentul fruits. "Annual crop yield" refers to the harvest of banana, cassava, and chili during the first two years of rubber-based agroforestry

estimation questions. Following the training, experts were able to provide more accurate assessments by recognizing biases and improving their judgments accordingly. Farmers, though not part of the training, contributed by providing minimum and maximum bounds of all variables based on their experiences, which were used to validate expert estimates.

Insights from both calibrated experts and farmers helped determine values of costs, tree and crop yields, potential yield losses, and risk events. Input variables, including crop yields, tree density, land clearing costs, labour, seedling and fertiliser costs, first harvesting times, equipment expenses, harvesting costs and transportation costs, were derived from farmer interviews. This information was expressed as value ranges that reflected farmers' actual experiences. Crop prices were derived from both farmers and local trader estimates, acknowledging market fluctuation. Initial estimates were reviewed by experts, with necessary adjustments made. All variables were compiled into a comprehensive assessment, cross-referenced with relevant literature.

Model simulation and output analysis

We used Monte Carlo simulation to implement model calculations involving probability distributions of uncertain inputs. In each model run, Monte Carlo simulation randomly selects values from the input distributions to feed into the model's mathematical equations. The simulation then generates probability distributions of outputs by running the model many times (Kroese et al. 2014). Monte Carlo simulation has been employed in various studies, e.g. to assess the viability of a desalination plant for irrigation (Almansa and Martínez-Paz 2011), to analyse agricultural policies to improve household nutrition (Whitney et al. 2017), to evaluate agroforestry interventions in Vietnam (Do et al. 2020), and to assess the viability of a pipeline project in northern Kenya (Luedeling et al. 2015). We executed 10,000 model runs to generate NPV distributions for all systems under investigation.

We employed Partial Least Squares (PLS) regression to identify input variables that had particularly strong impacts on model outputs. The Variable Importance in the Projection (VIP) scores derived from PLS regression are instrumental in highlighting variables that significantly contribute to variance in the response variable (Farrés et al. 2015). The regression coefficients indicate the direction and magnitude of each variable's impact on the NPV (Luedeling and Gassner 2012). Variables with VIP scores > 1 were considered influential (Chong and Jun 2005).

In addition, we used the concept of Expected Value of Perfect Information (EVPI) to quantify the value of information for each input variable. The EVPI measures the maximum amount of money that would hypothetically be worth allocating to completely eliminate uncertainty regarding specific variables (Hubbard 2014). The EVPI calculations help identify variables for which reducing uncertainty could significantly enhance decision-making clarity (Whitney et al. 2017).

All mathematical modeling and subsequent analyses were implemented in the R programming language using the *decisionSupport* package version 1.111 (Luedeling et al. 2022). The model script and input tables are available in the supplementary material (https://doi.org/10.5281/zenodo.15336807).

Results

Profitability of agroforestry farming systems

Rice-based agroforestry systems

Based on a simulation over 25 years, the two rice-based AF systems are projected to achieve positive cash flow after two years for both labour scenarios, primarily thanks to annual rice harvests (Fig. 6). The AF systems face higher initial establishment costs compared to rice monoculture (Fig. 6). The costs for AF establishment were incurred for the construction of the dikes needed to plant trees. With a 90% confidence interval, both rice-based AF systems, for both labour scenarios, were likely to generate positive cash flow in the second year, with a 73–78% probability. After harvesting started for areca palm in the third year and for coconut in the fourth year, benefits were greater compared to rice monoculture. In contrast, the rice monoculture model generated a 70–75% chance of positive cash flow in the second year (90% confidence interval), which persisted throughout the simulation period for both labour scenarios (Fig. 6). In the scenario excluding family labour costs, the cashflow of rice-maize-coconut-areca palm showed higher net values from the third year onward, compared to the scenario that included these costs (Fig. 6a). This is because areca nut begins to be harvested in the third year, followed by coconut in the fourth year, both of which may require hiring non-family labour. The need to pay for these additional costs reduces the net revenue for farmers when family labour costs are included.

After 25 years, when excluding family labour as costs, rice-maize-coconut-areca palm achieved an NPV ranging from −2648 to 13,597 USD/ha (90% confidence interval), with a 17% chance of negative values (Fig. 7a), while the rice-maize-areca palm AF system generated an NPV between 227 and 18,293 USD/ha (90% confidence interval), with a negligible chance of negative values (Fig. 7b). Rice monoculture showed a wider NPV distribution, from −3918 to 10,221 USD/ha, with a 27% chance of yielding negative outcomes (Fig. 7c).

When family labour was included as costs, the NPV for rice-maize-coconut-areca palm ranged from −5370 to 10,039 USD/ha (Fig. 7a), and rice-maize-areca palm generated an NPV between -1608 and 15,577 USD/ha (Fig. 7b), with similarly low chances of negative values. When family labour costs were included, the NPV of the rice monoculture ranged between -4718 and 9404 USD/ha, with a 33% chance of negative values (Fig. 7c).

We further analysed the differences between the outcomes of agroforestry and monoculture systems to better guide decision-making. We defined the 'net decision outcome' as the difference in the NPV of agroforestry and monoculture. The net decision outcome analysis revealed that opting for rice-maize-coconut-areca palm over rice monoculture resulted in NPV differences of −2032–2290 USD/ha, when

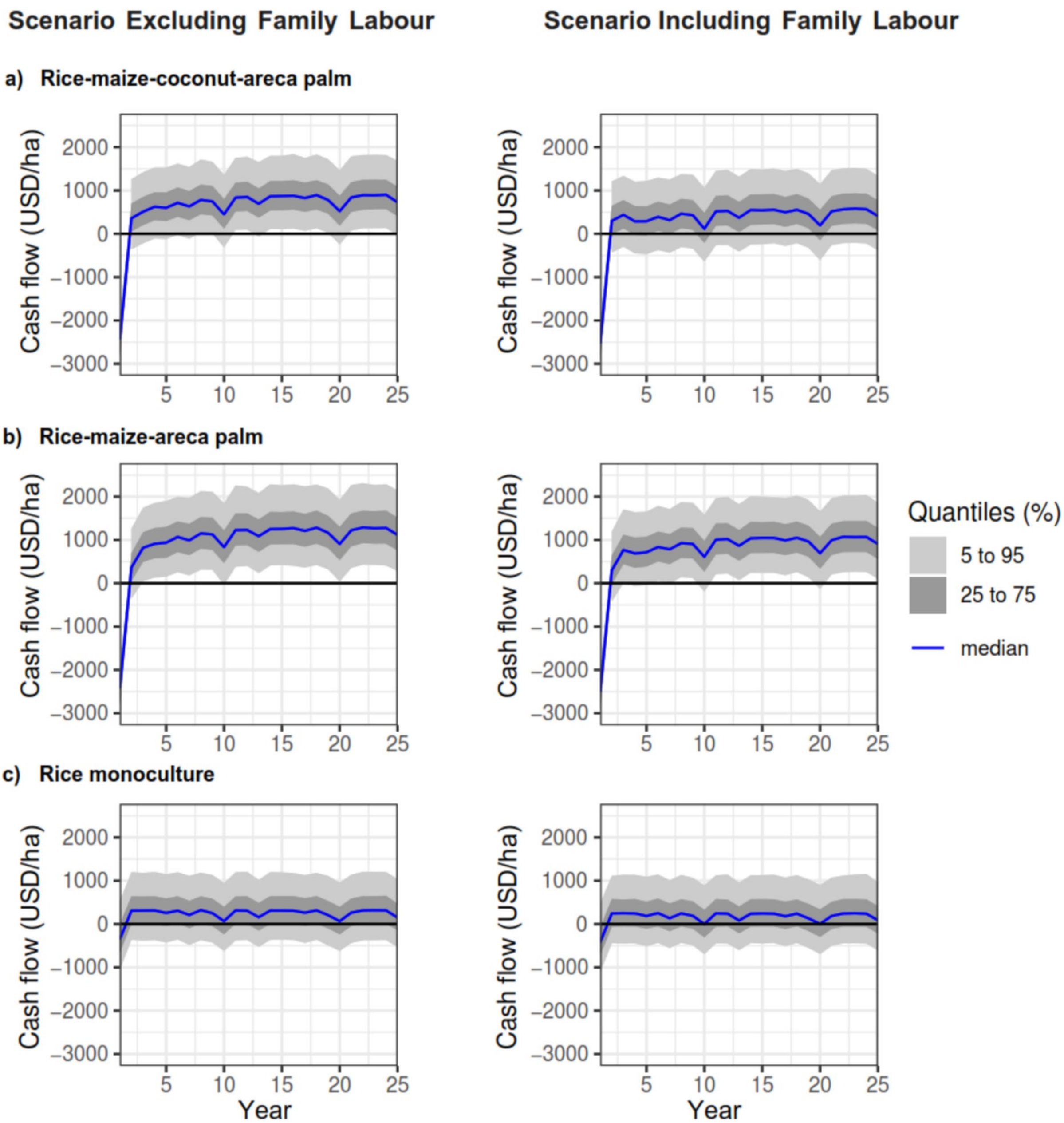


Fig. 6 Simulated cash flow of rice-based agroforestry farming systems and rice monoculture farming systems in Baru village, South Sumatra, for two scenarios: excluding family labour costs (left) and including family labour costs (right). **a** Rice-maize-coconut-areca palm; **b** Rice-maize-areca palm, **c** Rice monoculture. Cash flow plots were obtained from 10,000 Monte Carlo simulation runs of rice-based AF and rice monoculture over 25 years. The different colours of cash flows (right) indicate the 25% and 75% quantiles, and the 5% and 95% quantiles, with the median represented by the blue line

including family labour costs. When excluding family labour costs, the model resulted in NPV differences of −217–5270 USD/ha.

Choosing rice-maize-areca palm over rice monoculture offered NPV differences ranging from 727 to 8666 USD/ha in the scenario including family labour costs. When family labour costs were

Fig. 7 Net Present Values (NPV) of rice-based agroforestry and rice monoculture systems; simulated both excluding (**a, b**) and including (**c**, **d**) family labour costs: **a**, **c** Rice-maize-coconut-areca palm vs Rice monoculture, **b**, **d** Rice-maize-areca palm vs Rice monoculture. Distribution plots (left) reflect the NPVs of 10,000 Monte Carlo simulation runs for rice-based agroforestry and rice monoculture. Bar graphs (middle) represent variable importance (expressed by VIP scores) for variables to which the model was most sensitive (green bars indicate positive relationships with the outcome variables, red bars indicate negative relationships, with VIP scores > 1 leading to variables being considered important) and value of information (right) calculated as the expected value of perfect information (EVPI)

excluded, this range shifted to a 90% confidence interval of 1758–10,425 USD/ha.

Rubber-based agroforestry systems

The model simulation for rubber-based systems showed a significant difference between the two labour scenarios. The inclusion of family labour costs resulted in a higher probability of loss compared to the model where these costs were excluded (Fig. 8).

The negative cash flow of rubber-based AF systems during the first few years indicated significant establishment costs. For the rubber-areca palm-durian model, the median cash flow became positive in year 4 for both labour scenarios, coinciding with the start of areca nut harvesting (Fig. 8a). A notable increase in cash flow occurred in year 6 with the initiation of latex harvesting, and then again in year 8 when durian harvesting started. The

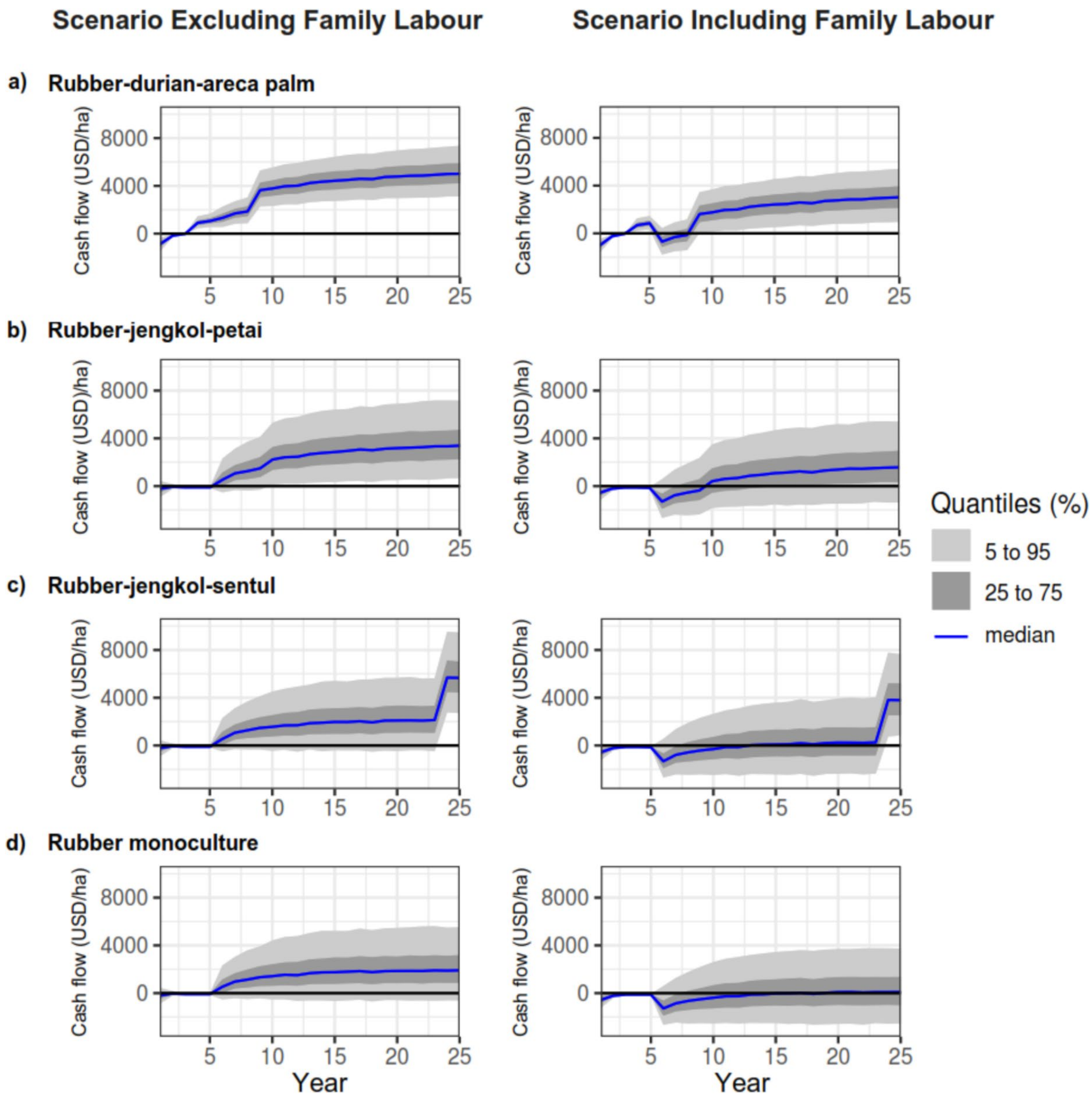
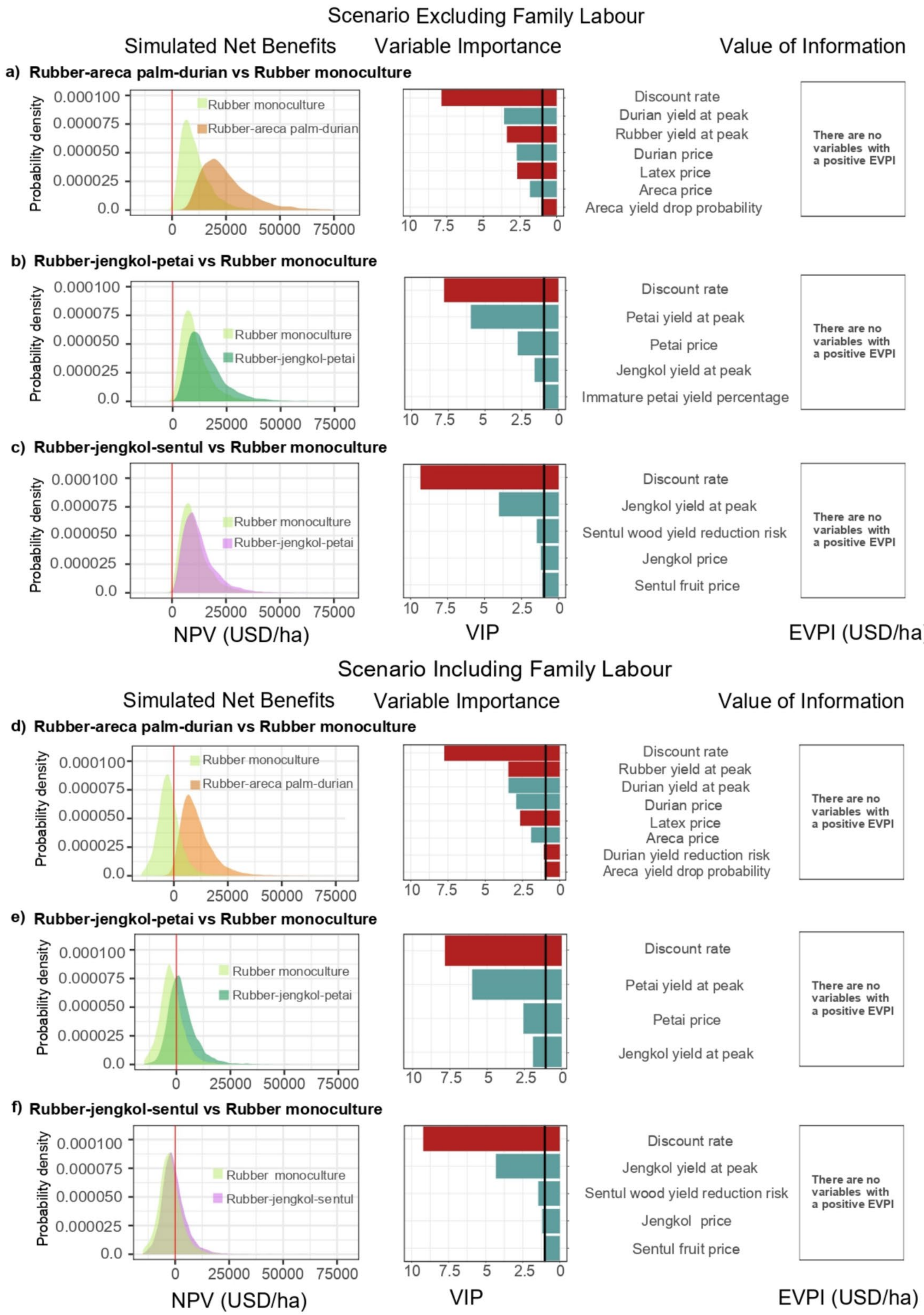


Fig. 8 Cash flow of rubber-based AF systems and rubber monoculture systems, simulated both excluding (left) and including (right) family labour costs. **a** Rubber-durian-areca palm; **b** Rubber-jengkol-petai; **c** Rubber-jengkol-sentul; **d** Rubber monoculture. Cashflow plots were obtained from 10,000 Monte Carlo simulation runs of rubber-based AF and rubber monoculture over 25 years of simulation. The different colours in the plots indicate the 25% and 75% quantiles, and the 5% and 95% quantiles, with the median represented by the blue line


Scenario Excluding Family Labour
Simulated Net Benefits
Variable Importance
Value of Information
a) Rubber-areca palm-durian vs Rubber monoculture
Probability density
Rubber monoculture
Rubber-areca palm-durian
Discount rate
Durian yield at peak
Rubber yield at peak
Durian price
Latex price
Areca price
Areca yield drop probability
There are no variables with a positive EVPI
b) Rubber-jengkol-petai vs Rubber monoculture
Rubber monoculture
Rubber-jengkol-petai
Discount rate
Petai yield at peak
Petai price
Jengkol yield at peak
Immature petai yield percentage
There are no variables with a positive EVPI
c) Rubber-jengkol-sentul vs Rubber monoculture
Rubber monoculture
Rubber-jengkol-petai
Discount rate
Jengkol yield at peak
Sentul wood yield reduction risk
Jengkol price
Sentul fruit price
There are no variables with a positive EVPI
NPV (USD/ha)
VIP
EVPI (USD/ha)
Scenario Including Family Labour
Simulated Net Benefits
Variable Importance
Value of Information
d) Rubber-areca palm-durian vs Rubber monoculture
Rubber monoculture
Rubber-areca palm-durian
Discount rate
Rubber yield at peak
Durian yield at peak
Durian price
Latex price
Areca price
Durian yield reduction risk
Areca yield drop probability
There are no variables with a positive EVPI
e) Rubber-jengkol-petai vs Rubber monoculture
Rubber monoculture
Rubber-jengkol-petai
Discount rate
Petai yield at peak
Petai price
Jengkol yield at peak
There are no variables with a positive EVPI
f) Rubber-jengkol-sentul vs Rubber monoculture
Rubber monoculture
Rubber-jengkol-sentul
Discount rate
Jengkol yield at peak
Sentul wood yield reduction risk
Jengkol price
Sentul fruit price
There are no variables with a positive EVPI
NPV (USD/ha)
VIP
EVPI (USD/ha)

◂**Fig. 9** Net Present Values (NPV) of rubber-based agroforestry and rubber monoculture systems: excluding family labour costs (**a**, **b**, **c**) and including family labour costs (**d**, **e**, **f**). Distribution plots (left) reflect the NPVs of 10,000 Monte Carlo simulation runs of rubber-based agroforestry and rubber monoculture. Bar graphs (middle) represent variable importance (VIP scores) for the most sensitive variables (green bars indicate positive relationships with the outcome variables, red bars indicate negative relationships, with VIP scores > 1 leading to variables being considered important) and bar graphs (right) represent the expected value of perfect information (EVPI)

cash flow continued to rise until the end of the simulation period.

Rubber-jengkol-petai started generating positive cash flow after year 6 with the first rubber harvest (Fig. 8b). Noticeable increases were observed in years 8 and 10 when jengkol and petai harvests began. After this, cash flow remained high throughout the simulation. The cash flow pattern for rubber-jengkol-sentul was comparable to the cash flow of the rubber monoculture, until it was boosted by sentul wood benefits at the end of the simulation period (Fig. 8c).

When family labour was considered as a cost, rubber monoculture generated an 87–100% probability of negative cash flow during the first six years until the initial latex harvest (Fig. 8d). After that, the chance of negative cash flow decreased, generating a 47–78% probability of negative cash flow. When excluding family labour costs, after the first latex harvest in year 6, rubber monoculture showed only a 10–24% chance of negative cash flow throughout the simulation period.

Rubber monoculture exhibited the narrowest NPV range, while the rubber-areca palm-durian system displayed the widest NPV distribution (Fig. 9). With family labour costs, 90% confidence intervals of the NPVs ranged from 1851 to 24,974 USD/ha for rubber-durian-areca palm, from −5984 to 14,747 USD/ha for rubber-jengkol-petai and from −8487 to 9551 USD/ha for rubber-jengkol-sentul. Without family labour costs, NPV distributions featured 90% confidence intervals of 11,187–48,002 USD/ha for rubber-areca palm-durian, 5043—32,980 USD/ha for rubber-jengkol-petai and 3630–27,809 USD/ha for rubber-jengkol-sentul. The ranges for rubber monoculture were −10,931–6986 USD/ha and 2536—23,948 USD/ha with and without family labour costs, respectively.

All the rubber-based AF systems demonstrated higher profitability compared to rubber monoculture. With a 90% confidence interval, the difference in the NPVs of rubber-based AF and rubber monoculture were 3291–28,483 USD/ha for rubber-areca palm-durian, 1242–11,835 USD/ha for rubber-jengkol-petai and 367–4,539 USD/ha for rubber-jengkol-sentul with family labour costs. Without family labour costs, the values were 4131–30,243 USD/ha for rubber-areca palm-durian, 1253–11,317 USD/ha for rubber-jengkol-petai and 556–4822 USD/ha for rubber-jengkol-sentul (90% confidence intervals). These findings imply that opting for rubber-based AF over rubber monoculture offers a gain in both family labour scenarios.

Important variables and their value of information

For both rice-based AF systems, VIP scores for the discount rate were high and negatively correlated with the model outcomes, highlighting this variable as the key factor in the decision (Fig. 7). In addition, the prices of coconut, areca nut and maize, along with variability in maize yield, were marked as positively correlated with outcomes. The percentage of rice yield loss due to risk events, the costs associated with maize cultivation, the harvesting costs of coconut and areca, the probability that areca-related risks occur, and the dike construction costs were also identified as key uncertain variables (VIP > 1), with high values and negative correlations with the decision outcomes.

For the rice-maize-coconut-areca palm system, in the scenario including labour cost, the key uncertain variables included discount rate, prices of coconut, areca nut and maize, harvesting cost of coconut, maize yield, percentage of rice yield loss, costs of planting, harvesting and fertilising maize, and dike construction cost, all of which had non-zero EVPI values (Fig. 7c). In the scenario excluding labour cost, the discount rate was the only key variable with non-zero EVPI. This means that obtaining more information on these variables could be helpful for guiding decisions on the adoption of rice-maize-coconut-areca palm for farmers currently engaged in rice monoculture.

For the rice-maize-areca-palm system, there were no variables with a positive EVPI in the scenario excluding family labour cost, indicating that further information would not reduce uncertainty on the decision to choose the rice-maize-areca-palm system over rice monoculture (Fig. 7b). For the scenario including family labour costs, the EVPI for the discount rate was non-zero, but the value was low, indicating low benefits to decision-makers from additional information on this variable (Fig. 7d).

For all rubber-based agroforestry options, VIP scores consistently indicated the discount rate as a key variable that was negatively correlated with the decision to adopt these systems (Fig. 9). Additionally, rubber price, peak rubber yield, the probability of areca yield decline, and the risk of durian yield reduction were identified as key variables that affected the NPV. Peak yields of petai, jengkol and durian, the price of durian, areca, petai and sentul fruit, as well as the risk of reduced yields of sentul fruit and timber, were identified as key variables whose values were positively correlated with the NPV.

The value of information analysis resulted in EVPI values of zero for all variables across all decision alternatives involving rubber-based systems. This indicates that further information would not reduce uncertainty about the decision of choosing agroforestry systems over rubber monoculture.

Discussion

We demonstrated an application of the decision analysis approach to assess the economic feasibility of agroforestry interventions on cultivated peatlands. The approach is based on probabilistic modeling, which integrates diverse data sources, including expert knowledge, to address risks and uncertainties. Using Monte Carlo simulation, the method overcomes the limitations of deterministic analyses by generating probability distributions of potential outcomes. This provides farmers with a comprehensive view of all possible results of their decisions, including potential undesirable consequences.

Uncertainties in the simulation of agroforestry decisions

Models for rice-based agroforestry resulted in wide NPV distributions with predominantly positive values, whereas rice monoculture systems displayed a narrower range of NPVs, including both negative and positive values. A comparison of predicted outcomes of rice-based AF and rice monoculture suggests that adopting a rice-maize-areca palm system is likely to raise farmers' net benefits. Adopting the rice-maize-coconut-areca palm system requires more consideration due to a high chance of loss.

The rice-maize-areca palm system presents a negligible risk of losses and offers greater benefits compared to rice monoculture. In contrast, the rice-maize-coconut-areca palm setting demonstrates a higher chance of losses, largely due to high establishment costs and increased risks of yield losses. In Baru village, where rice fields are flooded almost throughout the year, establishing agroforestry requires significant modifications, such as dike construction. This involves using an excavator to move mud to the field's border to build dikes that allow the cultivation of dryland crops. Field protection to safeguard against damage from free-ranging cows and buffaloes also incurs high costs. Rice cultivation in monoculture stands is considered high-risk due to a wide range of potential losses, attributed to multiple factors including pests and diseases such as rodents and green stink bugs (*Nezara viridula*), damage caused by cows and buffaloes, environmental stresses from strong wind, heavy rain, floods and drought, low soil fertility and competition among crops. Therefore, by diversifying crop production, rice-based AF systems in general can offer more benefits with a lower probability of loss, enhancing their overall potential advantage compared to monoculture.

Sensitivity analysis highlighted the discount rate as a critical uncertain variable affecting model outcomes of the rice-based AF. This finding is in line with the fundamental principle of the time value of money and the concept of opportunity cost. In our model simulations, we used a discount rate range of 4% to 15%. The lower bound of the range (4%) corresponds to a discount rate that is commonly used in economic evaluations of social projects or public sector investments in developing countries (Zhuang et al. 2007), while the upper bound (15%) captures market-based lending rates typically offered by financial institutions such as banks or rural credit unions. In our study location, the interest rate for micro-enterprise loans is approximately 6%, while the interest rate for bank loans is around 14%. Farmers typically seek loans from micro-enterprise financial institutions if the loan is less than USD 3300. According to the farmers, for loans exceeding USD 3300, the interest rate is generally higher than 6%. By including this wide range for the discount rate parameter, this study captures the diversity among farmers in their perceptions of farm investments.

The importance of the discount rate in long-term agroforestry investments has also been highlighted by Do et al. (2020), who explored various agroforestry settings in upland Vietnam using a similar approach. This uncertainty reflects the long-term nature of agroforestry investments and the relevance of the time value of money in such long-term ventures. In agroforestry, the choice of the discount rate greatly influences NPV results, particularly impacting poor farmers who are often characterized by a high preference for near-term profits. This underscores the importance of incorporating sources of short-term benefits into the design of agroforestry interventions (Atangana et al. 2014).

Rubber-based AF systems demonstrated a higher economic advantage compared to rubber monoculture. However, the investment costs of rubber-areca palm-durian were significantly higher than those of monoculture, making them potentially prohibitive for some farmers. In contrast, the investment costs of rubber-jengkol-petai and rubber-jengkol-sentul were comparable to the monoculture setting. Moreover, most farmers engaged in rubber AF systems face a substantial time lag of four to six years until gaining positive financial returns. As a strategy to cope with this delay, farmers commonly practice intercropping with annual crops such as bananas, cassava and chili for short-term income; some farmers choose off-farm work during these gap years.

Sensitivity analysis identified latex yield and latex price as key uncertain variables regarding adoption of the rubber-based AF, with a high yield and a high price of latex correlating with low favorability of these AF options. In many simulations that included high latex yields or prices, the AF option fell behind the rubber monoculture in terms of economic potential. The uncertainty in latex prices is influenced by the variation in latex quality and the leverage of local traders and brokers, which often leaves farmers with limited bargaining power. Farmers with access to information from regional traders sometimes delay sales until they get fair prices. Global market dynamics also play a significant role in the volatility of the latex price. Durian and areca nut prices exhibited high uncertainty with a positive effect on the NPV, which could be attributed to several factors such as seasonal harvest, product quality, global market conditions and intermediary pricing.

Fewer rubber trees in the rubber-areca palm-durian AF system, on the other hand, resulted in reduced exposure to rubber-related risks. With fewer trees dedicated to rubber cultivation, the potential financial impact of market fluctuations, pest outbreaks or weather events affecting latex yields becomes less dramatic. The diversification in the rubber-jengkol-petai and rubber-jengkol-sentul AF systems also helps mitigate risks, as it spreads the overall risk across different crops and income sources, offering greater resilience compared to monoculture systems.

Variables with non-zero EVPIs should be given attention, as reducing the uncertainty around them could enhance decision-making clarity. Models of rice-based AF generated non-zero EVPIs for variables such as the prices of coconut, areca and maize, maize yield, rice yield loss percentage and dike construction costs. Investigation efforts to reduce uncertainty on these variables are, however, complex and resource-intensive. Consequently, reducing uncertainty on such variables often requires better access to information, which may not always be readily available or affordable. Farmers have to invest their time and money to gather information, secure inputs, or adopt risk-mitigation strategies. In the study locations, efforts to reduce uncertainties may face some challenges due to remote locations, poor internet services, inadequate infrastructure, and a lack of extension agents. Rubber-based AF models generally yield higher NPVs compared to rubber monoculture, making the decision more straightforward. Additional information on variables involved in rubber-based AF models may not change decision recommendations.

Overall, model outputs help guide the decision-making process and identify knowledge gaps that should be addressed before implementing any changes.

Role of family labour in rice and rubber agroforestry

Based on our results, there is a significant difference in net decision outcomes in the scenarios with and without family labour costs. In both simulated rice-based AF and rubber-based AF, excluding labour costs resulted in higher net benefit outcomes compared to the model that included these family labour costs.

In Baru village, rice cultivation mainly relies on family members, who execute all required tasks including land clearing, fertiliser application, rice planting and harvesting. However, farmers who manage more than one hectare of land typically involve non-family labour for management practices that involve labour peaks. For instance, weeds that appear after harvest are difficult to remove due the deep mud and shallow peat, requiring extra labour to speed up the clearing process. Planting rice and applying fertilisers sometimes require additional labour, especially on tidal farms, as these tasks must be completed quickly when the water level is low.

The transition from rice monoculture to rice-based AF also leads to increased labour demand for managing coconut, areca and maize. The involvement of family labour may be crucial for AF farmers. Households with large family sizes may involve family members in most farming activities, whereas those with smaller families may need to hire external labour, especially during peak seasons, which can significantly impact their income (Hoekstra 1987).

Rubber cultivation is labour-intensive, particularly during land clearing, planting and latex harvesting. In Rambai and Lebung Itam, the effort required depends on the prior land use of the farm. Clearing woody areas is more time-consuming and costly than clearing shrublands due to tasks such as manual tree cutting and root removal. In this case, additional external labour is often necessary to expedite the process, which can otherwise take up several weeks per hectare.

Latex harvesting also requires intensive labour inputs, as latex can be tapped on 16–20 days per month. Availability of family labour, therefore, plays a vital role since hiring outside labourers can significantly impact revenues. In Rambai and Lebung Itam, farmers fall into two categories: those who fully manage all farm activities themselves and those who own and manage their farms but rely on hired labour for latex harvesting. When family labour cost is excluded from the calculation, the former group perceives the income from latex sales as a direct compensation for their labour. This approach implicitly accounts for the use of family labour, treating it as a form of self-remuneration.

Adopting rubber-based AF implies additional labour needs for system management. In the rubber-durian-areca palm system, additional labour is inevitable, especially during the durian harvest season. Farmers face challenges in allocating labour between rubber, which requires daily latex harvesting, and durian during its peak harvesting season. Prioritising durian harvesting can result in suboptimal latex collection. Consequently, extra labour is needed to ensure both activities are managed effectively. The rubber-jengkol-petai system also often relies on additional labour during the jengkol and petai harvesting season, but to a lower extent. The rubber-jengkol-sentul system involves less additional cost compared to other rubber-based AF systems, as sentul timber is harvested at the end of the cycle, and its sale is based on the final volume (typically measured in cubic metres) of timber handled by middlemen.

Conclusion

This study evaluated the economic potential of various agroforestry systems in South Sumatra, Indonesia using a decision analysis approach. By employing Monte Carlo simulation, we generated probabilistic outcomes for five agroforestry systems designed for cultivated peatlands, incorporating risks and uncertainties. Rice-based agroforestry systems showed potential for both short and long-term benefits, outperforming rice monoculture, which offers quick but less substantial returns, especially if the cost of family labour is excluded. If family labour is included as a cost, the relative advantage of rice-maize-coconut-areca palm combinations over rice monocultures is unclear, with additional information on crop yields and prices, as well as the percentage of rice yield loss within the system potentially adding clarity to the decision. Rubber-based agroforestry systems potentially offer greater benefits than monoculture, with family labour playing a crucial role, as including family labour costs significantly lowers economic returns. This study provides valuable insights for supporting agroforestry development through informed decision-making and targeted research, particularly in cultivated peatlands in South Sumatra.

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Declarations

Conflict of interest The authors declare no competing interests.

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