

Modelling Human-Landscape System Dynamics to Support Reward Mechanisms for Agro-biodiversity Conservation

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Abstract: A multi-agent simulation modelling approach (LB-LUDAS model) was applied to simulate and visualize the temporal and spatial scale effects of the Payments for Ecosystem services (PES) scheme on the tradeoffs between goods and services. The PES scheme under investigation is a form of eco-certification of biodiversity-friendly rubber agroforests, with quantitative performance criteria proposed for the villages of Jambi Province (Sumatra), Indonesia. Within the model, a process-based decision making sub-model is integrated in the agents' decision-making mechanism of the LB-LUDAS model, while species richness, carbon sequestration, and natural succession sub-models are imbedded in the landscape agents. Main results showed that PES for jungle rubber could offer synergies among carbon emission reduction, biodiversity and livelihoods when compared to the current trend (baseline). Thus, such a scheme could reduce the trade-offs resulting from possible land-use/cover change. The results of the simulation were validated using a role-playing game testing responses to external agents.

Keywords: payments for ecosystem services; eco-certification; rubber-agroforest.

1 INTRODUCTION

In an agricultural landscape, the main argument for creating payments for ecosystem services (PES) schemes is that ecosystems such as natural or secondary forests, as well as man-made landscapes exploited for agriculture, provide mankind not only with marketed commodities but also with additional services that create ecological benefits at complementary local, regional, and global scales (MA 2005; Van Hecken and Bastiaensen 2010). Based on that premise, the land users are seen as ES providers who are assumed to take the opportunity to add ES to the portfolio of their production choices. Furthermore, the positive externalities of environmentally sound land uses are assumed to be known. This paper presents how PES can help reduce the ES tradeoffs or enhance the synergies of various ES. However, there are at least two bottlenecks in the research efforts to determine successful PES: 1) understanding of land users' rationale and likelihood of adoption of the introduced PES concept and schemes, and 2) evaluation of positive externalities to be expected with respect to the ES bundle that alternative land uses can offer, depending on scale of participation. The use of an agent-based or multi-agent simulation (AB/MAS) framework was deemed appropriate for analyzing such dynamics in the social-ecological systems of rubber agroforests.

2 METHODOLOGY

2.1 Study area

The study site includes three villages, namely Lubuk Beringin, Laman Panjang, and Buat, all located in Jambi Province, (Sumatra) Indonesia. Together, they have a total population of 2,207 inhabitants belonging to 553 households (Rantau Pandan Statistics 2003). All-weather road access to markets roads is limited, and electric infrastructure is not available as the villages are located far from the nearest town center. The main source of staple food is rice paddies; the main source of income is rubber (*Hevea brasiliensis*) and occasionally durian and other local fruits, with medicinal plants obtained from the rubber agroforests. Rubber agroforest used to be the dominant land use in Jambi Province (van Noordwijk et al. 2012), and the science-based information on the various ES that rubber agroforests provide is growing. These agroforests form the main rural livelihoods of the people living in remote locations. However, due to the low latex productivity, farmers are now attracted to convert their farm lands into more profitable land use such as oil palm and monoculture rubber plantations. The big question is now whether eco-labeling of latex from rubber agroforest under a PES scheme could be a promising option for at least part of the households.

2.2 LB-LUDAS: model description

The study applies the Land Use Dynamic Simulator (LUDAS) framework developed by Le et al. (2008). The description of the LUDAS model using the ODD protocol (Overview, Design concept, and Details) (Grimm et al. 2006) is described in Le et al. (2010). For application of PES, in the following the modified and new features in the LB-LUDAS model are described (Villamor 2012).

Overview

Agents, state variables and scales: There are two types of agents. First, human agents are representations of individual farming households with state variables on social, natural, physical, financial and human resources, and policy access. Second, landscape agents (i.e. congruent land pixels or patches) with state variables corresponding to GIS-raster layers of biophysical spatial variables, spatial neighborhood characteristics, spatial economic variables (e.g. proximate distance to road and town center or market), spatial institutional variables (e.g. owner and protection zoning), and households' landscape vision (Le et al. 2008). One grid cell or pixel represents 30 m x 30 m (900 m²), and the model landscape covers 601 m x 441 m (156 km²). The adaptive traits of each individual agent are explicitly processed mainly by land-use decisions and the change in behavior strategies (i.e. preference coefficient of land-use choice function and willingness to adopt PES policies, and structure of labor allocation). A process-based decision making sub-model is integrated in the agents' decision making mechanism of the LB-LUDAS model (A companion paper for this conference describes the agent decision making in more detail [Villamor et al. 2012]).

Process overview and scheduling: One time step represents one year. The main time loop of the simulation program, called annual production cycle, includes sequential steps, which are agent-based and integrated with patch-based processes. The ten basic simulation steps are: (1) set-up initial state of the system, (2) update agent and patch attributes, (3) adopt behavior parameters, (4) farmland choice, (5) forest choice, (6) other income sources, (7) update changes in agent and patch attributes, (8) create new agents, (9) translate annual land-use changes, and (10) calculate ecosystem services (e.g. crop productivity, species richness, and carbon sequestration).

Details

Input: Data and parameters were parameterized and calibrated for each sub-model (Table 1).

Table 1 External input data and sub-models in LB-LUDAS model

Sub-model	Parameter	Data source
Species richness	26-80 tree species per ha	Rahayu 2009
Forest/ rubber agroforest growth (Le 2005)	Basal area: 21-41 m ² ha ⁻¹	Rahayu 2009; Rasnovi 2006
Rubber monoculture yield	1200-1800 kg ha ⁻¹ yr ⁻¹ (2009-2010)	ICRAF data
Upland rice yield	600-800 kg ha ⁻¹ yr ⁻¹	Field survey
Rubber agroforest latex yield	800- 1200 kg ha ⁻¹ yr ⁻¹	Field survey
Carbon stocks per land-cover type	Time average C-density: 1-150 Mg ha ⁻¹ *yr	Tomich et al. 1998; 2004
Land-use choice	Characteristics of farm plot owner (e.g. age, education status, income, etc.); natural land attributes (e.g. wetness index, slope, etc.); neighborhood characteristics of land use (e.g. enrichment factor of land-use types)	Field survey GIS-based calculations
PES adoption	Characteristics of farm plot owner (e.g. age, education status, income, etc.); access to conservation policies	Field survey

Sub-models

PES-adoption sub-model (nested within *Land-use choice sub-model*) calculates stochastically the probability of the household agents whether to adopt or not to adopt the PES scheme based on their preference coefficients. These preference coefficients were derived from binary logistic regression (Villamor et al. 2011). The sub-model is linked to the *Calculate-species-richness sub-model*, creating the interaction between socio-economic state variables and the bio-physical processes in the systems. This sub-model is integrated in the agent's decision-making routines with a simple rule base: (1) if the household decides to adopt the PES scheme, then do rubber agroforest, (2) otherwise look for other land-use types for current landholdings. If the latter case is realized, the household agent will execute *Land-use choice sub-model*. The main variables of the sub-models are shown in Table 2.

Calculate-species-richness sub-model deterministically calculates the estimated species richness of the land cover (e.g. rubber agroforests). The estimated species richness of rubber-agroforest serves as a biodiversity performance measurement for the eco-certification scheme (Table 2). The species richness is estimated using the power function of species-area relationship (SAR), which is formally expressed as:

$$S = kA^z \tag{Eq. 1}$$

where *S* is number of tree species, *A* is area of the sample, and *k* and *z* are fitted coefficients.

We parameterized this SAR for each succession or vegetation class: pioneer (0-5 years), young secondary (5-20 years), late secondary (20-50 years), and forest (>50 years). For each vegetation class, we first depicted the experimental/observed species-area curves using EstimateS software (Colwell, 2009) and plot-based survey data (Table 1), then estimated the *k* and *z* parameters in equation 1 by fitting to the experimental curve by log-linear regression (ln*S* = ln*k* + *z*ln*A*). The estimation result is shown in Table 2. The vegetation class (pioneer, young or late secondary) is determined by the plot age and the ecological distance from the forest that is covered in the *Natural-transition sub-model*.

Table 2 Tree species richness estimator equations

Vegetation class	Equation
Young secondary (5-20 years)	$S_e = 1.60A^{0.440}$ (Eq. 2)
Late secondary (20-50 years)	$S_e = 5.84A^{0.202}$ (Eq. 3)
Forest (>50years)	$S_e = 1.66A^{0.424}$ (Eq. 4)

Once the initial species richness is estimated, the updated species richness overtime in response to land-use change is estimated by applying the Tilman and Lehman (1997) equation for species loss, which is formally expressed as:

$$S_D = k[(1 - D)A_v]^z \quad (\text{Eq. 5})$$

where S_D is number of species remaining after land-use change, D is proportion of area destroyed, and A_v is area of original habitat. For k and z parameters, we used the value estimated in Equation 2. The D component here is sensitive to land use conversion due to farmers' activities.

Natural-transition sub-model performs the natural succession among vegetation types based on accumulated vegetation growth and ecological edge effects. Its rules are based on the evaluation of four patch variables, namely (i) previous cover type, (ii) life span of existing cover type, (iii) existing stand basal area, and (iv) distance to nearest forest.

Carbon emission: The land-cover-derived C-stocks method is applied by assigning the time-averaged C-stocks and is estimated in the LB-LUDAS model.

2.3 Tested scenarios

Baseline/current trend: The land-use policy context of this baseline scenario and other key socio-economic conditions are the following:

- Forest protection zoning restriction of 70%.
- The land-cover map of 2005 is the initial land-use state.
- Initial simulated population of 1520 individuals (380 households).
- A price of USD 2.5 kg⁻¹ for rubber latex, USD 1.0 kg⁻¹ for rice, and for hired labor USD 2 day⁻¹.
- A human population growth of 1.4%, based on low out-migration rates.
- The decision-making sub-model for the simulation follows the routine by Le et al. (2008).

PES scenario: Under an eco-certification scheme, the price of rubber latex is 50% (upper case limit) higher than the baseline price, i.e. about USD 3-4 kg⁻¹ (Akiefnawati pers. com.), but this is only granted if the biodiversity criteria are met (Table 3). The price of rice is USD 1 kg⁻¹.

- A population growth of 1.4% per year, based on low out-migration rates.
- The decision-making sub-model for the simulation follows the routine by Villamor et al. (2012).
- The actual land-use map of 2005 is used as a base for simulating the next 20 years.

Table 3 Proposed criteria for eco-certification of rubber agroforest based on Tata et al. (2007) and criteria fitting the LB-LUDAS model.

Proposed criteria for eco-certification of rubber agroforest	Fitting for LB-LUDAS model
○ <i>Criteria 1:</i> At least 4 tree species (> 10 cm DBH) in a circle with 8 m radius around a random starting point within the plot – average of 5 observations,	At least 27 tree species in a 900 m ² patch
○ <i>Criteria 2:</i> If the number of species is <6, determine the relative basal area of rubber trees, with 2/3 as threshold; (in case the number of species is > 6, this step can be skipped), and	Basal area requirement per patch as generated by the forest growth model
○ <i>Criteria 3:</i> Make sure that there is at least 1 tree with DBH > 40 cm per circle of 25 m radius – average of 5 observations	1 tree with DBH of >40cm for every 2 patches (1800 m ²)

2.4 Run set-up summary

A total of five simulation runs were independently repeated for each scenario. Each run has 20 time steps (or simulated years) and is programmed using Netlogo version 4.1.

2.5 Validation

The simulated results generated from the LB-LUDAS model were validated with the results of the role playing game (RPG) conducted in the rubber agroforest of Jambi province by Villamor and van Noordwijk (2011). The RPG was conducted to deepen the understanding of the system properties and dynamics, which are hardly communicated through interviews and surveys. At the same time, the RPG was designed to explore and understand the behavior and reactions of the households when buyers (e.g. PES negotiators, oil palm companies, and logging companies) were interested in converting their rubber agroforests or maintaining them through the PES scheme. Three land-use game boards were used to represent each of the investigated villages, and the players were the same farmers from each respective village in which a household survey had been conducted.

One of the main findings of the RPG that validates the LB-LUDAS output (i.e. under the PES scenario) is that no land-use change was observed throughout the whole game including the land-use arrangement that was set by the players (Figure 1). Interestingly, during the game, all the financial bids by external agents to secure an oil palm foothold in the village were rejected despite indications of declining income in the village.



Figure 1: RPG conducted to explore the behavior of the households and validate the results of LB-LUDAS simulation under PES schemes. Three board games represent the three villages under investigation (For further details see Villamor and van Noordwijk 2011).

3 RESULTS

In this section, we compare the major simulation results of the PES scheme to the current trend according to 1) landscape changes, 2) species loss, 3) carbon emissions, and 4) crop and latex production.

Landscape changes: The apparent trends observed when comparing the PES scenario with the baseline scenario (Figure 2) are: (1) forest cover slightly increased after year 13, (2) rubber monoculture slightly decreased after year 15, and (3) both rubber agroforest and rice were the most actively changing land uses/covers under the baseline scenario.

The minimal land-use change under the PES scenario resulted in the following estimation of species richness and carbon emissions in the study area.

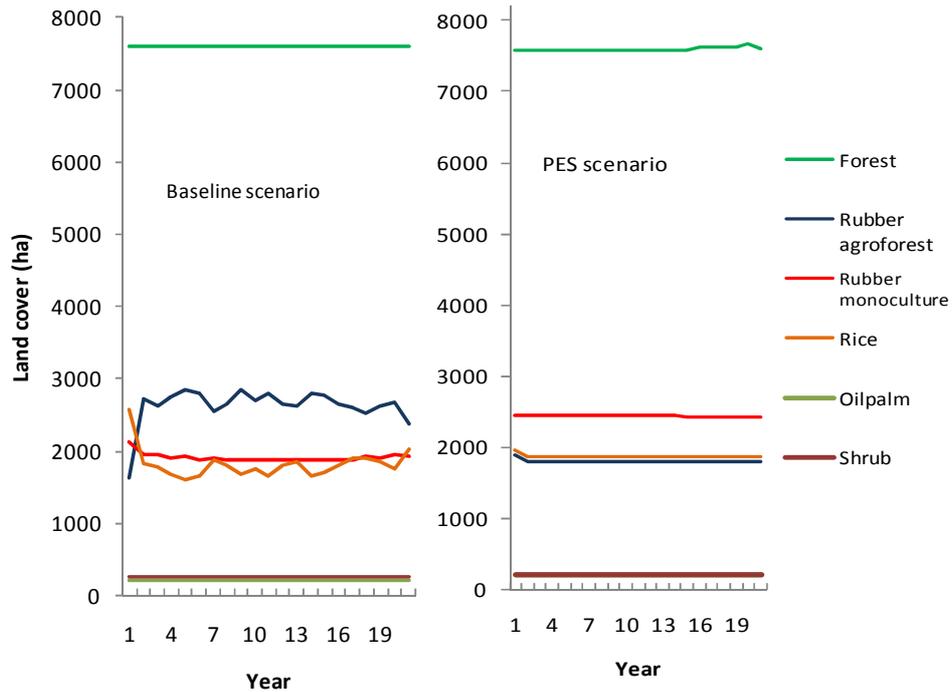


Figure 2: Simulation of land-use/ cover change in PES scenario compared to baseline scenario (Note: All graphs are with confidence intervals (95%) of the means, but removed for convenience).

Species loss: The proportion of the species that had survived after the conversion of rubber agroforest to rice or rubber monoculture was estimated. Findings show that under the PES scenario, an average of 22% of the tree species would remain in the rubber agroforests compared to the baseline scenario (Figure 3).

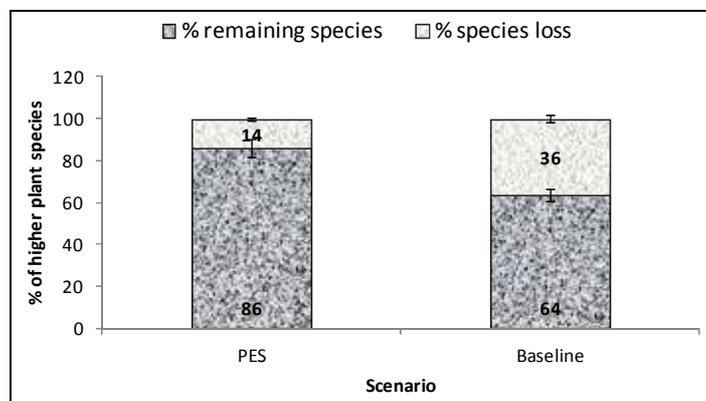


Figure 3: Average percent of remaining tree species (>10 diameter breast height) after land conversion (Note: vertical segments are the standard error of the mean).

Carbon emissions: The results show that the PES scenario has the lowest annual emissions of about 0.008 Mg ha⁻¹yr⁻¹(Figure 4). Under the baseline scenario, the carbon emissions are 46% lower compared to the emissions calculated for Y1993-2005. This is mainly due to the conversion of rubber agroforest (high carbon ecosystem) to rice paddies (low carbon ecosystem).

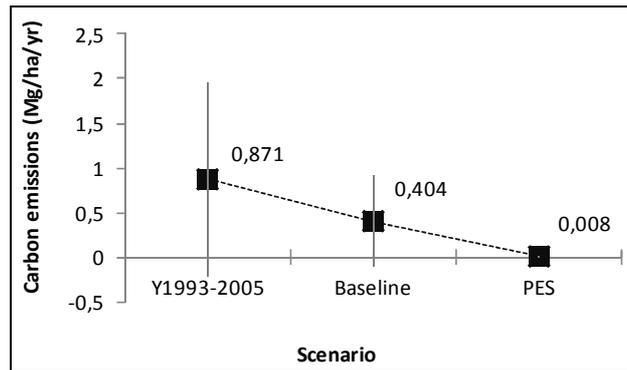


Figure 4: Annual carbon emissions ($\text{Mg ha}^{-1}\text{yr}^{-1}$) in simulated scenarios against calculated 1993-2005 carbon emissions (Villamor 2012). Note: vertical segments are the confidence interval (95%) of the means.

Crop and latex production (simulated crop yields): It can be observed that under the baseline scenario, the average rice yield is higher than under the PES scenario (Table 4). For latex production from rubber agroforests, the average latex yield is higher under the PES scenario. On the other hand, the average latex yield from monoculture plantations is slightly higher under the PES scenario. Comparing these results to those of other studies (ICRAF data of 2009; Wulan et al. 2008), the rice yield is comparatively low. Agroforest rubber latex yields are relatively higher, while those from rubber monoculture are consistent with the yields cited from literature.

Table 4 Average annual crop yield in baseline and PES scenarios and in literature

Crop	Baseline	PES	Literature
Rice ($\text{kg ha}^{-1}\text{yr}^{-1}$)	667 ± 122	511 ± 104	1200 (Wulan et al. 2008); 800 (ICRAF 2009)
Latex from rubber agroforest ($\text{kg ha}^{-1}\text{yr}^{-1}$)	1026 ± 222	1080 ± 241	917-1080 (Wulan et al. 2008); ~600 (Joshi et al. 2006)
Latex from rubber monoculture ($\text{kg ha}^{-1}\text{yr}^{-1}$)	1026 ± 173	1037 ± 61	971-1342 (Wulan et al. 2008); 650-2250 (Budidarsono and Wulan 2008)

Note: Values are mean ± SD of outcome variable for 5 simulation runs.

Effects of PES policy on ES tradeoffs: Under the PES scenario, agro-biodiversity conservation and carbon emission mitigation are better when compared to the current trend (baseline). With the eco-certification scheme, the latex production from rubber agroforest also becomes competitive. Thus, PES could offer synergies between ES. Results also suggest that the PES scheme, including the proposed design, i.e. biodiversity targets and protection zoning, is appropriate for the rubber agroforest landscape context.

4 CONCLUSIONS

The use of the AB/MAS framework (LB-LUDAS model) was found to be highly appropriate for understanding and quantifying ES trade-offs. This is necessary for assessing PES schemes. However, there are limitations in the study that we wish to address in the future, such as the inclusion of other pertinent ES (e.g. water quantity and flow, soil fertility) and agent behavior (i.e. crop sharing scheme). In the representation of biodiversity, the estimation of tree species richness was limited only to rubber agroforest to reduce the running time of the simulation. Some emergent properties (i.e. learning and adaptation) emanating from the interaction of the social and biophysical systems were also observed that need further analysis.

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