Towards an integrated ecological-economic land-use change model

Claudia Dislich, Elisabeth Hettig, Johannes Heinonen,
Jann Lay, Katrin M. Meyer, Suria Tarigan, and Kerstin Wiegand

EFForTS discussion paper series Nr. 17

Dislich, C.; Hettig, E.; Heinonen, J.; Lay, J.; Meyer, K. M.; Tarigan, S.; Wiegang, K.: Towards an integrated ecological-economic land-use change model
Göttingen : GOEDOC, Dokumenten- und Publikationsserver der Georg-August-Universität, 2015
(EFForTS discussion paper series 17)

Verfügbar:
PURL: http://resolver.sub.uni-goettingen.de/purl/?webdoc-3961

Die Deutsche Nationalbibliothek verzeichnet diese Publikation in der Deutschen Nationalbibliographie; detaillierte bibliographische Daten sind im Internet über <http://dnb.ddb.de> abrufbar.

Erschienen in der Reihe
EFForTS discussion paper series

ISSN: 2197-6244

Herausgeber der Reihe
SFB 990 EFForTS, Ecological and Socioeconomic Functions of Tropical Lowland Rainforest Transformation Systems (Sumatra, Indonesien) - Ökologische und sozioökonomische Funktionen tropischer Tieflandregenwald-Transformationssysteme (Sumatra, Indonesien)

Georg-August-Universität Göttingen
Johann-Friedrich-Blumenbach Institut für Zoologie und Anthropologie, Fakultät für Biologie und Psychologie

Abstract: Land-use changes have transformed tropical landscapes throughout the past decades dramatically. We describe here an ecologicaleconomic land-use change model to provide an integrated, exploratory tool to analyze how tropical land use and land-use change affect ecological and socio- conomic functions. The guiding question of the model is what kind of landscape mosaic can improve the ensemble of ecosystem functioning, biodiversity and economic benefit based on the synergies and trade-offs that we have to account for. The economic submodel simulates smallholder land-use management decisions based on a profit maximization assumption and a Leontief production function. Each household determines factor inputs for all household fields and decides about land-use change based on available wealth. The ecological submodel includes a simple account of carbon sequestration in above- and belowground vegetation. Initialized with realistic or artificial land use maps, the ecological-economic model will advance our understanding of the mechanisms underlying the trade-offs and synergies of ecological and economic functions in tropical landscapes.

Keywords: ecological-economic model, land-use change, smallholder, oil palm, rubber, Indonesia, simulation model, NetLogo.

Towards an integrated ecological-economic land-use change model

Claudia Dislich, Elisabeth Hettig, Johannes Heinonen, Jann Lay, Katrin M. Meyer, Suria Tarigan, and Kerstin Wiegand

EFForTS Discussion Paper Series

No. 17 (June 2015)

Ecological and Socioeconomic Functions of Tropical Lowland Rainforest Transformation Systems (Sumatra, Indonesia)

Funded by the German Research Foundation (DFG) through the CRC 990 “EFForTS, Ecological and Socioeconomic Functions of Tropical Lowland Rainforest Transformation Systems (Sumatra, Indonesia)”

www.uni-goettingen.de/en/310995.html

SFB 990, University of Goettingen

Berliner Straße 28, D-37073 Goettingen, Germany

ISSN: 2197-6244

Managing editors:

At the University of Goettingen, Germany

Prof. Dr. Christoph Dittrich, Institute of Geography, Dept. of Human Geography
(Email: christoph.dittrich@geo.uni-goettingen.de)

Dr. Stefan Schwarze, Dept. of Agricultural Economics and Rural Development
(Email: sschwar1@gwdg.de)

At the Universities of Bogor and Jambi, Indonesia

Prof. Dr. Zulkifli Alamsyah, Dept. of Agricultural Economics, Faculty of Agriculture, University of Jambi
(Email: zalamsyah@unja.ac.id)

Dr. Satyawan, Sunito, Dept. of Communication and Community Development Sciences, Faculty of Human Ecology, Bogor Agricultural University (IPB)
(Email: awansunito@gmail.com)

Contents

List of Figures

List of Tables

Towards an integrated ecological-economic land-use change model

Claudia Dislich[1], Elisabeth Hettig[2,3], Johannes Heinonen*[1], Jann Lay[2,3], Katrin M. Meyer[1], Suria Tarigan[4], and Kerstin Wiegand[1]

[1]Department of Ecosystem Modelling, University of Göttingen, Germany
[2]Department of Economics, University of Göttingen, Germany
[3]GIGA German Institute of Global and Area Studies, Hamburg, Germany
[4]Department of Soil and Natural Resources Management, Bogor Agricultural University, Indonesia

Abstract

Land-use changes have transformed tropical landscapes throughout the past decades dramatically. We describe here an ecological-economic land-use change model to provide an integrated, exploratory tool to analyze how tropical land use and land-use change affect ecological and socio-economic functions. The guiding question of the model is what kind of landscape mosaic can improve the ensemble of ecosystem functioning, biodiversity and economic benefit based on the synergies and trade-offs that we have to account for. The economic submodel simulates smallholder land-use management decisions based on a profit maximization assumption and a Leontief production function. Each household determines factor inputs for all household fields and decides about land-use change based on available wealth. The ecological submodel includes a simple account of carbon sequestration in above- and belowground vegetation. Initialized with realistic or artificial land use maps, the ecological-economic model will advance our understanding of the mechanisms underlying the trade-offs and synergies of ecological and economic functions in tropical landscapes.

Keywords: ecological-economic model, land-use change, smallholder, oil palm, rubber, Indonesia, simulation model, NetLogo.

*Corresponding author: johannes.heinonen@forst.uni-goettingen.de

1 Introduction

Land-use changes have transformed tropical landscapes throughout the past decades dramatically. In particular, large stretches of primary forests have been replaced by land used for agricultural purposes. These transformed landscapes remain subject to further land-use changes that bring about a variety of changes in ecosystem and socio-economic functions. Interdependencies among different functions both within and between the ecological and the socio-economic spheres are likely to be complex, often non-linear, and are not well understood. For example, the spatial configuration of land uses might play an important role for biodiversity (e.g., via edge effects, connectivity, buffer zones, or homogenization), ecosystem functions, e.g. hydrological functions via riparian buffer zones, and also for economic functions (e.g. via market access or spill-over effects). Understanding this complexity is of utmost importance to identify ways to maintain ecosystem functioning and biodiversity in the face of human needs.

Agent-based ecological-economic simulation models are a promising tool to develop a better understanding of the complex dynamics and interactions between ecological and socio-economic functions in agricultural landscapes (Villamor et al., 2014). They can incorporate decisions of agents such as individual farming households and evaluate their effect on ecological and socio-economic functions on different scales, e.g. local or landscape scales. Thereby these models connect the societal/economic and the ecological sphere. Carefully applied, such models allow for testing different scenarios, e.g. how certain external effects like certain policies or price shocks affect the behaviour of agents and thereby shape landscape mosaics.

In the Jambi Region of Sumatra, Indonesia, oil palm and rubber plantations represent the dominant land-use types. The landscape mosaic is shaped by different actors, for example smallholders with typical field sizes around two hectares and private or state-owned companies with large monoculture plantations. Using socio-economic and ecological data from the Jambi region as a case study, our guiding research question is: what kind of landscape mosaic can improve the ensemble of ecosystem functioning, biodiversity and economic benefit based on the synergies and trade-offs that we have to account for.

This paper describes an agent-based model that we have developed to answer this question. We aimed at a model sufficiently complex to capture all factors and processes relevant to our questions yet simple enough to be able to derive general principles (cf., Evans et al., 2013). The model description is structured according to the ODD protocol for describing individual-based models (Grimm et al., 2006, 2010) and the ODD+D extension of the protocol for describing agent-based models that involve human decisions (Müller et al., 2013)

Spatial unit	Meaning
cell	smallest spatial unit of the model (50x50 m)
field	contiguous cells of the same land-use type and age belonging to the same household (i.e. an agricultural field)
household area	cells belonging to the same household
patch	contiguous cells of the same land-use type and same/similar age (i.e. same type of habitat, independent of ownership)
landscape	largest spatial unit of the model: set of all cells

Table 1: Spatial units of the model.

2 Overview

2.1 Purpose

The purpose of our model is to provide an integrated, exploratory tool to analyze how land use and land-use change affect ecological and socio-economic functions. Relationships between different functions on different spatial and functional scales in the form of trade-offs or synergies will be investigated with the model.

As smallholders manage the majority of farm land in our study region, we focus on smallholder land management and decisions. Land-use and land-management decisions are modeled on the household level, based on household capital and external economic drivers like prices for inputs and products. Socio-economic functions in the model are economic development and welfare effects, on the ecological side we focus on carbon storage. Further ecological functions, e.g. species diversity will be incorporated in the near future. Concerning land-use types, we consider the perennial land-use types oil palm and rubber plantations, and secondary forest as a near natural habitat.

We choose a spatially explicit approach, as the location of the household and its farmland in the landscape might affect the decision-making process as well as ecological functions. For instance, biodiversity can be affected by the degree of landscape fragmentation. A combined agent-based and grid-based approach provides the flexibility needed to model diverse ecological and socio-economic functions. Interactions between grid cells, e.g. animal movement and intra-household dynamics, as well as interactions between households can be included explicitly in such a framework.

2.2 Entities, scales and state variables

The model simulates ecological and socio-economic aspects of land-use and land-use change and therefore comprises different entities: cells, fields, households, patches and the landscape (see Table 1). The smallest spatial unit of the model is a square cell where cell size corresponds to the typical size of small fields (in our case 50 x 50 meter). Each cell is characterized by its position in the landscape, land-use type and age. A field is defined as a number of contiguous

Variable name	Unit	Meaning
h_id	[-]	Household identifier
h_area	[-]	Number of cells belonging to the household
h_wealth	[$]	Amount available for the household
h_inefficiency_op	[-]	Inefficiency factor for oil palm [0,1]
h_inefficiency_rubber	[-]	Inefficiency factor for rubber [0,1]
h_debts	[$]	Annual debts taken up for agricultural production
h_capitalstock	[$]	Amount of capital fixed in plantations
h_exincome	[$]	Annual external income, i.e. income external to agriculture
h_netcashflow	[$]	Net cash flow from all household cells
h_consumption	[$]	Annual consumption of household (fix + variable consumption)
h_cost_investment	[$]	Annual investment costs from all household cells
h_cost_labor	[$]	Annual labor costs from all household cells
h_cost_tinput	[$]	Annual technical input costs from all household cells
h_cost_capital	[$]	Annual capital costs from all household cells
h_cost_land	[$]	Annual land rent costs from all household cells
h_revenue	[$]	Annual revenue from agriculture
h_op_production	[tons]	Annual production of oil palm fruit buches from all household cells
h_rubber_production	[tons]	Annual production of rubber from all household cells
h_debt_years	[-]	Number of consecutive years in which the household had debts > 0

Table 2: List of the most important household variables.

cells under the same land-use of the same age belonging to one household. Each household can own several fields and decide on land-use and management of these fields. The size of existing fields remains constant throughout simulation. Similar to fields, patches are contiguous cells of the same land-use and the same (or similar) age, but regardless of ownership. While fields are important units in the economic sub-model, patches define areas of similar habitat suitability and may thereby play an important ecological role for species diversity and distribution. Households are characterized by their location in the landscape, the sizes and locations of fields belonging to the household and specific household characteristics. The landscape comprises a regular grid of cells and is the highest level entity of the model (in our case 100 x 100 cells, i.e. 25 square kilometers). All processes in the model, i.e. vegetation growth as well as household-related processes, work with an annual time step. Prices for yield are external and do not vary within the landscape.

Household variables describe the size and production of the land owned by the household as well as the financial resources of the household (details in Table 2). A detailed description of the household model is given in Section 4.4.1 *Household model*. Cell variables describe ecological and economic properties of the land use in that cell such as type (e.g. oil palm), age, technical input, production and amount of carbon stored in the vegetation of that cell (details in Table 3).

2.3 Process overview and scheduling

Each model run starts with the initialization procedure, see Section 4.2 *Initialization* for details. After initialization, each grid cell has a certain land use (oil palm, rubber or secondary forest). Each grid cell under agriculture (oil palm or

Variable name	Unit	Meaning
p_landuse	[-]	Land use of the cell (oil palm, rubber, secondary forest)
p_age	[years]	Age of the plantation in the cell
p_fieldsize	[-]	Total number of cells beloning to the same field as this cell
p_carbon	[ton]	Carbon stored in the vegetation of this cell
p_owner	[-]	h_id, if this cell is owned by a household, otherwise -1
p_homebase	[-]	h_id if this cell is homebase of a household, otherwise -1
p_production	[ton]	Annual production from this cell
p_id	[-]	Field identity; all cells beloning to the same field have the same field identity
p_labor	[h]	Labor hours invested in this cell in one year
p_tinput	[kg]	Technical input invested in this cell in one year
p_capitalstock	[$]	Capital stock of this cell

Table 3: List of the most important cell variables.

rubber) has an owner (smallholder farmer or big company) and a certain age. Within each time step (year) the following processes are scheduled (Fig. 1).

At the beginning of each year, the economic household model is executed. At first, household wealth is reduced by the planned consumption which comprises a subsistence component and a wealth-based component (for details see Section 4.4.1.2 *Decision on land-use change and production*). Subsequently, households decide on land management and land-use change. This decision is based on expected profits from different land-use options and available financial resources. The actual annual profit from agricultural land use is then calculated for all household cells according to age-specific yields and costs and actual commodity prices. At this point also the costs for land-use change in this time step are accounted for.

Subsequently, household wealth is updated by adding profits from agriculture and potential external income and deducting a variable, profit-based part of household consumption. This updated household wealth serves as a basis for the land-use decision module in the next time step. After the economic household model, the ecological part of the model is updated, i.e. new carbon stocks are calculated for all cells and ecological functions are calculated.

3 Design concepts

3.1 Theoretical and Empirical Background

3.1.1 Economic household model

The economic household model is based on the concept of ”agricultural household models” (Singh et al., 1986). In this type of model, a rural household simultaneously decides on production and consumption under given constraints, for example initial endowments with land or access to credit. The land management decision comprises the decision on land-use change and production, including the use of factor inputs.

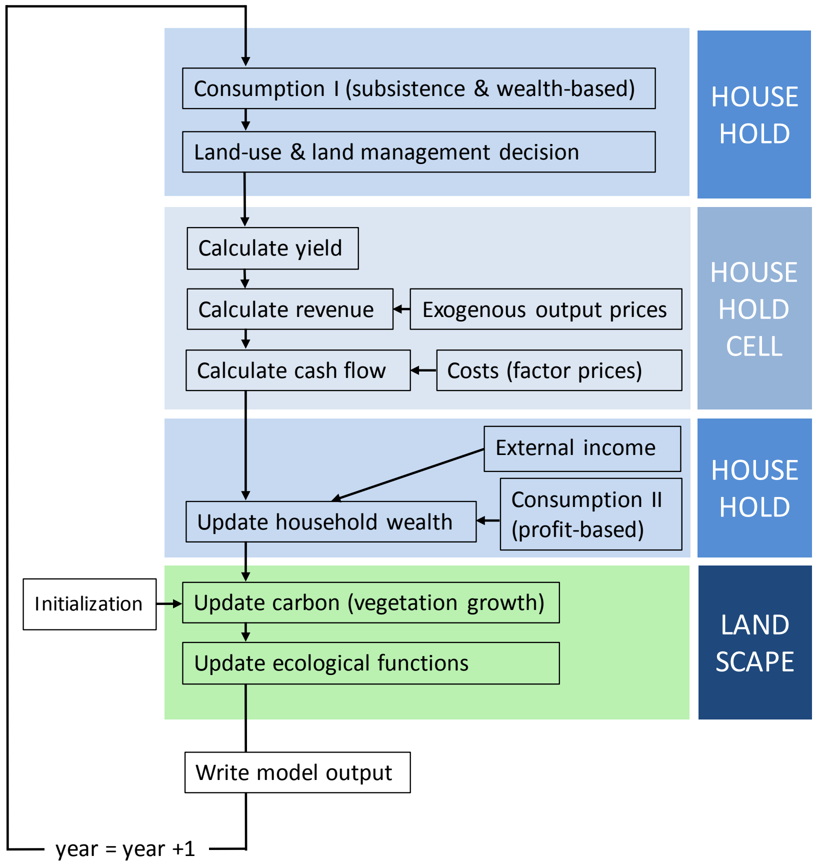

Figure 1: Process overview

3.1.2 Ecological submodels

The currently applied carbon submodel describes carbon stored in the vegetation and utilizes simple age-dependent carbon stock equations for the land-use types oil palm and rubber plantation, and constant carbon stock values for forest cells. Other factors that might influence carbon stocks, e.g. edaphic conditions, fertilizer management etc. are not considered in this model version.

3.2 Individual Decision-Making

Every year, households decide on land management and land-use change on the cells that belong to the household. These decisions are driven by their agricultural production choices, which, in turn, are determined by production technologies, initial conditions, and household endowments. Households maximize profits and decide between different land uses according to the relative profitability of different options, i.e. households compare expected profits for different land-use options over a certain time horizon. In computing these profits, household-level constraints are taken into account, for example with regard to the availability of capital needed for investment. Households hence produce and invest, thereby accumulating capital. The proceeds from agricultural production are used to finance investments, to save and to consume.

3.3 Individual learning, sensing and prediction

The model in its present version does not include adaptive behavior, e.g. learning of agents. Each agent makes its decision independently, i.e. no neighbor effects are incorporated. The agents hence do not sense the other agents. Agents' knowledge is restricted to current commodity prices, therefore they forecast future prices by current prices and anticipate zero change. The current prices are used for the computation of future expected cash flows from agriculture.

3.4 Interaction, Collectives and Heterogeneity

The model does not incorporate interactions between agents. Also, no collective groups, e.g. groups of agents that behave differently, are considered. Agents differ in their land and capital endowments, as well as their initial land uses and ages of fields. An additional optional parameter which introduces heterogeneity between agents is the inefficiency parameter which affects the production function of households (see Section 4.4.1 *Household model*).

3.5 Stochasticity

During initialization, the initial wealth of households is drawn from a log-normal distribution and resulting values are assigned to households according to household areas (for details see Section 4.2 *Initialization*). Parameters for crop- and household-specific inefficiency (see Eq. 2) are drawn from a normal distribution and stay constant throughout the simulation. Different options of stochastic price dynamics are implemented (e.g. Gaussian random walk, see Section 4.4.3 *Price dynamics*). However, this option can be turned off, i.e., using constant prices.

3.6 Observation

Patterns observed at the household level are land-use changes and the dynamic development of yields, cash flows and household wealth. On the landscape level we observe the fractions of different land-use types and carbon stocks.

4 Details

4.1 Implementation details

The land-use change model is implemented in the open source modelling platform NetLogo 5.0.2. It is still under further development. For questions please contact jheinon@gwdg.de.

4.2 Initialization

The most important part of the initialization is the initial spatial distribution of the different land uses, the location of farming households and the ownership

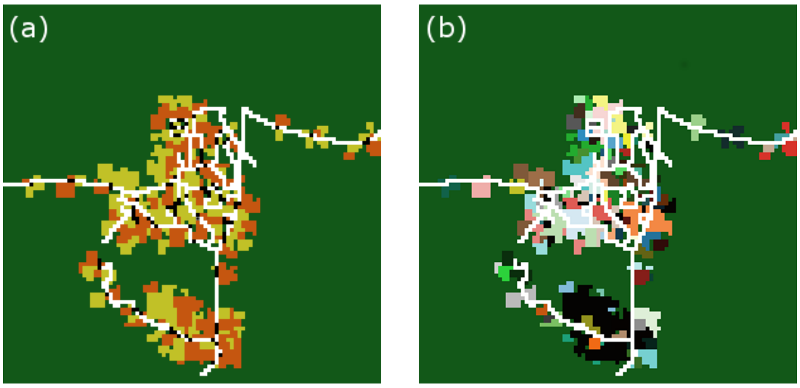

Figure 2: (a) Initial land-use map, orange: oil palm plantations, yellow: rubber plantations, green: secondary forest, white: road patches. (b) Household map: different colors represent areas of different households, black patches represent household home bases.

of fields. All these state variables are determined using a landscape generator (see Appendix), which was developed specifically for this purpose. The outputs of the landscape generator are different raster maps which are read into the land-use change model at the beginning of each simulation run. The following maps are used as inputs:

- Household home-base locations
- Ownership of cells
- Field identity number
- Roads
- Land-use type
- Forest patches

Exemplary maps which were used for the initialization of the presented model runs are shown in Figure 2.

Apart from these initial maps, the following state variables are initialized as follows:

- Initial household wealth is drawn from a log-normal distribution with parameters given in Table 4 (see also Appendix 7.2). The resulting values for initial wealth are sorted and assigned to households in a way that households owning larger areas have a higher initial wealth.
- The initial age of agricultural fields is drawn from a uniform distribution with typical age ranges of oil palm and rubber plantations (see Table 4).
- Initial prices for oil palm fresh fruit bunches (FFB) and rubber as given in Table 5 (for details see section 4.4.3 *Price dynamics*).

Initialisation	Unit	Value	Justification
Number of households	[-]	50	
Household area μ (log-normal distribution)	[ha]	1.02	derived from CRC990 data
Household area σ	[ha]	0.91	derived from CRC990 data
Field size μ (log-normal distribution)	[ha]	0.49	derived from CRC990 data
Field size σ	[ha]	0.77	derived from CRC990 data
Household wealth μ (log-normal distribution)	[$]	7	derived from CRC990 data
Household wealth σ	[$]	1	derived from CRC990 data
Household wealth scaling factor	[-]	10	estimated
Age range of oil palm plantations (uniform distribution)	[year]	[0 , 30]	estimated from CRC990 data
Age range of rubber plantations (uniform distribution)	[year]	[0 , 40]	estimated from CRC990 data
Fraction of agricultural area under oil palm and rubber	[-]	0.5:0.5	

Table 4: Initial variables and their distributions.

Details on the initialization used for the simulation runs of this paper are given in the Appendix and initial values to variables are summarized in Table 4; model parameters are presented in Table 5 and Table 6.

4.3 Input data

The model uses maps which are produced by a landscape generator as external input for model initialization. Apart from that, the only variables which potentially vary over time but are not affected by the model dynamics are the yield prices. Different price functions are implemented (see Section 4.4.3 *Price dynamics*) and can be chosen from a menu in the graphical user interface (GUI). For the simulations presented in this paper we use the constant price function.

4.4 Submodels

The dynamic land-use change model comprises two main sub-models: the economic household submodel that models land-use decisions by rural households and the ecological submodel that simulates ecosystem functions on different spatial scales. In this section we describe the details of these submodels and their parametrization.

4.4.1 Household model

The economic household model consists of submodels dealing with household production and capital accumulation (4.4.1.1) as well as the corresponding land-use change decisions (4.4.1.2 and 4.4.1.3). In short, the economic household model includes the following processes (Fig. 3). At the beginning of each time step, household wealth is reduced by its planned consumption (box Consumption I in Fig. 3). Each household then decides on land management (box Land management in Fig. 3) including the decision on factor inputs and land-use change. This decision is based on the expected cash flows from different land use options over a certain time horizon (e.g. 10 years). We assume that households are credit constrained. This means that households might not be able

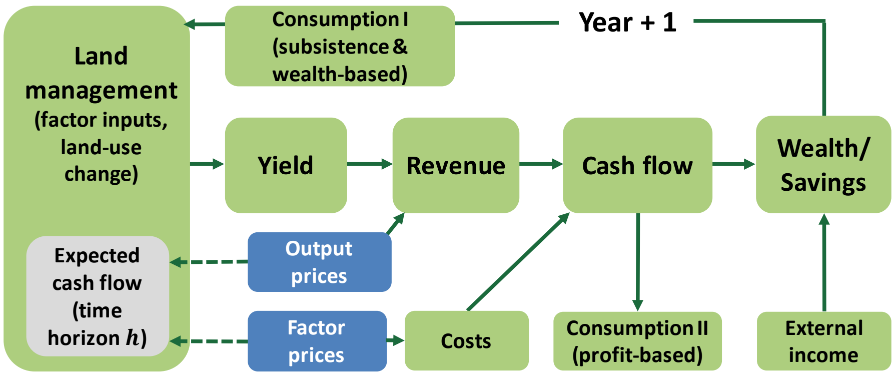

Figure 3: Process overview of the economic household model.

to realize the most profitable land-use option, as they might, for example, not be able to mobilize the capital necessary for initial investment. Following the land management decision, annual yields (Yield in Fig. 3) of all household cells are calculated. Yields are affected by the age of plantations, factor inputs and household inefficiency, reflecting inefficient knowledge and site-specific conditions. Given current output prices (Output prices) the realized annual revenue (Revenue) is derived. Given current factor prices (Factor prices), costs (Costs) for agricultural production are calculated and subtracted from the revenue, resulting in the annual cash flow (Cash flow) of the household. In the case of positive annual cash flow, a part of the cash flow is consumed (Consumption II). The household's wealth (Wealth/Savings) is updated by adding the remaining cash flow and external income. The updated household wealth influences which land-use options are feasible for the household in the next time step.

4.4.1.1 Production function, cash flows and capital accumulation

For each household cell j we apply a Leontief production function (Diewert, 1971). This implies that factors cannot be substituted and production is determined by the input factor which is applied in the smallest relative amount. Thus, production is calculated as

$$\hat{y}_{j,l,n}(L, K, TI, \overline{LA}) = min \left\{ y_n^* \frac{L}{L_n^*}, y_n^* \frac{K}{K_n^*}, y_n^* \frac{TI}{TI_n^*}, y_n^* \frac{\overline{LA}}{\overline{LA}} \right\} \tag{1}$$

with

$\hat{y}_{j,l,n}$: production [ton] from crop l of age n on cell j under the factor inputs labor L, capital K, technical inputs TI and land $\overline{LA}$

y_n^*: production [ton] of a plantation of age n on one cell with optimal factor inputs (see section 4.4.2.1 for the derivation of the optimal production)

L_n^*: the optimal factor input of labor [hour] for a plantation of age n

K_n^*: the optimal capital stock [US$] for a plantation of age n

TI_n^*: the optimal factor input of technical input [US$] for a plantation of age n

$\overline{LA}$: Land [ha], which is fixed to the size of one cell.

The Leontief production function defines the potential production[1] given a certain age of a plantation and certain levels of inputs. However, due to varying experience of farmers in the cultivation of different land uses, incomplete knowledge, e.g. about ideal timing of fertilization or harvesting, as well as variation in site-specific conditions, this potential production might not be realized by a household. We incorporate the gap between potential and realized yield by introducing an inefficiency factor $\delta_{i,l}$ for each household i and land-use type l. The realized production from cell j which is owned by household i is therefore

$$y_{j,l,n}(L,K,TI,\overline{LA}) := \delta_{i,l} \cdot \hat{y}_{j,l,n}(L,K,TI,\overline{LA}) \ . \tag{2}$$

Based on the assumption that input factors are the same for all cells belonging to one field, the production for a field consisting of m cells of crop l of age n is given by

$$yfield_{l,n} = y_{j,l,n}(mL,mK,mTI,m\overline{LA}) = m \cdot y_{j,l,n}(L,K,TI,\overline{LA}) \ . \tag{3}$$

The revenue [US$] from cell j in year t is

$$Rcell_{j,t} = y_{j,l,n_t}(L,K,TI,\overline{LA}) \cdot p_{l,t} \tag{4}$$

with
n_t: the age [year] of the plantation in cell j at time t
$p_{l,t}$: price [US$/ton] of the product of land use l at year t.

The total revenue [US$] from agricultural land use of household i in year t is thus given by

$$R_{i,t} = \sum_{household\ cells\ j} Rcell_{j,t} \ . \tag{5}$$

The net cash flow [US$] from cell j in year t is

$$\Pi cell_{j,t} = Rcell_{j,t} - rcost_{j,l,n_t}(L,K,TI,\overline{LA}) - icost_{j,l,n_t} \tag{6}$$

with
$rcosts_{j,l,n_t}$: recurrent costs [US$] on cell j under crop l in year t, depending on factor inputs of labor L, capital K, technical inputs TI and land $\overline{LA}$
$icost_{j,l,n_t}$: investment costs on cell j for agricultural production of crop l in period t.

The net cash flow [US$] from agricultural land use for household i in year t is thus given by

$$\Pi_{i,t} = \sum_{household\ cells\ j} \Pi cell_{j,t} \ . \tag{7}$$

[1]For oil palm plantations, yield is calculated in tons of fresh fruit bunches per hectare and year; rubber yield is calculated in tons of rubber per hectare and year.

The recurrent costs for cell j are calculated as

$$rcost_{j,l,n_t}(L, K, TI, \overline{LA}) = \begin{cases} r_t K + r_{L,t}\overline{LA} \ , \ \text{if } n_t < n_m \\ w_{l,t}L + r_t K + p_{TI,l,t}TI + r_{L,t}\overline{LA} \ \text{if } n_t \geq n_m \end{cases} \tag{8}$$

with
n_t: the age of the plantation on cell j at time t
n_m: the maturation age of the plantation, i.e. the first year with non-zero yields
r_t: rental rate of capital in year t
K: the current capital stock [US$] on cell j
$r_{L,t}$: rental rate of land [US$/ha] in year t (independent from what crop is on the cell)
$w_{l,t}$: wage for one hour of work [US$/h] in crop l in year t
L: input of labor [hour] on cell j in year t
$p_{TI,l,t}$: price for one unit of technical input [US$/kg] in crop l at time t[2]
TI: technical input [kg] on cell j in year t.

We assume that investment costs occur only within the immature phase of a plantation life-cycle, i.e. as long as yields are zero. The total investment costs $icost\_total_{j,l}$ for a plantation of crop l in one cell j are therefore

$$icost\_total_{j,l} = \sum_{k=0}^{n_m-1} icost_{j,l,k} \quad . \tag{9}$$

These investment costs include non-recurrent costs, e.g. for buying seedlings, as well as all costs for labor and technical input in the immature phase. For establishing oil palms, for example, labor is needed for lining, the transportation of seedlings, and digging holes. Land is already owned by the household, i.e. part of its initial endowments, and we only consider the opportunity costs of holding this asset. During the immature period, the capital stock is built up and we assume that no further investment costs occur once positive yields are produced. From this point onwards all labor and input costs are classified as recurrent costs. We acknowledge that some of these recurrent costs could similarly be conceptualized as maintenance, i.e. reinvestment costs, but our simplification facilitates modelling of the crop choice decision later on.

Each household cell j has a capital stock $K_{j,t}$, representing the resale value of the capital stock embodied in rubber trees or oil palms on the cell at time t (see Eq. (1) and (8)). The capital stock is calculated as the cumulative investment costs in this cell minus depreciation

$$K_{j,t} = (1 - d_l(n_t)) \cdot K_{j,t-1} + icost_{j,l,n_t} \tag{10}$$

with depreciation rate $d_l(n_t)$. The depreciation rate, which captures the natural productivity of the plantation, depends on the plantation age n_t: for young plantations, d is negative, for older ones positive. This is because productivity generally increases in young plantations and decreases in old plantations; the

[2] Both wages and prices for technical input as well as rental rates for capital and land can vary with time. However, in our current model version, we keep them fixed and therefore omit the index t in the remainder of the model description.

productivity inflection point is crop-specific. The total capital stock of household i in year t is accordingly

$$Ktot_{i,t} = \sum_{household\ cells\ j} K_{j,t} \ . \tag{11}$$

4.4.1.2 Decision on land-use change and production

The decision on land management and production, i.e. land-use change and the corresponding factor inputs, is determined by the profitability of land use options, as well as wealth (and consumption) of the household. Let $W_{i,t-1}$ be the wealth of household i at the end of year $t-1$, i.e. the wealth available at the beginning of year t. For simplicity we assume, that, apart from the profit-based component of household consumption, all expenditures occurring in year t need to be disbursed by the household, i.e. paid before the income from agricultural production and external sources in the year t is available. Household consumption is calculated in a two-step process, partly before and partly after net cash flow realization of that time step. The planned household consumption of household i, $C\_plan_{i,t}$ consists of a fixed base consumption $\bar{C_i}$ representing the subsistence level, and a variable additional consumption $c(W_{i,t-1})$ which depends on the actual wealth $W_{i,t-1}$.

Thus the planned consumption of household i in year t is

$$C\_plan_{i,t} = \bar{C_i} + C_W \cdot W_{i,t-1} \tag{12}$$

with C_W the fraction of wealth that is additionally consumed.

The actually realized consumption $C_{i,t}$ can increase by a profit-based component, if a positive net cash flow in this year permits additional consumption (see Table 6 for parameter values of consumption). Thus, after the calculation of the net cash flow $\Pi_{i,t}$, household consumption is updated according to

$$C_{i,t} = \begin{cases} C\_plan_{i,t} + C_\pi \cdot \Pi_{i,t} & \text{, if } \Pi_{i,t} > 0 \\ C\_plan_{i,t} & \text{, if } \Pi_{i,t} \leq 0 \end{cases} \ . \tag{13}$$

The wealth after planned consumption is available to cover investment and recurrent costs of agricultural production. We define a minimum wealth level W_{min} that is always available to a household, assuming that the household can, if necessary, cover costs for consumption from a safety net (family, friends, etc. as a short term credit). Therefore the available resources for factor inputs and land-use change in year t are

$$W_{i,temp} := \begin{cases} W_{i,t-1} - C\_plan_{i,t} & \text{, if } W_{i,t-1} - C\_plan_{i,t} \geq W_{min} \\ W_{min} & \text{, else} \end{cases} \tag{14}$$

If the actual household wealth does not cover the planned consumption, the household temporarily takes up debts $D_{i,t,temp}$ of the amount

$$D_{i,t,temp1} := C\_plan_{i,t} + W_{min} - W_{i,t-1} \quad . \tag{15}$$

In each period t each household decides on management of its household fields after reducing the wealth by the annual households planned consumption (see Eq. 14). This decision includes the decisions on factor inputs and land-use changes, which is taken simultaneously. It depends on the available capital for agricultural production $W_{i,temp}$.

Since we consider two possible land-use types (oil palm and rubber plantation), there are three possible options for each household field: to continue the actual land-use, to replant the actual land-use type or to change to the alternative land use. If a household has u fields, the number of possible options is thus 3^u. As the calculation of expected cash flows from different land-use options is the most time-consuming part of the model, we implemented two versions of this process: the "all-fields"-option, which allows the full number of options, i.e. in principal a change of land use in all fields of a household within one year, and a "one-field-per-year"-option in which each household can change only one field per year. The latter reduces the number from 3^u to $3u$. The option can be chosen on the GUI. For this paper, we apply the one-field-per-year option.

From the set of all options, only those are potentially possible, for which total investment costs (i.e. investment costs from all household fields within the next three years) as well as unavoidable recurrent costs in the current year can be covered by the actual wealth $W_{i,temp}$ (see Eq. 17) while not falling under the minimum wealth level.

Let o be an arbitrary option, p_k the fields of the household ($k = 1, ...g$) and let l_k be the intended land uses on these fields under option o. Let furthermore m_k be the field sizes (i.e. number of cells in the field). The discounted total investment costs under the option o within the next three years are

$$^{o}Itot_i := \sum_{household\ fields\ p_k} \left(m_{pk} \cdot \sum_{n=0}^{2} icost_{j_{p_k}, l_{p_k}, n_t+n} \cdot (1+r)^n \right), \qquad (16)$$

with j_{p_k} a representative cell of field p_k, l_{p_k} the intended land use on field p_k, n_t the age of field p_k at time t and discount rate r.

Therefore, if

$$W_{i,temp} \geq^{o} Itot_i + \underbrace{\sum_{household\ cells\ j} (rK^*_{n_t,j} + r_L\overline{LA}) + W_{min}}_{\text{unavoidable recurrent costs}}, \qquad (17)$$

the option o can potentially be afforded by the household. This is a simplifying assumption as it neglects that a household could potentially cover the investment costs of the second and third year by the income in these years from other fields. If no option is affordable, the household chooses the "no change" option, i.e. all land uses remain the same and no replanting takes place.

The following steps are executed for each affordable option with the goal to choose the most profitable one.

In the current year t, investment costs due to the implementation of option o are

$$\sum_{household\ fields\ p_k} m_{p_k} \cdot icost_{j_{p_k},l_{p_k},n_t} \ . \tag{18}$$

Therefore, if option o is implemented, the remaining capital available for factor inputs in year t is

$$^{o}W_{i,rest} := W_{i,temp} - \sum_{household\ fields\ p_k} m_{p_k} \cdot icost_{j_{p_k},l_{p_k},n_t} \geq 0 \tag{19}$$

If the remaining capital $^{o}W_{i,rest}$ is sufficient for optimal factor input on all fields, i.e. if

$$^{o}W_{i,rest} \geq \sum_{household\ fields\ p_k} m_{p_k} \cdot rcost_{j_{p_k},l_{p_k},n_t}(L^*_{n_t}, K^*_{n_t}, TI^*_{n_t}, \overline{LA}) \ , \tag{20}$$

and no additional external constraints are existent, the household will apply optimal factor inputs to maximize production and profit from agricultural land use. If the remaining capital is not sufficient for optimal factor inputs, i.e.

$$^{o}W_{i,rest} < \sum_{household\ fields\ p_k} m_{p_k} \cdot rcost_{j_{p_k},l_{p_k},n_t}(L^*_{n_t}, K^*_{n_t}, TI^*_{n_t}, \overline{LA}) \ , \tag{21}$$

factor inputs are reduced (see section 4.4.1.3). Net cash flow $^{o}\Pi_{i,t}$ under option o and actual factor inputs is calculated. The fictive household wealth under application of option o is updated to

$$^{o}W_{i,t} = W_{i,temp} +^{o} \Pi_{i,t} + \tilde{Y} \tag{22}$$

with external household income $\tilde{Y}$.

To decide, which of the affordable options should be chosen by the household, we calculate the expected cash flow from agricultural use within a certain time horizon h for each potential option o. For this we also need to calculate the expected factor inputs during that time. As optimal factor inputs vary with plantation age and actual factor inputs depend on wealth, we need to simulate the wealth development of the household over the given time horizon. For this we assume, that within this period of h years no more land-use changes occur.

Prices for input, output and labor are assumed to stay constant within the considered time horizon and at the level of prices in period t. Also the external income is assumed to stay the same as in year t. Household consumption for each year is calculated based on the expected wealth in the respective year. Let $^{o}\Pi_{i,t}$,...,$^{o}\Pi_{i,t+h}$ be the expected net cash flows from agricultural use under option o within the time horizon h. For each option o the discounted accumulated expected cash flow is calculated as

$$ {}^{o}\Pi\_expected_i := \sum_{j=0}^{h} \frac{{}^{o}\Pi_{i,t+j}}{(1+r)^j} \ , \tag{23} $$

with discount rate r. The option with the maximal expected cash flow is then implemented.

4.4.1.3 Reduction of factor inputs

In the case of Equation 21 the household cannot afford optimal factor inputs if option o is implemented. Therefore, factor inputs need to be reduced. However, Equation 17 assures that the unavoidable rental costs for capital and land can be covered as

$$ {}^{o}W_{i,rest} \geq \sum_{household\ cells\ j} (rK^*_{n_{t,j}} + r_L\overline{LA}) + W_{min} \ . \tag{24} $$

We assume that costs for capital and land are fixed and only the input factors labor L and technical input TI can be reduced. The amount of available resources for factor input is

$$ {}^{o}W_{i,FI} :=^{o} W_{i,rest} - \sum_{household\ cells\ j} (rK^*_{n_{t,j}} + r_L\overline{LA}) \ . \tag{25} $$

To determine on which fields factor inputs are reduced, the marginal loss for a representative cell j_m of each household field m is calculated. Factor inputs are reduced on the fields with lowest marginal losses, until all remaining capital is used.

The production of one unit of output less involves less labor and technical input and thus reduces the costs by an amount of $cost\_red$. Since we apply a Leontief production function, each unit of production in a plantation of age n involves factor inputs of L^*_n/y^*_n of labor and TI^*_n/y^*_n of technical input, where L^*_n and TI^*_n are the optimal factor inputs to produce the maximum output y^*_n in a plantation of age n. Therefore, the optimal factor input for the production of $y^*_n - 1$ output units on one cell is

$$ \left(L^*_n - \frac{L^*_n}{y^*_n}, K^*_n, TI^*_n - \frac{TI^*_n}{y^*_n}, \overline{LA} \right) \ . \tag{26} $$

The cost reduction involved in producing one unit of output less on one cell is thus

$$ \begin{aligned} cost\_red &= rcost(L^*_n, K^*_n, TI^*_n, \overline{LA}) - rcost\left(L^*_n - \frac{L^*_n}{y^*_n}, K^*_n, TI^*_n - \frac{TI^*_n}{y^*_n}, \overline{LA} \right) \\ &= w \cdot \frac{L^*_n}{y^*_n} + p_{TI} \cdot \frac{TI^*_n}{y^*_n} \end{aligned} \tag{27} $$

with
w: wage for one hour of work [US$/h]

p_{TI}: price for one unit of technical input [US$/kg].

The marginal loss ($mloss$) in net cash flow from cell j under land use l is thus

$$\begin{aligned} mloss &= \Pi cell_{j,t}(L_n^*, K_n^*, TI_n^*, \overline{LA}) - \Pi cell_{j,t}\left(L_n^* - \frac{L_n^*}{y_n^*}, K^*, TI_n^* - \frac{TI_n^*}{y_n^*}, \overline{LA}\right) \\ &= p_{l,t} - cost\_red \end{aligned} \tag{28}$$

with
$p_{l,t}$ the revenue for one unit of production (= price [US$/ton] of product of land use l in year t.).

Those fields with high marginal losses should receive optimal factor input, if possible. Therefore factor inputs are determined starting with the field with the highest marginal loss. Let p be the field with the highest marginal loss, m be the number of cells in p and n_p the age of the plantation in field p.

If the remaining resources for factor inputs ${}^oW_{i,FI}$ cover the costs for optimal input of labor and technical input on field p, i.e.

$${}^oW_{i,FI} \geq m \cdot (wL_{n_p}^* + p_{TI}TI_{n_p}^*)\ , \tag{29}$$

this field will receive optimal factor input and ${}^oW_{i,FI}$ is reduced by these costs:

$${}^oW_{i,FI} :={}^o W_{i,FI} - m \cdot (wL_{n_p}^* + p_{TI}TI_{n_p}^*)\ . \tag{30}$$

This process is continued for the other household fields with decreasing marginal loss until the field is reached at which the remaining resources ${}^oW_{i,FI}$ are not sufficient anymore to cover optimal factor inputs.

Let q be this field of size m_q and age n_q, where

$${}^oW_{i,FI} < m_q \cdot (wL_{n_q}^* + p_{TI}TI_{n_q}^*)\ . \tag{31}$$

As each unit of production involves labor and technical input costs of

$$w \cdot \frac{L_{n_q}^*}{y_{n_q}^*} + p_{TI} \cdot \frac{TI_{n_q}^*}{y_{n_q}^*}\ , \tag{32}$$

the household can afford a production of

$$f :={}^o W_{i,FI} \Big/ \left(w \cdot \frac{L_{n_q}^*}{y_{n_q}^*} + p_{TI} \cdot \frac{TI_{n_q}^*}{y_{n_q}^*}\right) \tag{33}$$

units. The factor inputs for labor and technical input on this field are thus

$$f \cdot \frac{L_{n_q}^*}{y_{n_q}^*} \quad \text{and} \quad f \cdot \frac{TI_{n_q}^*}{y_{n_q}^*}\ . \tag{34}$$

The remaining fields do not receive inputs of labor or technical inputs in this year.

At the end of this step, factor inputs for each household cell are known. Thus the profit from land use under option o with these factor inputs can be calculated for each household cell and household wealth can be updated according to Equation 22.

4.4.1.4 Implementation of the land management decision

Now it is clear which of the affordable options is implemented and also the factor inputs are known. Let o be the chosen option, then the unavoidable costs in this year are potential investment costs as well as the recurrent costs for capital and land

$$^{o}costs_u := \sum_{household\ cell j} (^{o}icost_j + r_t K_j + r_{L,t}\overline{LA}) \quad . \tag{35}$$

Similar to Equation 14, these unavoidable costs are subtracted from the current wealth, respecting the minimum wealth level

$$W_{i,temp2} := \begin{cases} W_{i,temp} -^{o} icost_j & \text{, if } W_{i,temp} -^{o} icost_j \geq W_{min} \\ W_{min} & \text{, else} \end{cases} \tag{36}$$

If the household needs to take up debts to assure the minimum wealth level, these debts amount to

$$D_{i,t,temp2} :=^{o} icost_j + W_{min} - W_{i,temp} \quad . \tag{37}$$

Finally, the factor inputs of labor and technical inputs under option o reduce the wealth

$$W_{i,temp3} := W_{i,temp2} - (^{o}cost_{L,t} +^{o} cost_{TI,t}) \quad , \tag{38}$$

with
$^{o}cost_{L,t}$ costs for labor in year t under option o,
$^{o}cost_{TI,t}$ costs for technical inputs in year t under option o.

Any debts a household gets into in the current year, e.g. due to consumption or due to unavoidable costs (see Eq. 15 and 37), are added to the potentially remaining debts from the previous year, and if possible, payed off at the end of the period, when cash flows are realized. Household debts in period t before pay off are therefore

$$D_{i,temp3} := D_{i,t-1} + D_{i,t,temp1} + D_{i,t,temp2} \tag{39}$$

with
$D_{i,t-1}$ debts after pay off in period $t-1$.

Now the cash flow from the realized option o as well as the external income are added to the household wealth and the cash flow dependent part of consumption is accounted for

$$W_{i,temp4} := \begin{cases} W_{i,temp3} + (1-\beta)^{o}\Pi_{i,t} + \tilde{Y}_i & \text{, if } ^{o}\Pi_{i,t} > 0 \\ W_{i,temp3} +^{o} \Pi_{i,t} + \tilde{Y}_i & \text{, if } ^{o}\Pi_{i,t} \leq 0 \end{cases} \tag{40}$$

with
$^{o}\Pi_{i,t}$ the cash flow in this year,
$\tilde{Y}_i$: external income in year t,
β the cash flow dependent fraction of consumption (see Eq. 13).

Finally, the household pays off debts but respects the minimum wealth level. Therefore the household wealth which is available for the next year is

$$W_{i,t} := \begin{cases} W_{i,temp4} - D_{i,t,temp} & \text{, if } W_{i,temp4} - D_{i,t,temp3} > W_{min} \\ W_{min} & \text{, if } W_{i,temp4} - D_{i,t,temp3} \leq W_{min} \end{cases} . \tag{41}$$

The household debts are updated accordingly to

$$D_{i,t} := \begin{cases} 0 & \text{if, } W_{i,temp4} - D_{i,t,temp3} > W_{min} \\ D_{i,temp3} - (W_{i,temp4} - W_{min}) & \text{if, } W_{i,temp4} - D_{i,t,temp3} \leq W_{min} \end{cases} \tag{42}$$

Households which do not manage to pay back debts within a certain period, i.e. $D_{i,t} > 0$ for D_{max} consecutive years (see Table 5), are assumed to be incapable of acting and are frozen in the model.

4.4.2 Parametrization of the household submodel

For the implementation of the Leontief production function, we consider the following economic functions: optimal production, optimal labor use, optimal amount of technical inputs, optimal capital stock, and the use of land. Apart from land, all economic functions depend on the age of the respective plantation. To derive these functions and their parameters we used data from a household survey in the province of Jambi, Sumatra (Euler et al., 2012; Faust et al., 2013). Jambi is the focus of the Collaborative Research Center EFForTS (Ecological and Socioeconomic Functions of Tropical Lowland Rainforest Transformation Systems (Sumatra, Indonesia)) which has started in 2012. Interdisciplinary research on social and economic dynamics has provided a household survey of 701 households, which include information such as households' land holdings, agricultural and non-agricultural activity, endowments and household composition (for more details see Krishna et al., 2014; Euler et al., 2015a,b; Krishna et al., 2015). The survey represents a random sample out of 40 villages which in return are randomly chosen out of 5 regencies within the province Jambi. The respective sample sizes per village are chosen proportionally to village size. Out of the household sample, we use information on the production of 246 oil palm farmers cultivating 385 oil palm fields and 579 rubber farmers cultivating 962 rubber fields. Drawing on the reported ages of plantations, the oil palm fields of oil palm farmers are between 0 and 23 years old and the rubber fields have an age between 0 and 45 years. This enables a data-based parametrization of the economic functions for these time spans. Since we do not assume a maximum plantation age in our model, we also need to extrapolate economic functions for plantation ages beyond the data. To derive the production function, we estimate optimal yield, labor and technical inputs. For the estimation of optimal yields we selected the 30% highest yielding fields per plantation age ($N = 105$ for oil palm and $N = 244$ for rubber) (see Fig. 4 (a) and (b)). Assuming that these fields are optimally managed, they were also used to derive model functions and parameters for optimal labor and technical input.

4.4.2.1 Production functions for oil palm and rubber

Optimal production

Yields of the 30% highest yielding oil palm and rubber fields is presented in Figure 4 (a,b). As an estimation of the optimal, i.e. maximal potential fresh fruit bunch production over palm age, we use a function derived by Hoffmann et al. (2014) which is based on data from 13 sites in Indonesia and Malaysia (see Fig. 4 c). After the immature phase of three years, in which yield is zero, this function has a roughly exponential increasing phase, which is followed by a plateau and a decreasing yield phase. The applied function is

$$production_{oil\ palm}(x) = \begin{cases} 0 \text{ , if } x \leq 2 \\ p_{o1} \cdot exp(p_{o2} \cdot x) \text{ , if } 2 < x \leq 7 \\ p_{o3} \text{ , if } 7 < x \leq 11 \\ max\{0, p_{o4} \cdot x + p_{o5}\} \text{ , if } x > 11 \end{cases} \tag{43}$$

with parameters shown in Table 5. As we do not assume a maximum plantation age in our model, this function is also used to extrapolate production for plantation ages beyond the data (see Fig. 4 e).

For rubber, we estimated the potential yield from our data and used a parabola which reflects the limited life span of tapped rubber trees. As we are interested in the maximal possible yields, we require rather an envelope function above the data than a fit. Therefore, we shift the fitted function upwards so that 95% of the data from high yielding fields are under the curve (Fig. 4 (d)). We fix the production of rubber in the first five years to zero. The resulting optimal production function for rubber is shown in Figure 4 (f). The applied optimal production function for rubber is therefore

$$production_{rubber}(x) = \begin{cases} 0 \text{ , if } x \leq 4 \\ max\{0, p_{r1} \cdot x^2 + p_{r2} \cdot x + p_{r3}\} \text{ , if } x > 4 \end{cases} \tag{44}$$

with parameters shown in Table 5.

Optimal labor input

To estimate optimal labor use we draw on the labor data from the same 30% highest yielding fields per plantation age, but exclude data from the first three years for oil palm, and respectively the first five years for rubber, as we consider input of labor during this period as part of the investment. The data on labor comprise operations such as land clearing, pits taking, seedling transportation, planting and replanting, manure and fertilizer application, chemical and manual weeding, harvesting, pruning and marketing. Working hours per hectare are accumulated for each best performing field. The data were very scattered for both land uses (see Fig. 5 (a) and (b)). For oil palm an increase in labor after the plantation establishment phase followed by a slight decrease in labor input was apparent. We tested different relationships: a hump-shaped function

$$lab(x) = l_1 + \frac{x}{l_2} exp^{-\frac{x}{l_2}} \quad , \tag{45}$$

Category	Land-use type	Parameter	Unit	Meaning	Value	Reference/Justification
Production	**Oil palm**	p_{o1}	[-]	scaling (exponential growth phase)	0.3	
		p_{o2}	[-]	exponent (exponential growth phase)	0.7	
		p_{o3}	[T]	plateau value (plateau phase)	40	Hoffmann et al. 2014
		p_{o4}	[-]	slope (decreasing phase)	-0.6	
		p_{o5}	[T]	intercept (decreasing phase)	46	
			[$/ton]	price fresh fruit bunches	90	CRC990 data
	Rubber	p_{r1}	[-]	quadratic parameter of parabola	-0.007	
		p_{r2}	[T]	linear parameter of parabola	0.3	derived from CRC990 data
		p_{r3}	[-]	constant parameter of parabola	2.5	
		p_{r4}	[$/ton]	price rubber	1100	CRC990 data
Labor	**Oil palm**	l_{o1}	[y]	breakpoint 1	5	
		l_{o2}	[y]	breakpoint 2	7	
		l_{o3}	[y]	breakpoint 3	25	
		l_{o4}	[h/y]	slope segment 1	100	
		l_{o5}	[h/y]	slope segment 2	-80	derived from CRC990 data
		l_{o6}	[h/y]	slope segment 3	-0.8	
		l_{o7}	[h]	intercept segment 1	-230	
		l_{o8}	[h]	intercept segment 2	690	
		l_{o9}	[h]	intercept segment 3	120	
		l_{o10}	[h]	plateau value (old plantations)	1400	calibrated
	Rubber	l_{r1}	[h/(ha year)]	labor input (plantation age > 4)	700	derived from CRC990 data
	all land-use types	P_w	[$/hour]	wage	1.6	CRC990 data
Technical input	**Oil palm**	t_{o1}	[kg/(ha y)]	constant input mature phase	740	CRC990 data
	Rubber	t_{r1}	[kg/(ha y)]	constant input mature phase	150	CRC990 data
	all land-use types	P_t	[$/kg]	price technical input	0.5	CRC990 data
Capital	**Oil palm**	c_{o1}	[$/ha]	Investment costs immature phase	[600 200 150]	CRC990 data
		c_{o2}	[-]	depriciation rate young plantations	-0.1	
		c_{o3}	[-]	depriciation rate old plantations	0.1	estimated
		c_{o4}	[year]	age in which depriciaton rate switches	10	
	Rubber	c_{r1}	[$/ha]	Investment costs immature phase	[200,70,70,70,70]	CRC990 data
		c_{r2}	[-]	depriciation rate young plantations	-0.05	
		c_{r3}	[-]	depriciation rate old plantations	0.05	estimated
		c_{r4}	[year]	age in which depriciation rate switches	15	
	all land-use types	rc	[-]	rental rate of capital	0.1	estimated
Land	**all land-use types**	r_l	[-]	rental rate of land	0.1	estimated
		P_l	[$/ha]	land price	750	CRC990 data

Table 5: Parameters of the economic household model related to the Leontief production function and costs.

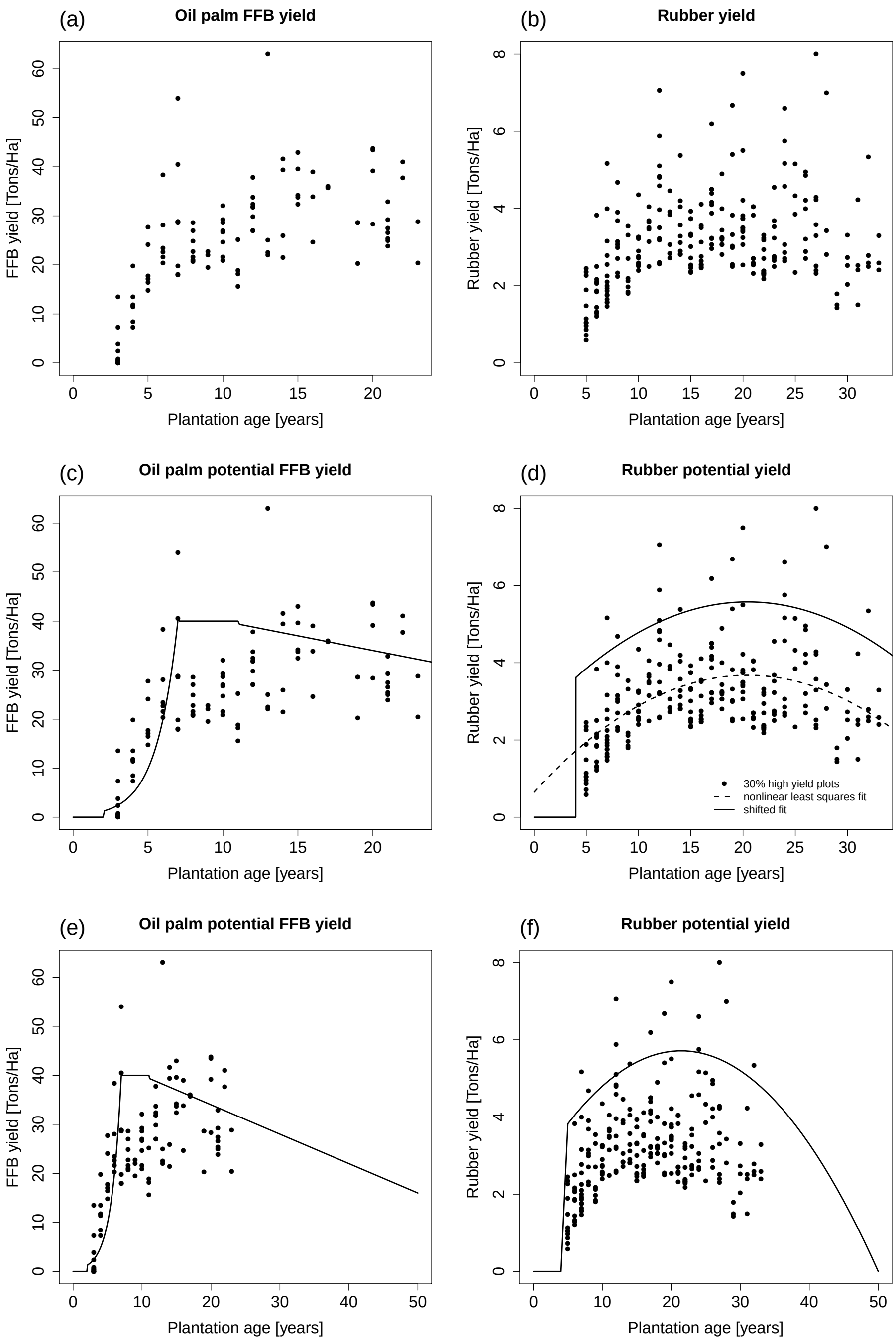

Figure 4: (a) Production of oil palm fresh fruit bunches [T/Ha] of the 30% highest yielding fields per plantation age. (b) Rubber production [T/Ha] of the 30% highest yielding fields per plantation age. (c), (d) nonlinear least square fit to data (dotted line) and upwards shifted fit (95% of data under the curve). (e), (f) Optimal yield functions applied in the model (parameter values were rounded).

Parameter	Unit	Meaning	Value
W_{min}	[$]	minimum wealth level	30
D_{max}	[year]	maximum number of consecutive debt years	5
$\tilde{Y}$	[$]	external annual household income (constant)	500
$\bar{C}$	[$]	base consumption (subsistence level)	1000
C_W	[-]	consumption fraction of wealth	0.05
C_π	[-]	consumption fraction of net cash flow	0.1

Table 6: Parameters of the economic household model related to household wealth and consumption.

and a segmented linear regression with one and two breakpoints (see Fig. 5 (c)). An AIC comparison of the three fits resulted in the lowest AIC for the segmented linear regression with two breakpoints. We therefore apply this function in the model and set the optimal labor input for the first three years to zero. One critical aspect is the extrapolation of labor inputs beyond the age where data were available. Apparently one reason why oil palm plantations generally have a lifespan of $25-30$ years is that after that period, yields decrease and harvesting becomes very difficult as the trees reach a height in which the fruit bunches are difficult to harvest with the conventional pole method. Therefore, we assume a steep increase in labor costs when palms reach a height after which the conventional harvesting method with long sticks is not possible anymore (see also Corley and Tinker (2008) p. 303 ff. and p. 318). As plantation cycles in our data end after about 25 years, we assume, that at this time, labor costs increase and result in plantations being unprofitable. We calibrate the amount of labor needed by assuming that at this point, the net cash flow is approximately zero, given optimal inputs and observed input and output prices.

The optimal labor input function is therefore

$$labor_{oilpalm}(x) = \begin{cases} 0 \text{ , if } x \leq 2 \\ l_{o4} \cdot x + l_{o7} \text{ , if } x > 2 \text{ and } x \leq l_{o1} \\ l_{o5} \cdot x + l_{o8} \text{ , if } x > l_{o1} \text{ and } x \leq l_{o2} \\ l_{o6} \cdot x + l_{o9} \text{ , if } x > l_{o2} \text{ and } x \leq l_{o3} \\ l_{o10} \text{ , if } x > l_{o3} \end{cases} \tag{46}$$

with parameters shown in Table 5 (see Fig. 5 (e)).

For rubber, we tested a constant, linear and hump-shaped function (see Eq. 45), with the AIC suggesting the hump-shaped curve (Fig. 5 (d)). However, since there was no large difference between the fits and labor input in rubber plantations seems to be rather steady over the years (regular tapping, harvesting and weeding), we decided to choose the constant function for optimal labor input. Therefore the optimal labor input for rubber is

$$labor_{rubber}(x) = \begin{cases} 0 \text{ , if } x \leq 4 \\ l_{r1} \text{ , if } x > 4 \end{cases} \tag{47}$$

with parameter in Table 5 (see also Fig. 5 (f)).

Optimal technical input
To estimate optimal technical input for both land uses, we use the data on technical inputs from the 30% highest yielding fields per plantation age (see Fig. 6 (a) and (b)). As for labor, technical input in the immature phase of the plantation are considered as part of the investment. The data on technical inputs refer to seedlings, plant and animal waste, soil amendments, fertilizer, herbicides, machinery and input and output transportation (measured in fuel). Except seedlings, quantities of inputs are generally measured in liters per hectare and are also accumulated for each best performing field. Seedlings are plausibly assumed to have a weight of 1 kilogram. The data on technical inputs are very scattered for both land uses. For oil palm, the data suggest an increase in technical inputs over time, while the inputs for rubber seem quite uniform. For both land-use types we tested a linear and a constant relationship.

The resulting fits are shown in Figure 6 (c,d). For oil palm, although the AIC comparison suggests the linear increase, we decide for the constant relationship as the linear fit results in unrealistically high technical input when extrapolated for old plantations. Also fertilizer recommendations for oil palm plantations typically suggest a two-level fertilization scheme and differentiate only between immature and mature plantation phase (Comte et al., 2012). Figure 6 (e) shows the applied relationship for optimal technical inputs, where inputs for the first three years are set to zero. The optimal technical input function is therefore

$$tinput_{oilpalm}(x) = \begin{cases} 0 \text{ , if } x \leq 2 \\ t_{o1} \text{ , if } x > 2 \end{cases} \tag{48}$$

with parameters shown in Table 5.

For rubber we compared a linear regression with constant technical inputs and decide for the constant function which is also suggested by AIC. The applied relationship for optimal technical inputs in rubber is therefore

$$tinput_{rubber}(x) = \begin{cases} 0 \text{ , if } x \leq 4 \\ t_{r1} \text{ , if } x > 4 \end{cases} \tag{49}$$

with parameter in Table 5 (see also Fig. 6 (f)).

Optimal capital input
The optimal capital input over time represents the capital stock of an oil palm or rubber plantation, i.e. the accumulated, discounted investment costs (see section 4.4.1.1). During the immature period of plantations we regard all labor costs and costs for technical inputs as investment costs. The accumulated value of costs for labor and technical inputs in this period are considered as total establishing costs of the plantation. All costs have been also derived from the household survey.
As investment costs for labor we include costs for the operations land clearing, pits taking, seedling transportation, planting and replanting, manure and fertilizer application, chemical and manual weeding, harvesting, pruning and marketing. Due to the high variance within the data of labor use, all labor

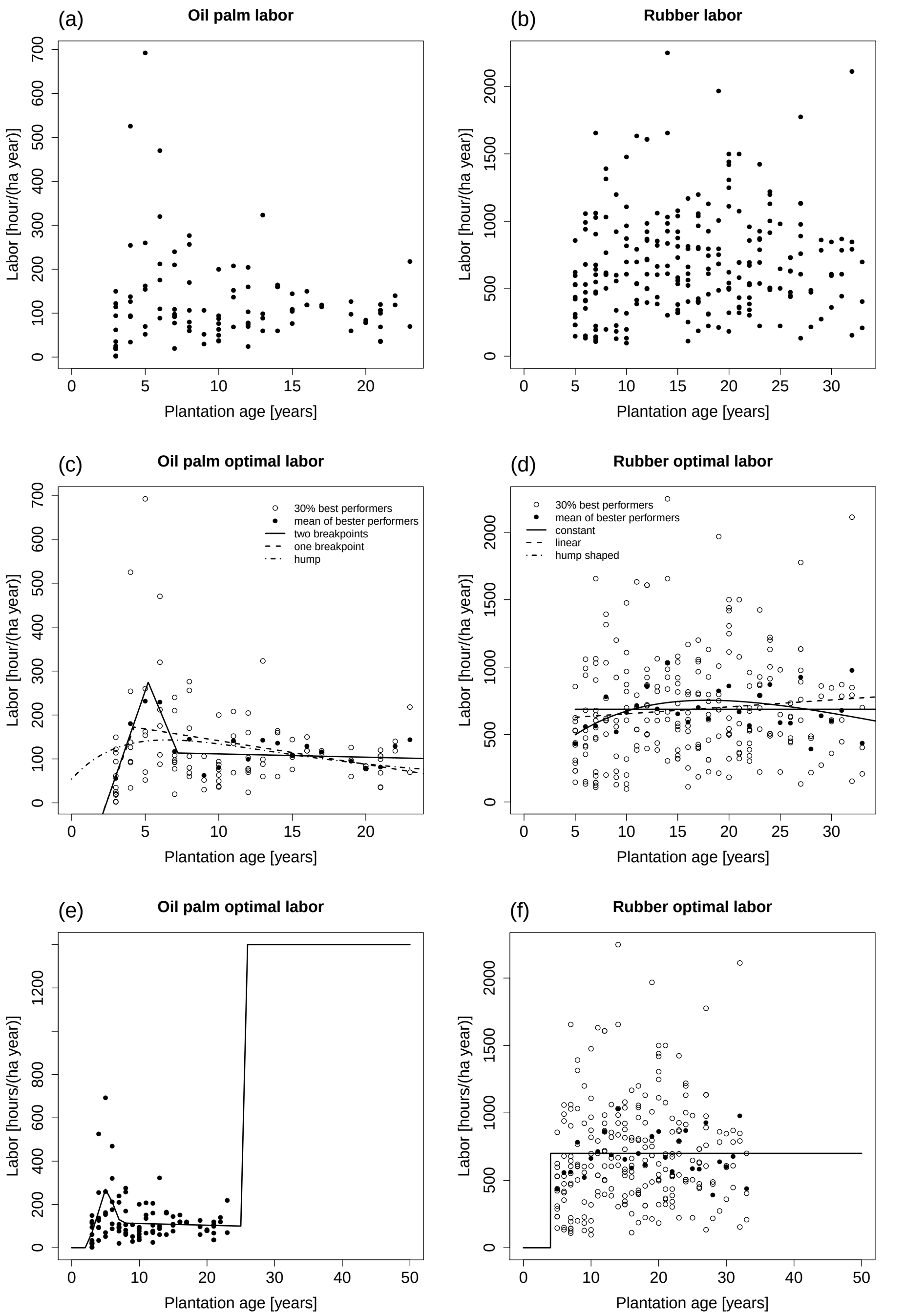

Figure 5: (a) Labor input oil palm [h/(Ha year)] of the 30% highest production fields per plantation age. (b) Labor input rubber [h/(Ha year)] of the 30% highest production fields per plantation age. (c) Different fits to the data: Segmented linear regressions with one and two breakpoints and a hump-shaped function of the form Equation 45. AIC results: 1257.5 (two breakpoints) < 1264.2 (one breakpoint) < 1271.5 (humped shape). (d) Different fits to the data: Constant labor input, linear regression and a hump-shaped function of the form Equation 45. AIC results: 3596.9 (hump shaped) < 3600.9 (linear) < 3601.4 (constant). (e), (f) optimal labor function applied in the model (parameter values were rounded).

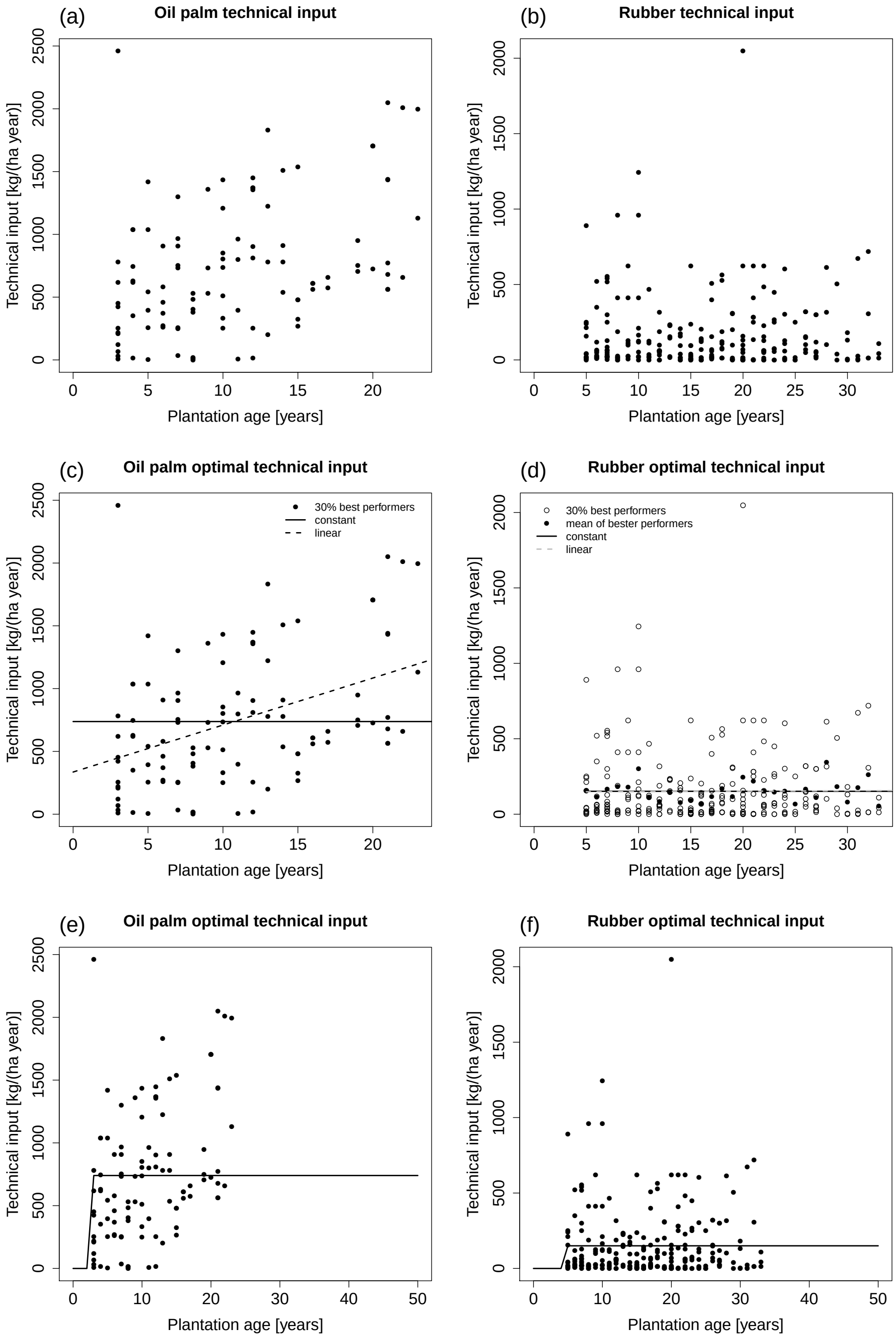

Figure 6: (a) Technical input in oil palm plantations [Kg/(Ha Year)] of the 30% highest production fields per plantation age. (b) Technical input in rubber plantations [Kg/(Ha Year)] of the 30% highest production fields per plantation age.(c) Different fits: exponential increase (continuous line), linear (dashed) and power law (dotted). AIC comparison: 1600.2 (exponential) < 1601.3 (linear) < 1602.9 (power law). (d) Different fits: constant function (continuous line) and linear regression (dashed). AIC comparison: 3358.7 (constant) < 3360.7 (linear). (e), (f) optimal technical input function applied in the model (parameter values were rounded).

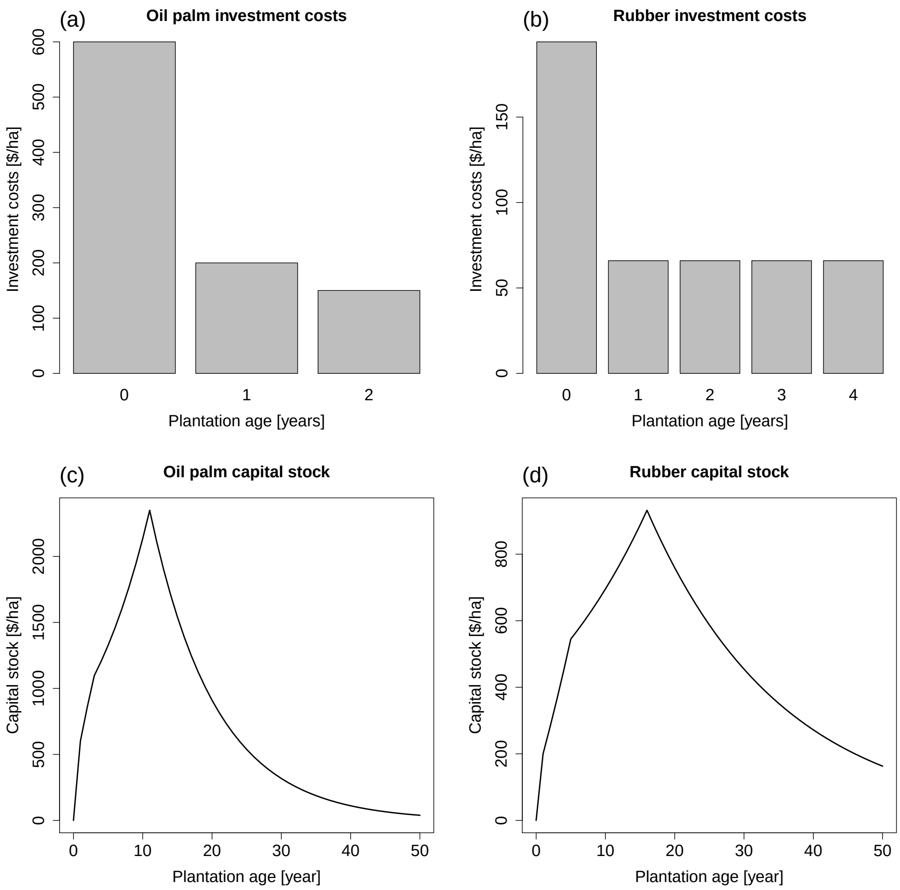

Figure 7: (a) Investment costs [$/Ha] for the first three years of an oil palm plantation. (b) Investment costs [$/Ha] for the first five years of an rubber plantation. As there was no large difference between the years 1 and 4, we apply the average of these years. (c), (d) Capital stocks over time.

costs per operation are calculated in multiplying the median hours of work per operation with the mean value of wages per operation. We also include costs for out-contracted labor. The costs for technical inputs are calculated in multiplying the idiosyncratic prices of inputs with the respective quantities of inputs. The respective inputs are seedlings, plant and animal waste, soil amendments, fertilizer, herbicides, machinery and input and output transportation. The resulting investment costs during the immature phase are shown in Figure 7 (a) and (b). As described in section 4.4.1.1, we assume a positive depreciation rate, i.e. increasing capital stocks in young plantations, and afterwards a negative depreciation rate, i.e. decreasing capital stocks. All parameters concerning capital costs in oil palm and rubber plantations are given in Table 5. The resulting optimal capital inputs for the Leontief production function are shown in Figure 7 (c) and (d).

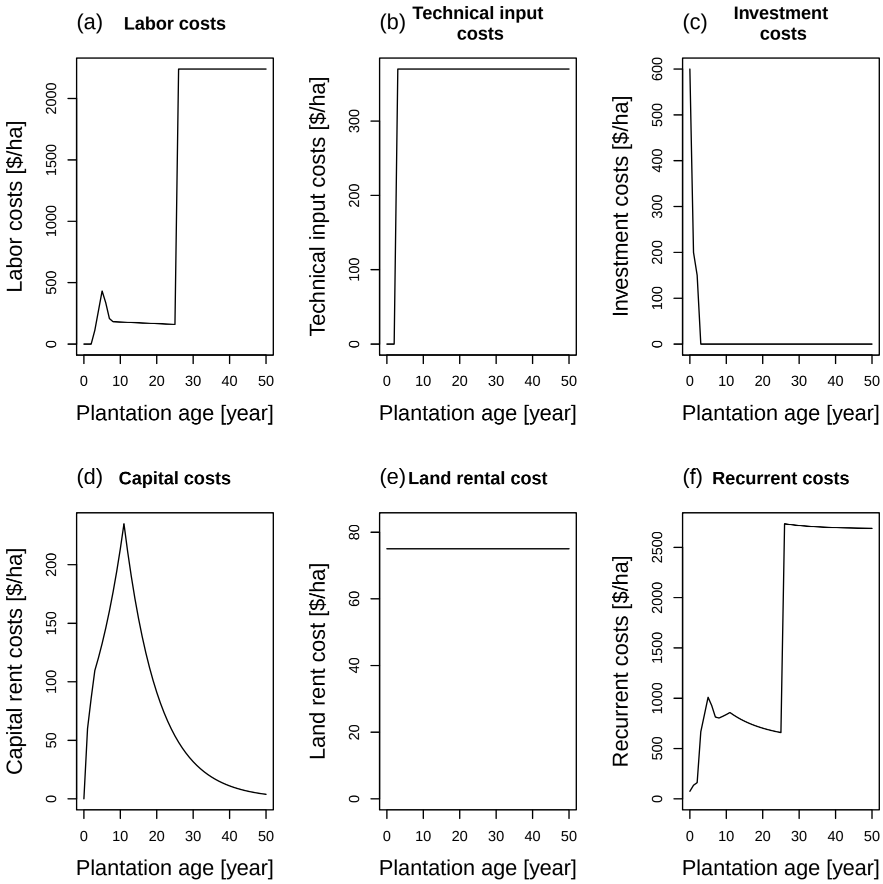

Figure 8: Overview of the different cost functions for oil palm over plantation age under optimal production inputs. Recurrent costs are the sum of labor, technical input, capital and land rental costs.

Optimal land input
Since we always calculate the Leontief production function based on a cell, the input for land is fixed to the cell size, in this case to 0.25 *ha*.

4.4.2.2 Costs, revenue & Cash flow

For the calculation of the different costs occurring in plantation agriculture over time, we use the household data to derive mean values for wages, prices of technical inputs and prices of land. We also include a price for capital, which captures the opportunity costs of capital referring to a rental rate of capital. Prices of fresh oil palm fruit bunches and rubber are also derived from the household survey (see Table 5).

All data are calculated as mean values over all fields considering only the mature period after the first three or five years, for oil palm and rubber, re-

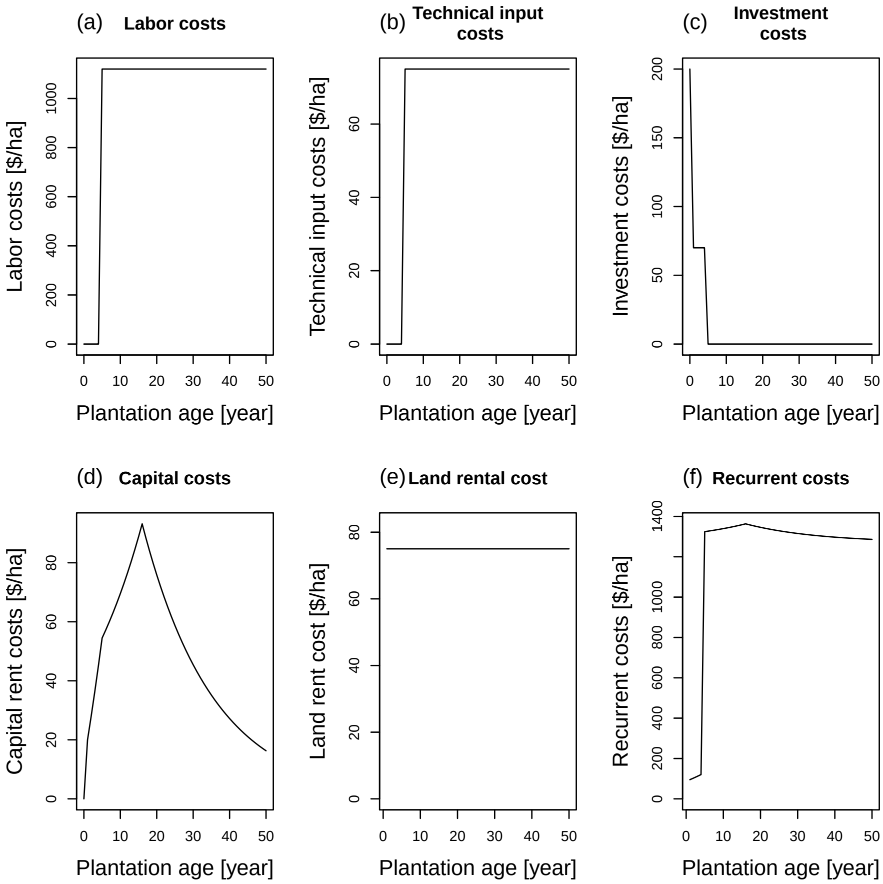

Figure 9: Overview of the different cost functions for rubber over plantation age under optimal production inputs. Recurrent costs are the sum of labor, technical input, capital and land rental costs.

spectively. To receive the final mean value for wage measured in hours, we first calculate the average wage per day (per operation), which is divided by the average numbers of working hours (per operation). The kinds of operation we considered are land clearing, pits taking, seedling transport, replanting, manure and fertilizer application, chemical and manual weeding, harvesting, cutting leaves, marketing, intercultural operations and irrigation. From all mean wages per operations we took a final mean. For calculating the overall mean price of technical inputs, we consider only the most applied and widely representative technical inputs used in the survey, which are fertilizer and herbicides. For each input the mean price and quantity is calculated. To generate a final price and quantity, we weight the final quantities of fertilizer and herbicides with the respective mean price and divide them by the sum of both quantities.

The rental rates for capital (r_c) and land (r_l) are fixed to 0.1 and are calculated as the average interest rate for informal and formal credits reported in the household survey. The price for land (p_l) captures the average price for land per hectare, which has been sold between 2009 to 2012 (see Table 5). Applying theses factors to the optimal factor inputs derived in section 4.4.2.1, we arrive at costs over the plantation lifetime presented in Figure 8 (oil palm) and Figure 9 (rubber).

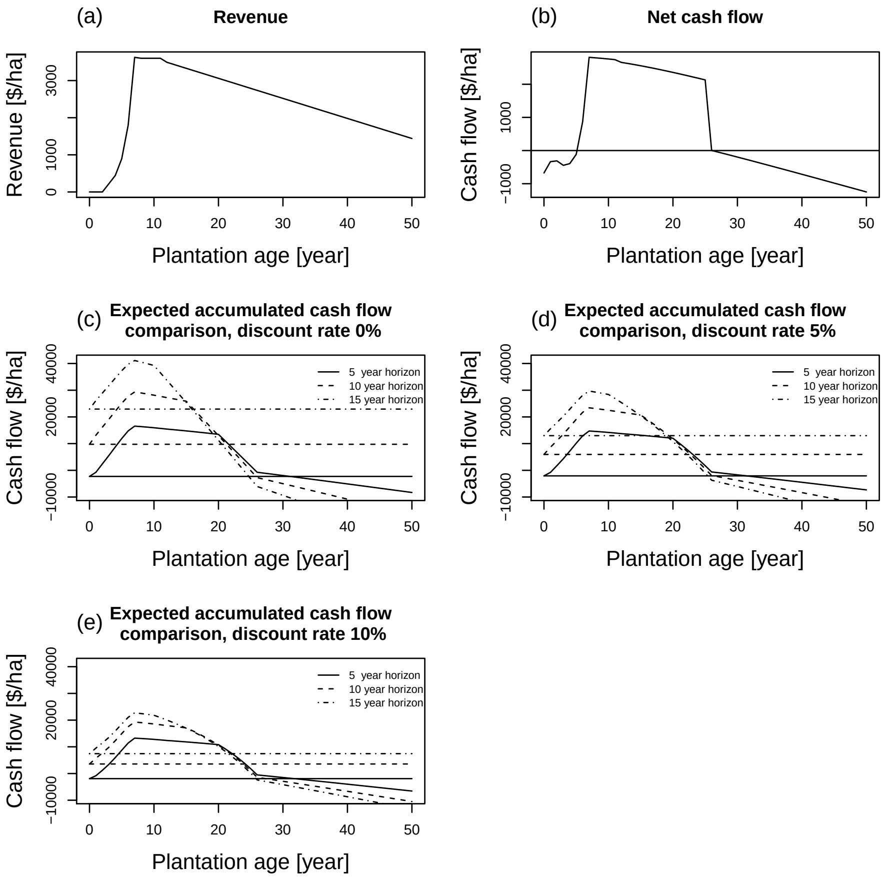

Figure 10: (a, b) Annual revenue and net cash flow of an oil palm plantation under optimal production inputs. (c), (d) and (e) Comparison of expected net cash flow of existing plantations (curves) with expected net cash flows from a newly established plantation (straight lines) under different planning horizons (5,10,15 years). Different fields represent different levels of discount rates (0, 0.05 and 0.1, respectively). The second intersection of each pair of lines marks the plantation age, in which replanting becomes the more profitable option.

Applying the average farm-gate prices as an example, we arrive at revenues and net cash flows shown in Figure 10 (a,b) and Figure 11 (a,b). Finally, Figure 10 (c,d,e) and Figure 11 (c,d,e) depict expected cash flows over the plantation lifetime (curves), as well as the expected cash flow for newly established plantations (straight lines). These expected cash flows are used in the model to compare different land-use change options (see section 4.4.1.2).

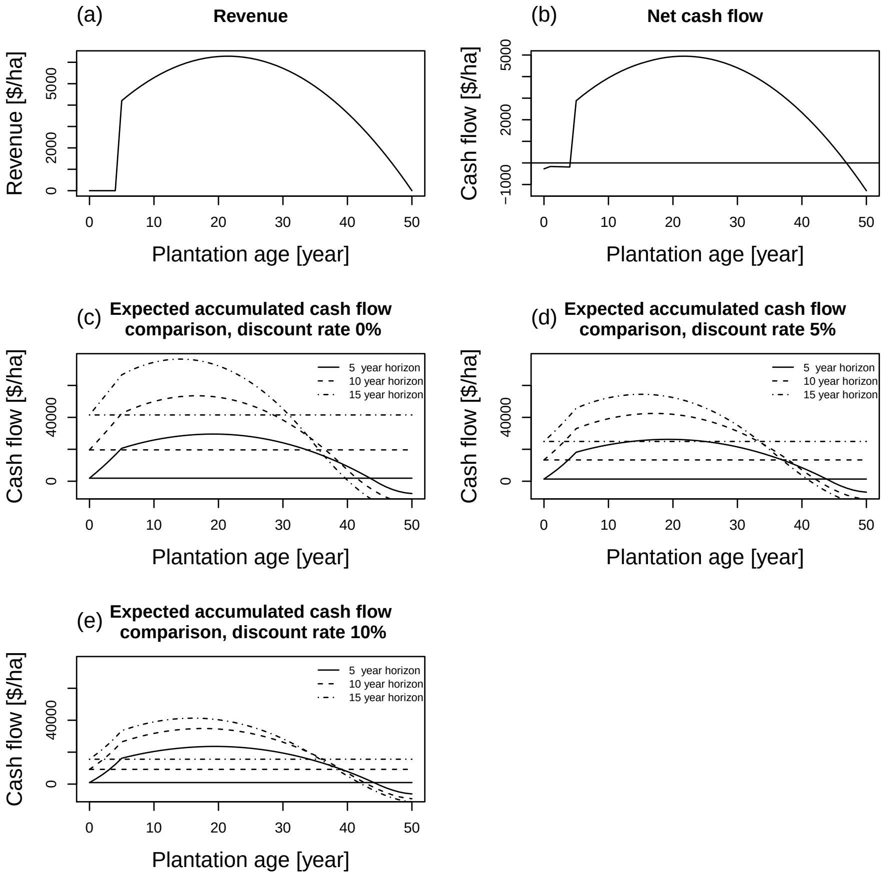

Figure 11: (a, b) Annual revenue and net cash flow of a rubber plantation under optimal production inputs. (c), (d) and (e) Comparison of expected net cash flow of existing plantations (curves) with expected net cash flows from a newly established plantation (straight lines) under different planning horizons (5,10,15 years). Different fields represent different levels of discount rates (0, 0.05 and 0.1, respectively). The second intersection of each pair of lines marks the plantation age, in which replanting becomes the more profitable option.

The accumulated expected net cash flow for newly established plantations over different time horizons and different price scenarios is shown in Figure 12. With the applied prices for oil palm fresh fruit bunches and rubber, rubber is the more profitable option, independent of the time horizon considered (Fig. 12 (a)). However, if the price relation between oil palm and rubber changes, e.g. with considerably lower prices for rubber, the profitability can depend on the considered time horizon (Fig. 12 (b)).

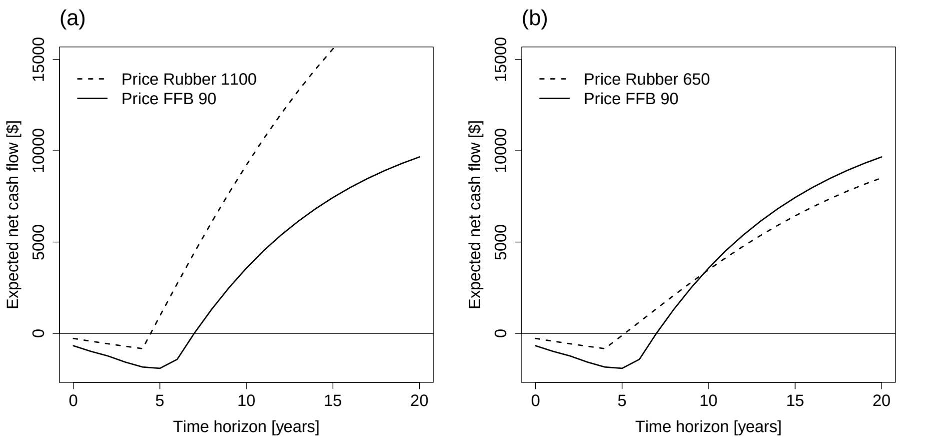

Figure 12: Accumulated expected net cash flows with discount rate of 0.1 for newly established oil palm and rubber plantations under different time horizons. (a) Prices for FFB and rubber as derived from CRC data. (b) Hypothetical lower price for rubber.

4.4.3 Price dynamics

All farmers are assumed to receive the same price for the same crop. These prices are related to world market prices of the respective crops, but we used information on price transmission from survey data. Farm-gate prices are considerably lower than world market prices mainly because of trade and transport margins. Average farm gate prices received by smallholders were 885 IDR/kg (about USD 0.09) of fresh fruit bunches for oil palm and 10412 IDR/kg (about USD 1.10) for rubber in the final quarter of 2012 (with an exchange rate of 9500 IDR/USD) see Euler et al. (2015b). The world market price for rubber at that time was about 3.20 USD/kg; in April 2015 it had declined to 1.71 USD/kg. For palm oil, the prices of which cannot be readily compared to the price for fresh fruit bunches, prices also declined, but the decline was less pronounced; from 768 USD/metric ton in 10/2012 to 592 USD/metric ton in 04/2015 (all international price data from the World Bank).

Different options for price dynamics are implemented in the model and can be chosen from the GUI. Prices can be kept constant, or variable around the initial prices with a specifiable range of variation ("price-fluctuation-%"). In the latter case, the price variation is drawn from a uniform distribution. Prices can also be chosen as correlated, again with a specifiable variation. In this case the price for the next year is calculated based on the current price with the variation again drawn from a uniform distribution. Finally, prices can be chosen to follow a Gaussian random walk with crop-specific mean and standard deviation. For example, if p_n is the price per harvested ton fresh fruit bunches in year n, the price for the following year is determined as

$$p_{n+1} = p_n + r(\mu, \sigma) \tag{50}$$

where r is a normally distributed random variable with mean μ and standard

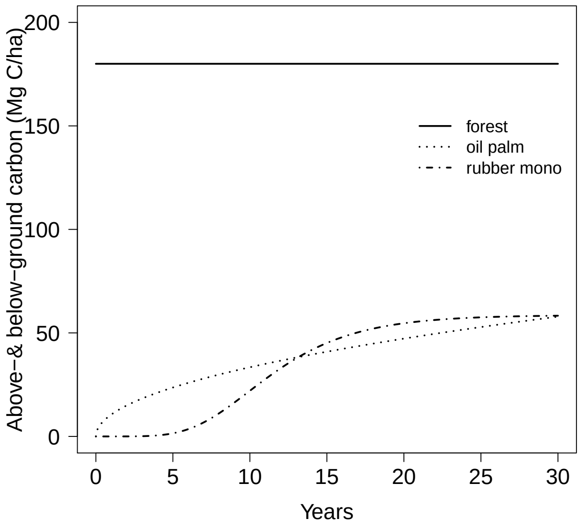

Figure 13: Carbon stocks of different land-use types

deviation σ. While μ determines the expected slope of the price function, σ determines price volatility.

As this paper focuses on basic model dynamics, we apply the constant price option.

4.4.4 Ecological model

4.4.4.1 Carbon storage

For the calculation of carbon stored in the vegetation of oil palm plantations, we use a function of Germer and Sauerborn (2008), that estimates aboveground biomass (AGB) of oil palm plantations as a function of plantation age

$$AGB_{oilpalm}(age)[Mg\ ha^{-1}] = 18.95 * age^{0.5} \tag{51}$$

Assuming a carbon content of 41.3% and a constant root-shoot ratio of 0.35, i.e. 74% of total carbon is aboveground and 26% is below ground (Syahrinudin, 2005), we arrive at a vegetative carbon stock of

$$carbon_{oilpalm}(age)[Mg\ ha^{-1}] = (18.95 * age^{0.5} \cdot 0.413) \cdot 1.35 \tag{52}$$

For rubber monoculture we apply the function for rubber trees in the Mato Grosso, Brazil from Wauters et al. (2008)

$$carbon_{rubbermono}(age)[Mg\ ha^{-1}] = 58.609 * exp(-13.696 * exp(-0.264 * age)) \tag{53}$$

For forest we assign a constant carbon content (we do not consider the option of converting plantations into forest yet). A mean carbon stock value is derived

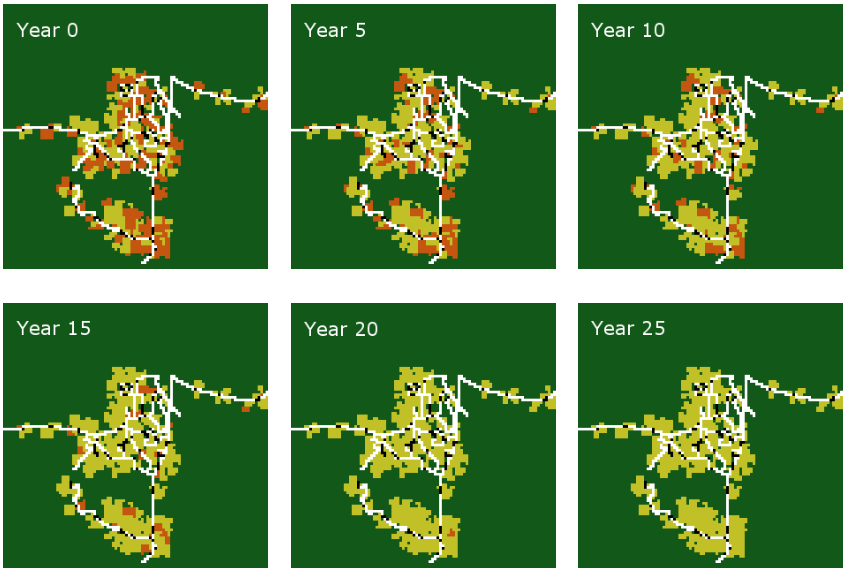

Figure 14: Snapshots of the simulated landscape in different years (0, 5, 10, 15, 20 and 25) of an exemplary simulation run. Roads are marked in white, household home bases black, oil palm plantations orange, rubber plantations yellow. Dark green is the area which is not used for agriculture.

from estimations of total biomass from the CRC core plots (M. Kotowska, unpublished data), applying a carbon content of 0.47% (default value for insular Asian tropical rainforests IPCC (2006))

$$carbon_{forest}[Mg\ ha^{-1}] = 389 \cdot 0.47 \approx 180 \tag{54}$$

The resulting carbon stocks are shown in Figure 13.

5 Results and Discussion

As the main purpose of this paper is to introduce and describe the developed model we restrict ourselves to some few exemplary results that illustrate the basic features of the model and the type of results it can produce.

The key mechanism of the model is the land management decision of the households. Farmers will tend towards the more profitable land use and will convert land with some time lag conditional on the current land use. For instance, the plantation age as well as endowments with capital need to be sufficient to cover the investment costs of conversion. This implies that the model should produce convergence towards the more profitable land use, at least if productivity is homogeneous and input and output prices are constant and common to all farmers. Indeed, we observed this behavior. For example, at the farm-gate prices of the last quarter of 2012 with rubber at US$1100 per ton and oil palm at US$90 per ton of fresh fruit bunches (FFB), rubber turns out more profitable than oil palm regardless of the time horizon used (Fig. 12 (a)). In such a scenario and with default settings (see Table 5), the fraction of fields planted with

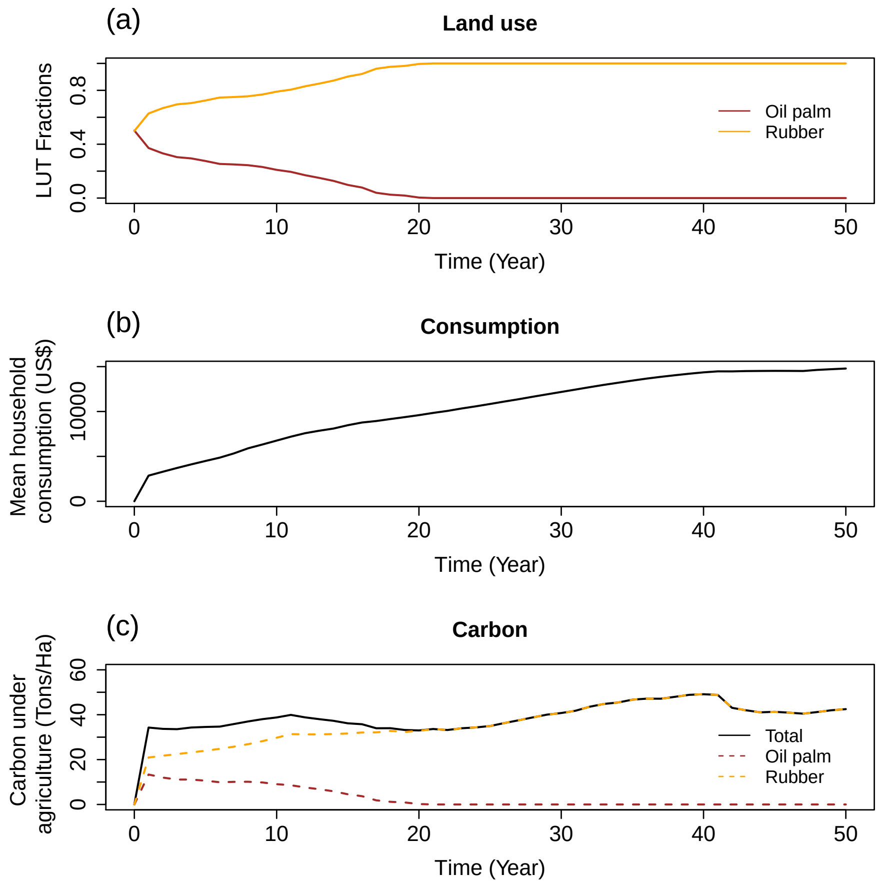

Figure 15: Fractions of different land-use types within the agricultural area, mean household consumption, and vegetation carbon stocks over time.

rubber increases to 1.0 and the fraction of fields planted with oil palm decreases to 0.0 (Fig. 14 and Fig. 15). The transition phase from a fraction around 0.5 for both crops in the initial situation is about 20 years under the current simplified specification and parametrization of the model. Note that the model can produce more diverse land-use patterns if we introduce heterogeneity in productivity. Then, the relative profitability of rubber and oil palm will possibly differ between farmers and therefore also their choice between rubber and palm oil.

The simulated land-use change scenario is associated with a considerable increase in household consumption (Fig. 15 (b)). In general, two forces are at work in the model that can increase profits and thus consumption over time. One is the "natural" yield growth of both crops; the second force is the option to switch to a more profitable crop. However, the investment costs of switching will cut into consumption and may temporarily decrease household welfare. The model results (see Fig. 15 (b)) show the average implications of these mechanisms for the consumption levels of farmers, the key indicator for household

Ecological model	Socio-economic model
• Incorporate **soil organic carbon** dynamics to allow estimation of the total carbon stock • Incorporate **biodiversity** as a function of patch size, surrounding habitats, land-use history (potentially also include animal movement to emphasize the role of space) • Incorporate **hydrological functions** to estimate the impact of land use on water availability and quality	• Incorporate location and function of **traders/mills/markets** in the model to capture socio-economic and spatial effects • Incorporate **migration**: e.g. increasing number of farming households, migration into towns (abandonment of farms) • Incorporate a **land market** to enable household expansion in terms of buying/selling/renting of land

Table 7: Intended model extensions for the ecological and the socio-economic model.

welfare in the model. Overall, consumption more than doubles within a time horizon of about twenty years. This is driven by both switching to more profitable rubber as well as increasing yields in rubber. The latter effect clearly drives the observed consumption increase after period 15. After period 40, the growth of consumption slows down again as the necessary replanting of rubber plantations involves new investments. This fairly steady improvement of average household welfare is accompanied by rather steady vegetation carbon dynamics (Fig. 15 (c)). The amount of carbon in the agriculturally used area fluctuates around $35 - 40$ tons per hectare within the first 20 simulation years, i.e. as long as there is a mixture of oil palm and rubber plantations. During this time, the reduction of vegetation carbon stock due to land-use change is roughly balanced by vegetation growth on those plots where land use does not change. After all oil palm plantations are replaced by rubber plantations, the vegetation carbon stock increases up to almost 50 tons per hectare, and then slightly decreases again. The decrease in carbon after period 40 is caused by the replanting of old rubber plantations. This means that with the applied land-use decision criterion and at the applied spatial scale and number of households, we observe a slight synchronization not only of land-use types but also of plantation ages, which might have both socio-economic and ecological consequences.

6 Outlook

What can be done with our model in its current state without further extensions? In the following we present a non-conclusive list of points to be analyzed in the future:

- The effect of alternative human behavior/decision rules on ecological and socio-economic functions: How do different decision making rules (e.g. profit maximization, risk minimization) affect land-use change? How does different consumption behavior affect the production decision of a household? How do different planning horizons affect production decision and thereby ecological and socio-economic functions? How does (variability in) inefficiency of plantation management affect ecological and socio-economic functions?

- The effect of external effects/drivers on land-use change via an analysis of land-use change under different hypothetical price developments, including economic shocks: How do global price shocks for agricultural products affect the production decisions of households and land-use change? How much land-use change (e.g. from rubber to oil palm) is expected within the next 30 years, given certain price development scenarios? What are the potential effects of different policies (PES) on land-use change?

- Synergies and trade-offs between ecological and socio-economic functions in realistic and hypothetical landscapes: How do landscapes look like if optimized for a certain function/several functions, e.g. maximum carbon sequestration? Are there win-win situations for socio-economic and ecological functions and what are the conditions for these win-win situations? How should smallholder behavior change to improve ecological functions on the local and landscape level?

After some extensions we will be able to also evaluate the following aspects:

- Spatial effects: How does proximity between farms and mills or markets affect selling prices? As a consequence, how does profitability of land-use choices vary in space? How do neighborhood effects such as learning and imitating change the outcomes of the model? How are such effects related to inter-individual differences, e.g. groups of agents with different behavior rules such as preferences for certain land-use types?

- Large-holder vs. smallholders: What are the differences in ecological and socio-economic functions with respect to large monocultures, homogenization vs. heterogeneous landscapes, fragmented landscapes. How does an increase of large-holder plantations affect ecological functions (e.g. biodiversity)? How do farmers association (such as INTI-PLASMA schemes in Indonesia) change the observed effects on functions?

The model is currently still under development. Important aspects we intend to incorporate next are presented in Table 7. To enable a validation of the model over longer time periods (e.g. few decades) and to test whether the model reproduces past land-use changes on the landscape scale, it is essential to integrate additional processes such as migration and the expansion of large scale plantations.

Acknowledgments

This study was financed by the German Research Foundation (DFG) in the framework of the collaborative German - Indonesian research project CRC990 ”EFForTS, Ecological and Socioeconomic Functions of Tropical Lowland Rainforest Transformation Systems (Sumatra, Indonesia)”. We thank M Euler, V Krishna, M Qaim and S Schwarze for providing the household survey data as well as M Kotowska, C Leuscher and D Hertel for providing tree biomass data.

7 Appendix

7.1 Landscape generator

The landscape generator is an extended version of the simple process-based landscape generator G-RaFFe (Pe'er et al., 2013), which originally simulates the extension of fields from roads and creates binary maps with forest- and non-forest cells. For our purpose we added different land uses and households as an intermediate level between fields and landscape. Households can own several fields of different sizes with different land uses. Household locations are always close to roads. For the creation of maps for model initialization, we used a section of a real road map from the Jambi region. Main input parameters for the landscape generator are the density of farming households, the distribution of household sizes, the distribution of field sizes, and the fraction of the different land uses. For a full description of the landscape generator please contact cdislic@gwdg.de.

7.1.1 Parameterization of the landscape generator

Household sizes
We use data from a household survey (701 households, Euler et al. (2012); Faust et al. (2013)) to determine the distribution of household sizes (= total area available for agricultural use). We scaled the histogram of household sizes to $[0, 1]$ and fitted the density functions of a log-normal distribution to the data (see Fig. 16) using maximum likelihood fitting (function *fitdistr* of the package MASS in R). The resulting parameters for mean and standard deviation of household area are presented in Table 4. Within the landscape generator, household sizes are determined by drawing a random number from the log-normal density function and rounding for the cell resolution (0.25 ha).

Field sizes
In the same manner as for household sizes, we use data from a household survey to determine the distribution of field sizes. We again fitted a log-normal distribution to the data (see Fig. 17). The resulting parameters for mean and standard deviation of field sizes are presented in Table 4.

7.2 Initial household wealth

For the estimation of initial household wealth we use data on assets purchased by households between 2000 and 2012 from the household survey. Asset categories included for example cellphones, television, satellite dishes, motorbikes and cars, fridges and washing machines. Figure 18 shows the histogram of the cumulative value of purchased assets to which we fitted a log-normal distribution. We use this distribution as a proxy for household wealth. Since these purchased assets represent only a fraction of household wealth, we multiply the drawn values with a scaling factor (in this case 10), to obtain the initial values for household wealth.

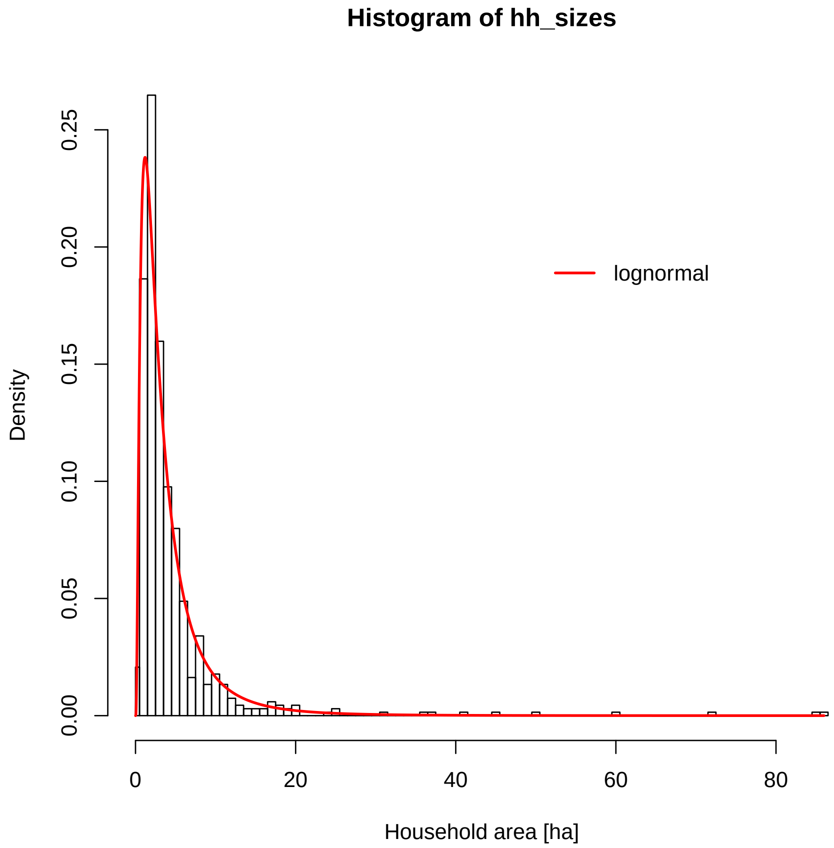

Figure 16: Histogram of household sizes with maximum likelihood fit of the log-normal distribution.

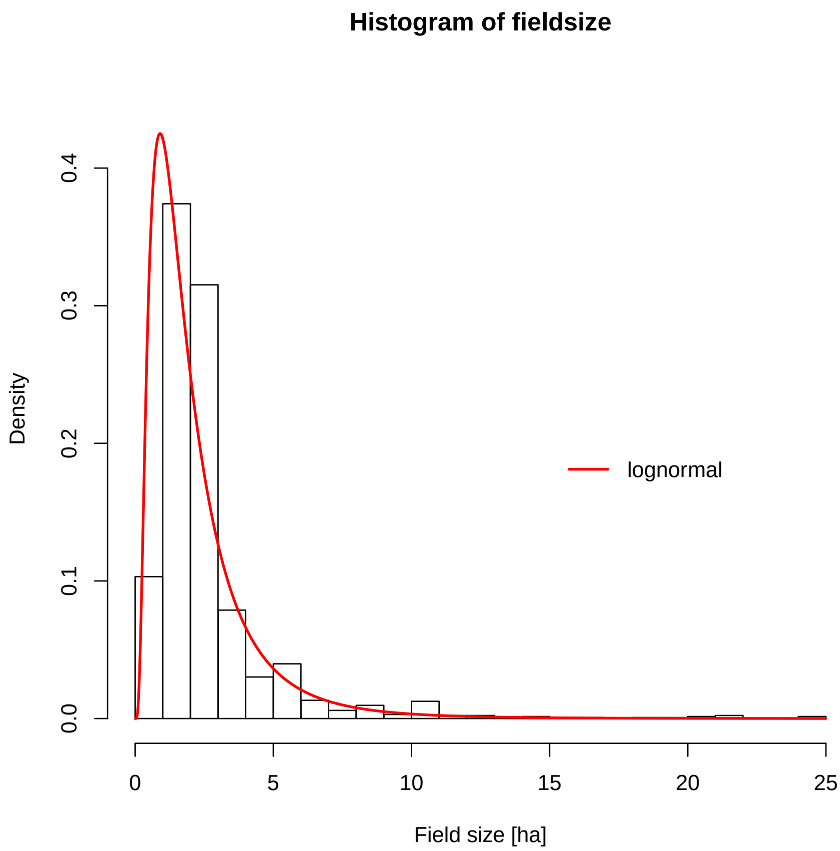

Figure 17: Histogram of field sizes with maximum likelihood fit of the log-normal distribution.

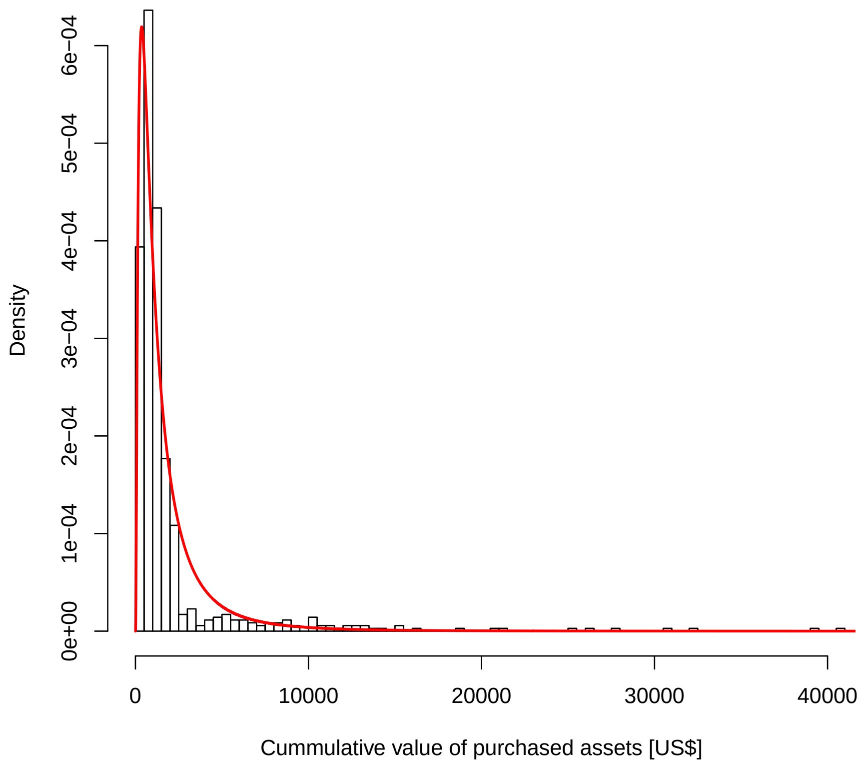

Figure 18: Histogram of cumulative value of purchased assets by households between 2000 and 2012.

References

Comte, I., Colin, F., Whalen, J.K., Gruenberger, O., Caliman, J.P., 2012. Agricultural Practices in Oil Palm Plantations and Their Impact on Hydrological Changes, Nutrient Fluxes and Water Quality in Indonesia: a Review, in: Sparks, D. (Ed.), Advances in Agronomy 116, pp. 71–124.

Corley, R., Tinker, P., 2008. The Oil Palm. John Wiley & Sons.

Diewert, W.E., 1971. An application of the Shephard duality theorem: A generalized Leontief production function. The Journal of Political Economy 79, 481–507.

Euler, M., Krishna, V., Fathoni, Z., Hermanto, S., Schwarze, S., Qaim, M., 2012. Ecological and Socioeconomic Functions of Tropical Lowland Rainforest Transformation Systems (Sumatra, Indonesia), Household Survey 2012. Göttingen, Germany; Jambi, Indonesia; Bogor, Indonesia. Georg-August University of Goettingen, Bogor Agricultural University, and University of Jambi (datasets).

Euler, M., Krishna, V., Schwarze, S., Siregar, H., Qaim, M., 2015a. Oil palm adoption, household welfare and nutrition among smallholder farmers in Indonesia. EFForTS Discussion Paper Series 12, University of Göttingen.

Euler, M., Schwarze, S., Siregar, H., Qaim, M., 2015b. Oil palm expansion among smallholder farmers in Sumatra, Indonesia. EFForTS Discussion Paper Series 8, University of Göttingen.

Evans, M.R., Grimm, V., Johst, K., Knuuttila, T., de Langhe, R., Lessells, C.M., Merz, M., O'Malley, M.A., Orzack, S.H., Weisberg, M., et al., 2013. Do simple models lead to generality in ecology? Trends in Ecology & Evolution 28, 578–583.

Faust, H., Schwarze, S., Beckert, B., Brümmer, B., Dittrich, C., Euler, M., Gatto, M., Hauser Schäublin, B., Hein, J., Holtkamp, A.M., Ibanez, M., Klasen, S., Kopp, T., Krishna, V., Kunz, Y., Lay, J., Mußhoff, O., Qaim, M., Steinebach, S., Vorlaufer, M., Wollni, M., 2013. Assessment of socio-economic functions of tropical lowland transformation systems in Indonesia. EFForTS Discussion Paper Series 1, University of Göttingen.

Germer, J., Sauerborn, J., 2008. Estimation of the impact of oil palm plantation establishment on greenhouse gas balance. Environment, Development and Sustainability 10, 697–716.

Grimm, V., Berger, U., Bastiansen, F., Eliassen, S., Ginot, V., Giske, J., Goss Custard, J., Grand, T., Heinz, S.K., Huse, G., Huth, A., Jepsen, J.U., Jorgensen, C., Mooij, W.M., Mueller, B., Pe'er, G., Piou, C., Railsback, S.F., Robbins, A.M., Robbins, M.M., Rossmanith, E., Rueger, N., Strand, E., Souissi, S., Stillman, R.A., Vabo, R., Visser, U., DeAngelis, D.L., 2006. A standard protocol for describing individual-based and agent-based models. Ecological Modelling 198, 115–126.

Grimm, V., Berger, U., DeAngelis, D.L., Polhill, J.G., Giske, J., Railsback, S.F., 2010. The ODD protocol A review and first update. Ecological Modelling 221, 2760–2768.

Hoffmann, M., Vera, A.C., Van Wijk, M., Giller, K., Oberthür, T., Donough, C., Whitbread, A., 2014. Simulating potential growth and yield of oil palm (Elaeis guineensis) with PALMSIM: Model description, evaluation and application. Agricultural Systems 131, 1–10.

IPCC, 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. IGES. volume 4. chapter 4: Forest Land. pp. 4.1–4.83.

Krishna, V.V., Euler, M., Siregar, H., Fathoni, Z., Qaim, M., 2015. Farmer heterogeneity and differential livelihood impacts of oil palm expansion among smallholders in Sumatra, Indonesia. EFForTS Discussion Paper Series 13, University of Göttingen.

Krishna, V.V., Pascual, U., Qaim, M., 2014. Do emerging land markets promote forestland appropriation? Evidence from Indonesia. EFForTS Discussion Paper Series 7, University of Göttingen.

Müller, B., Bohn, F., Dreßler, G., Groeneveld, J., Klassert, C., Martin, R., Schlüter, M., Schulze, J., Weise, H., Schwarz, N., 2013. Describing human decisions in agent-based models - ODD + D, an extension of the ODD protocol. Environmental Modelling & Software 48, 37–48.

Pe'er, G., Zurita, G.A., Schober, L., Bellocq, M.I., Strer, M., Müller, M., Pütz, S., 2013. Simple process-based simulators for generating spatial patterns of habitat loss and fragmentation: A review and introduction to the G-RaFFe model. PloS One 8, e64968.

Singh, I., Squire, L., Strauss, J., et al., 1986. Agricultural household models: extensions, applications, and policy. Johns Hopkins University Press.

Syahrinudin, 2005. The potential of oil palm and forest plantations for carbon sequestration on degraded land in Indonesia. Cuvillier Verlag Göttingen. Number 28 in Ecology and Development Series, pp. 1–107.

Villamor, G.B., Le, Q.B., Djanibekov, U., van Noordwijk, M., Vlek, P.L., 2014. Biodiversity in rubber agroforests, carbon emissions, and rural livelihoods: An agent-based model of land-use dynamics in lowland Sumatra. Environmental Modelling & Software 61, 151–165.

Wauters, J.B., Coudert, S., Grallien, E., Jonard, M., Ponette, Q., 2008. Carbon stock in rubber tree plantations in Western Ghana and Mato Grosso (Brazil). Forest Ecology and Management 255, 2347–2361.