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Assessing farmers' income vulnerability to vanilla and clove export economies in northeastern Madagascar using land-use change modelling

Enrico Celio [a], R. Ntsiva N. Andriatsitohaina [b], Jorge C. Llopis [c,d] and Adrienne Gret-Regamey [a]

[a]Eidgenossische Technische Hochschule Zurich, IRL - PLUS, Zurich, 8092 Switzerland; [b]Universite d'Antananarivo Ecole Superieure des Sciences Agronomiques, Mention Foresterie et Environnement Antananarivo Madagascar; [c]School of Natural Sciences, , UK Bangor University UK; [d]Centre for Development and Environment (CDE), University of Bern Switzerland

ABSTRACT

Using a participatory Bayesian network-based land-use decision model, we simulate future land-use patterns under various scenarios, including changes in vanilla and clove market prices as well as changes in irrigation water availability and potential harvest failures. Findings indicate that specifically the vanilla value chain (compared to the clove value chain) has a major influence on farmers income vulnerability. Abandoning vanilla cultivation may lead to poverty once income from vanilla reaches a certain threshold. By comparing farmer's income gains from cash crop production with costs for buying rice to cover basic needs, we show that while focusing on cash crop production is more lucrative, it is, however, highly risky with regard to climate change, price volatility and possible crop thefts. Such lock-in-effects in cash crops, like the vanilla ones in north-eastern Madagascar, are essential to be considered, when designing policies for a more sustainable development of resource-rich but poverty-prone regions.

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1. Introduction

Global demand for cash crops is increasing at an unprecedented rate, leading to significant land-use changes, especially in tropical and subtropical countries (Creutzig et al., 2019; Winkler et al., 2021). The economic, social, and ecological consequences of cash crop production are feeding international debates around economic growth, land rights, and ecological degradation (FAO, 2017). On the one hand, short-term economic benefits are traded-off for basic food sufficiency, ecological security, and social interactions (Ulrich, 2014; Zaehringer et al., 2018). On the other hand, the agrifood export production brings investment as well as technical and institutional spillovers impacting the development of local value chains (Feyaerts et al., 2020). Influences of these changes on household income is highly dependent on the local biophysical and socio-economic context (Minten et al., 2007; Van Den Broeck et al., 2017; Van Hoyweghen et al., 2018) as well as on exogenous drivers such as market development, demographical and technological changes (Creutzig et al., 2019). While place-based knowledge on the social, ecological and economic impacts of the transition from subsistence to market-oriented production is growing (Junquera & Grêt-Regamey, 2020), there is

CONTACT Enrico Celio ecelio@ethz.ch Eidgenossische Technische Hochschule Zurich, IRL - PLUS, Zurich, 8092 Switzerland
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missing understanding of the various long-term consequences of such transitions under increasingly uncertain markets and climate conditions.

Farmers optimize worldwide their farms related to criteria such as economic return, labor force availability, subsidies, subsistence needs, and, in occasions, to the cultural significance of certain production systems (Malek et al., 2019). While, in industrialized countries, farmers optimize mostly their economic profit following market demand or state subsidies, in less industrialized economies meeting subsistence needs is a key purpose of agricultural production, in particular, when access to food by market mechanisms or other transfers is insecure due to failing entitlements (see Amartya Sen's contribution in (Maxwell & Slater, 2003)). Across the globe, smallholder farmers are in majority and more likely to be subsistence farmers and poor compared to large farm holders (Rapsomanikis, 2015).

In the transition from subsistence-based agricultural systems to market-oriented cash crop productions, several effects have been observed: farm income often increases (Rasmussen et al., 2018), ecosystem services' supply is reduced (Dressler et al., 2017), and resilience to price volatility lowered (de Roest et al., 2018). However, arable land availability, market access, and farmers strategy of securing subsistence crop production play a crucial role in determining farmers' well-being (Thanichanon et al., 2018). Furthermore, there is growing evidence that climate change impacts affect smallholder farmers in developing countries disproportionately due to their heavy dependence on rainfed agriculture for their livelihoods (Anderson et al., 2009; Pachauri et al., 2014).

Uncertain market developments, environmental degradation and impacts of climate change have led to various farmers' adaptation strategies (Harmer & Rahman, 2014). Livelihood diversification, for example, allows improving the standard of living by distributing risks across various activities. More specifically, cultivating a subsistence crop has been shown to reduce market-related risks in a globalized world (Ruel et al. (1998) in: Baiphethi and Jacobs (2009)), (similar in Baiphethi & Jacobs, 2009), and maintaining a minimum rice self-sufficiency has been demonstrated to increase well-being (Junquera & Grêt-Regamey, 2020). However, poor households often face entry barriers to involvement in trade as well as in salaried jobs, hence preventing them from benefitting from this diversification mechanism, which might create ultimately more inequality (Gautam & Andersen, 2016). Furthermore, studies on farmers' strategies to adapt to climate change suggest that diversification measures might be effective in supporting farm productivity, but that they are often (too) costly to implement and inconsistent with other societal and environmental objectives (Khanal et al., 2018).

In this study, we investigated the income vulnerability of smallholder farmers to cash crop market uncertainties and climate change in northeastern Madagascar. Madagascar is one of the key exporter of vanilla and cloves worldwide (United Nations, 2022). Malagasy farmers are particularly vulnerable to cash crop price volatility and climate change, as they are highly dependent on agriculture for their livelihoods (Harvey et al., 2014). Vulnerability 'denotes susceptibility to harm, and is composed of exposure, sensitivity, and adaptive capacity' (Ford et al., 2018). We consider that a 'household is said to be vulnerable [if exposed] to future loss of welfare below socially accepted norms caused by risky events. The degree of vulnerability depends on the characteristics of the risk and the household's ability to respond to risk.' (Alwang et al., 2001). More specifically, we addressed the following research questions: (1) How do changes in market prices as well as in irrigation water availability and potential harvest failures potentially change land use in the coming years? (2) How does income vulnerability change given prices fluctuations as well as changes in irrigation water availability and potential harvest failures? (3) How does cash crop expansion interact with local rice production?

We used a participatory Bayesian Network-based land-use decision model to assess uncertainties in farmer's income under uncertain market prices and climate conditions exemplified for two study sites in northeastern Madagascar. Bayesian Networks (BN) allow to explicitly take into account uncertainties when assessing land-use changes (Celio et al., 2014; Ma et al., 2007). We set the scene by investigating how global value chains of clove, vanilla, and rice are characterized in order to see how this global price system could potentially affect local prices of clove, vanilla, and rice in

Madagascar. We then integrated market price values and possible environmental changes into the BN-based land-use decision model to assess future farmer's income vulnerability to changes in market prices as well as changes in irrigation water availability and potential harvest failures. Finally, we reflected on the trade-offs between income gains and rice production losses driven by land conversion.

2. Methods

In the following, we show how we embedded the case study context into the global value chain of rice, vanilla, and clove. We then explain the participatory process we conducted to develop the BN-based land-use decision model and show how the model was run under various climate conditions and market prices to understand future farmer's income vulnerability to these changes.

2.1 Study area

The case study area consists of two study sites in northeastern Madagascar, each one including two villages (Figure 1). The northern site encompasses a flat flood plain, and gently rises to a hilly area. The two villages (fokontany) Mahalevona (area: 58.23 km^2) and Fizono (area: 71.66 km^2) are located on the lower and the upper level of this rising hilly landscape, respectively. The southern site is located in a hilly area and consists of the village Morafeno (area: 20.05 km^2) and Beanana (area: 37.67 km^2). Area calculations are based on data by Llopis et al. (2019) and include cultivated area, but also primary forest. Secondary forests are not of relevance as forest-like areas are used as agroforestry systems and farmers rarely allow vegetation regrowth to reach a secondary forest stage in this context.

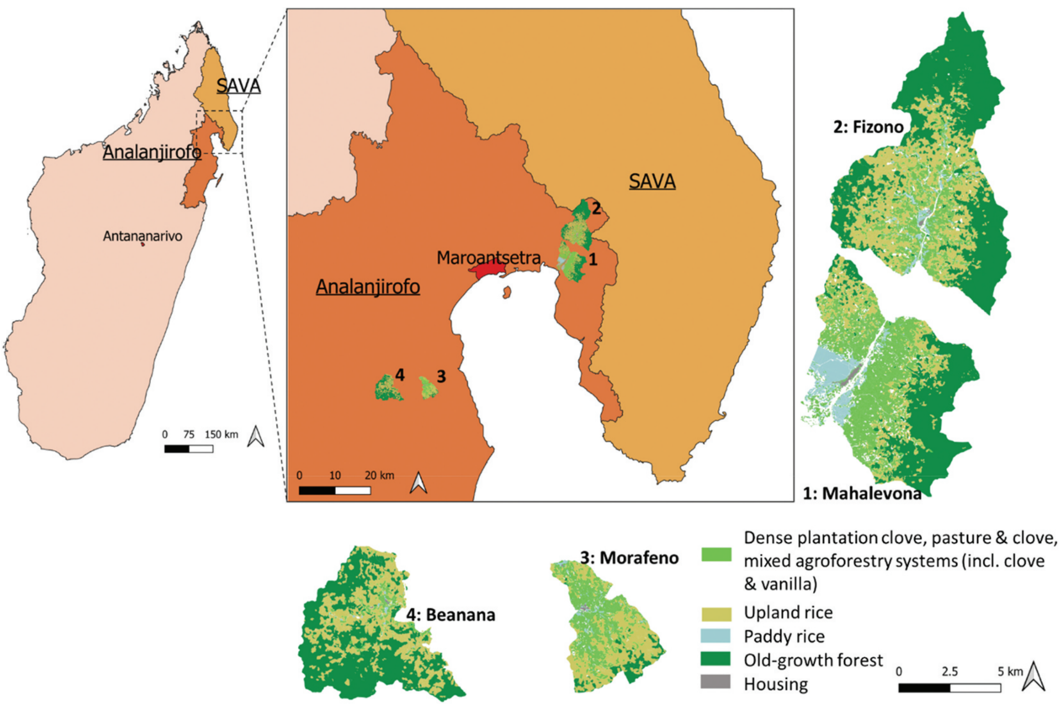

Figure 1. Case study villages in northeastern Madagascar with related land uses. Villages (Fokontany): Mahalevona, Fizono, Morafeno, Beanana. Land use in 2017 (referred as t0 in the model) based on Llopis et al. (2019). All land-use categories related to agroforestry systems merged into one category. Underlined names are regions of the Malagasy administrative system.

Madagascar's average farm covers 0.8 to 1.6 ha (Cadot et al., 2006; 1.6 ha; New Agriculturist, 2013; Rasoarahona et al., 2015) and feeds 4.6–7.5 household members[1] (Harvey et al., 2014; Institut National de la Statistique (INSTAT) [Madagascar] & ORC Macro, 2005; (United Nations, Department of Economic and Social Affairs, Population Division, 2017). Labor productivity is low as investments (e.g. in tools or infrastructure) are prohibitively high for small farms (Cadot et al., 2006). At the same time, there is increasing land scarcity due to the inheritance system, which leads to a sharing of land among the descendants (Burnod et al., 2016), resulting in chronical food insecurity for many farmers (Harvey et al., 2014).

Malagasy farmers report market price fluctuations for agricultural products as some of the most challenging problems (Harvey et al., 2014). Besides economic driving forces, climate change (Harvey et al., 2014) and cyclones (Rakotobe et al., 2016) are threatening livelihoods. The northeastern coast of Madagascar is a landing zone for cyclones, regularly destroying infrastructure and crops (e.g. Rakotobe et al., 2016). Expected climate change effects include higher temperature (1.1°-2.6°C) and less precipitation in the South of Madagascar and more rainfall during summer months (January to April) in the North (but uncertainty in the model outputs is high) (Tadross et al., 2008). In addition, the potential damage of irrigation systems induces water scarcity for cultivating paddy rice (USAID, 2016).

Commodity prices of consumer goods in the case study areas are relatively high due to low accessibility (see e.g. Minten & Ralison, 2005). This emphasizes the need for either income generation to increase spending power, or subsistence farming to reduce spendings. Farmers do not use chemical fertilizers (due to high prices) and rarely use dung or compost in paddy rice cultivation (cf. Dröge et al., 2022). Additionally, according to farmers, fertilizing is not needed because soil is (still) fertile. Additionally, farmers often report deterioration of irrigation systems due to cyclones or heavy rainfall. Their ability to buffer extreme weather events or changing market conditions is relatively low. Unlike other places, our study area does not feature large-scale land acquisitions (Andrianirina–Ratsialonana et al., 2011) or a monopolizing value chain-actor (like the example given in Balde et al., 2019).

Farmers reported, however, a decline in soil fertility (when discussing yield development on upland rice fields), negatively influencing subsistence yields, which need to be buffered by higher labor input and the need for financial income to buy food or employ additional labor force. While smallholder farmers in other regions or countries might not add much liquidity to their income through sales (FAO 2015), in northeastern Madagascar cloves and vanilla bring major cash flows (e.g. see price estimates for vanilla booms in Watteyn et al., 2022; Zhu, 2018). These crops are luxury goods solely produced for exportation.

2.1.1 Global and local value chains of clove, vanilla, and rice

In order to parametrize the influence of global markets on local land-use decisions in our BN, we assess Madagascar's local and global value chains of clove, vanilla, and rice. Worldwide clove and vanilla production originate from a few countries covering 90 and 95% of the global production, respectively (Appendix A, Appendix Figure A1). We observe the important role of Madagascar and Indonesia in the worldwide production, the increase of vanilla production in both countries over time, and of clove in Indonesia with important yearly fluctuations. Interestingly, the market dynamic (reflected in export quantities) differs between the two commodities (Figure 2). For clove, we observe a fluctuating world market that seems generally steered by Indonesia's production level. Comparing the years 2011 (low production in Indonesia) and 2014 (high production in Indonesia), we find a different market pattern. In 2011, Indonesia was absorbing the production of Madagascar (via the intermediary Singapore), while in2014Madagascar's production was exported to India. In the specific case of Madagascar, clove prices have been rising since 2004 and are fluctuating at relatively high level (20,000 MGA at farmgate (own observation) or 5–10 US$ at export (FAOSTAT Price index; tridge.com, accessed 12/23/2020).

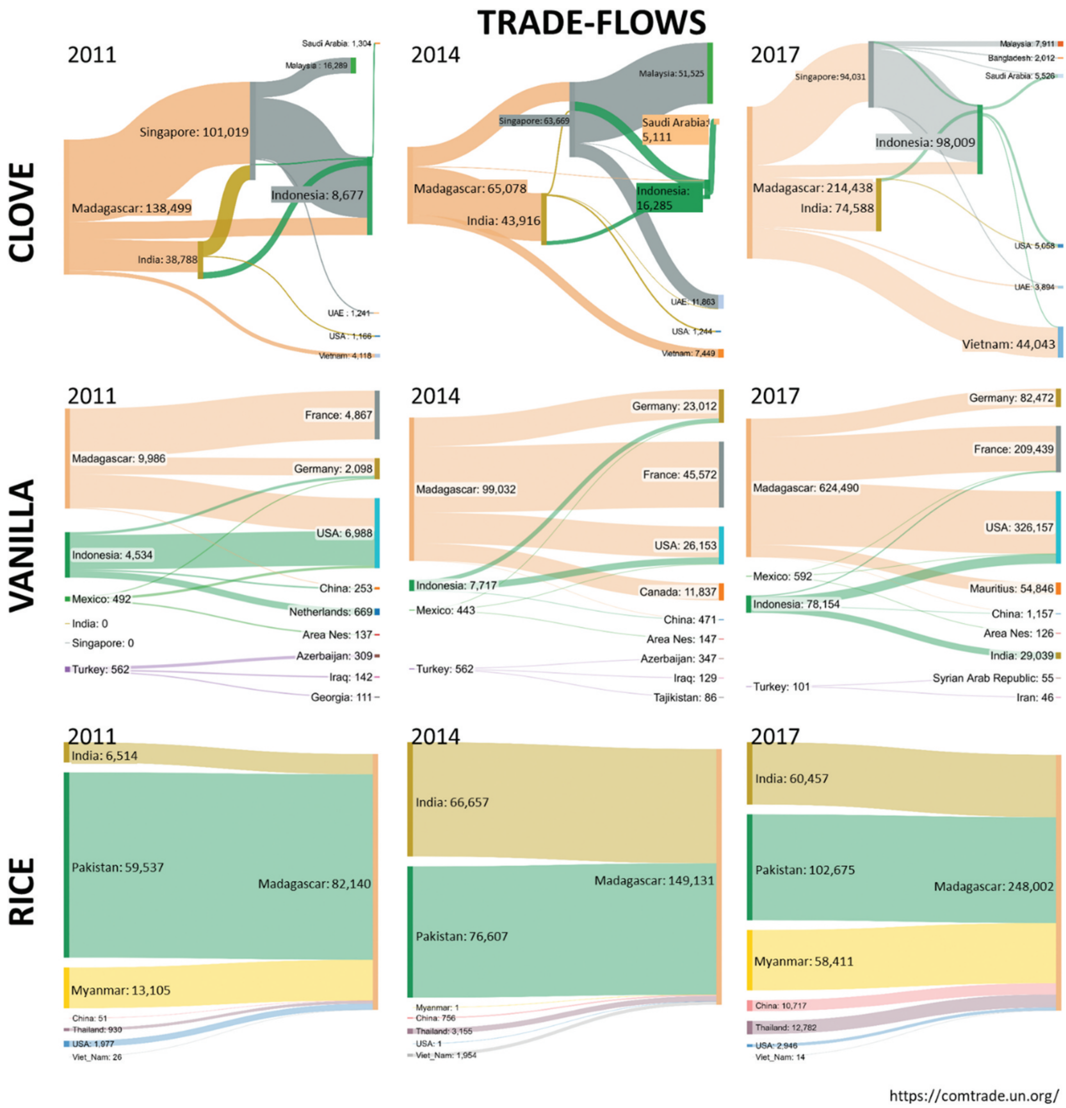

Figure 2. Clove, vanilla, and rice export value in 1000 US Dollars between major market participants in the clove market. Sankey diagram for 2011–2017 Attention: Source node's colour indicate origin of good and hence, flow direction. Source: Using FAOSTAT (Food and Agriculture Organization of the United Nations, 2021, for production quantities) and Trademap (International Trade Centre UNCTAD/WTO, 2021, for export and import values), we assembled time series for production quantities (1961–2018), export and import values for rice, vanilla, and clove (2011–2017). Including the biggest producing and exporting/importing countries worldwide. Results are presented as production quantity-time series and Sankey diagrams (using sankeymatic.Com).

A few European and North American countries are absorbing the production of vanilla. This pattern is similar over all observed years. Interestingly, there is a completely disconnected market consisting of Muslim-majority countries, i.e. the production of Turkey is exported to Iraq, Iran, Syria, and Azerbaijan. Vanilla prices reached a peak in 2003 (after droughts and a cyclone), and prices decreased afterwards, peaking again around 2018 (Hänke et al., 2019). However, in the course of writing this article, prices busted and the government of Madagascar even set a minimum export price of 250 US$/kg for prepared vanilla (Aust & Hachmann Canada Ltd, 2020; Mercier, 2021).

While cash crops such as vanilla and clove represent important sources of income, in rural northeastern Madagascar, livelihoods are heavily based on rice production (Zaehringer et al., 2016,

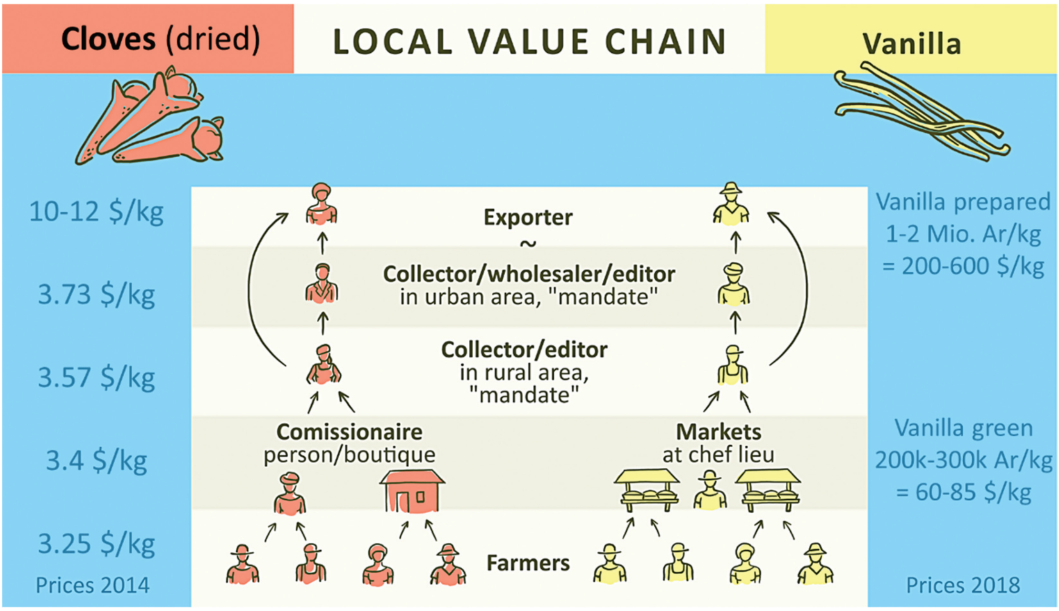

Figure 3. Local- to regional-level value chain structure for clove and vanilla. Remark: Different years for price development along the value chains. Source: own research.

2017). This production is mainly for subsistence use or sale on local markets. Appendix A shows the rice producing countries, including Madagascar, summing up to more than 80% of the world's production. In rice production, China and India are leaving other producers behind. Figure 2 shows that mainly Pakistan and India are exporting rice to Madagascar. Furthermore, the value imported by Madagascar is fluctuating strongly (82 Mio. to 248 Mio. US$). The peak was reached in 2017, when cyclone ENAWO hit Madagascar's east coast (Probst et al., 2017; Terazono, 2017).

These world market dynamics connect to local realities and impact local livelihoods via a value chain that is composed of usually 3 to 5 levels (Figure 3). Value chains of clove and vanilla are functioning differently: Vanilla market is centralized in a 'chef lieu' (main settlement) of a municipality, whereas clove sales are contracted at farmers' homes. While cloves are dried by farmers themselves and are sold dried, vanilla are sold green. Vanilla pods are typically prepared at a next level of the value chain. At this stage vanilla reduces its weight to about a fifth.

2.3 Land-use decision modelling

In order to assess future land-use changes, we applied a participatory BN-based land-use decision modelling approach (Celio et al., 2014). BNs are directed acyclic graphs (Pearl, 1988). The relationships are assumed to be causal and quantified by conditional probabilities (Jensen & Nielsen, 2007). These probabilities are specified for relationships between adjacent nodes in conditional probability tables (CPTs). In a BN (focusing two nodes), posterior probability is calculated as follows

$$P(x|e) = P(x) * P(e|x)/P(e) \quad (1)$$

where x is the probability of a parent node state and e is the evidence of a child node state. For solving a complete BN, marginalization helps to efficiently determine posterior probability. Bayesian rule is used in software that provide graphical user or application programming interfaces (Jensen & Nielsen, 2007; Kjaerulff and Madsen 2008; Norsys 2011). Using these software, entire network structures can be calculated. We used Norsys Netica (version 5.18, 64 bit) and the platform gBay (Stritih et al., 2020) to allow the BN interact with spatial data and to run multiple time steps.

BNs can be explored by changing the states of the nodes incorporated within the network. When the state of a node is known, it is said to be instantiated (hard evidence) (Jensen & Nielsen, 2007). Once a node has been instantiated, this will influence the probabilities associated with the states of other nodes to which it is linked, according to the values in the CPTs associated with specific nodes. CPTs are set-up using data representing empirical cases for the node states (parameter learning) or with the help of expert knowledge.

Being able to integrate both quantitative data and expert knowledge is one of the main advantages of BN (Marcot et al., 2006; Varis & Kuikka, 1997). In addition, the elicited relationships between the nodes help assess causal links between factors influencing decision-making. Furthermore, their probabilistic nature and their capacity to simulate various scenarios while continuously updating probabilities allow to investigate uncertainties. In particular, when they are linked to geodata, they allow to represent uncertainties in a spatially explicit manner (Stritih, 2021). Finally, their graphical and transparent structure allows to calibrate and validate the model in a participatory process, which is essential when quantitative data are limited (Celio et al., 2012).

In the following (Table 1 and below, steps 1–7), we describe the BN elaboration process comprising seven, partly iterative, steps conducted between 2015 and 2018 in the frame of four site visits

Table 1. Overview of empirical data collection: Date, purpose, method, participants, location. Villages of Mahalevona, Fizono, Morafeno, and Beanana were main study sites. Maroantsetra is the district capital and the place where the MSF took place.

Date	Purpose	Method	Number of participants	Location	Step
Aug. to mid-Sept. 2015.	Exploration & problem definition	Semi-structured interviews	13 farmers	Navana, Mahafidina, and Marofototra	1
April 2016	Identification of dominant land-use change and land-use change drivers	Structured discussions in workshop setting	MSF[1]	Maroantsetra	2
Mid-Apr. to the end of Apr. 2016	Identification of household characteristics, plot characteristics, sources of revenue, perception of well-being, and land-use change	Semi-structured interviews	14 farmers	Mahalevona, Fizono, Morafeno, Beanana	2
Mid-Apr. to the end of Apr. 2016	Collect rationales for land-use change	Transect walks	Farmers cultivating land in the case study villages	Mahalevona, Fizono, Morafeno, Beanana	2
April 2016	Ranking of land-use change drivers and establish an impact matrix	Exercises in a workshop setting	16 participants	Maroantsetra	2
Nov. to mid-Dec. 2016	Validation of cause-effect relations	Exercises in a workshop setting	MSF[1] Group of representatives in each case study village	Maroantsetra Mahalevona Fizono Morafeno Beanana	3
	Info for parameterization	Questionnaire	71 households, 173 parcel characteristics	Mahalevona, Fizono, Morafeno, Beanana	4
	Info for parameterization: “if-then exercise”	Exercises in a workshop setting	11: MSF[1]	Maroantsetra	4
Feb. 2018	Validation of model and outputs	Exercises in a workshop setting	14, 11, 10, 19	Mahalevona, Fizono, Morafeno, Beanana	5

Note: [1] *Multi-stakeholder Forum which is a constant group of 10–20 persons.*

(methodologically similar to Celio et al., 2012; Chen & Polino, 2012). The process was embedded in a six-year research project elaborating system knowledge for sustainable transformations in forest frontiers. The project established a multi-stakeholder forum (MSF) at the regional level encompassing both of our study sites and being approximately congruent with the administrative borders of the district of Maroantsetra. The MSF included farmers (farmer organizations), government representatives (agricultural service, district administration), conservation groups (Madagascar National Parks, Wildlife Conservation Society), and a regional development organization (coordinating platform for the sustainable development of the Antongil Bay). The forum meets on a regular basis.

Step 1: Exploration and problem definition

An explorative field visit took place from end of August to mid-September 2015. We conducted 13 interviews with farmers in the surroundings of our northern study site. The interviews in the villages Navana, Mahafidina, and Marofototra (nearby our study villages) allowed us to frame the farmers' challenges regarding their land-use challenges (e.g. rice, clove, vanilla production; land availability; price fluctuations).

Step 2: Setting-up Bayesian network structure (including nodes and states)

Stakeholders of the MSF gathered on 14 April 2016 and worked on two tasks: (a) Identification of the dominant land-use changes and their consequences for local communities, the national economy, and environment, and (b) the elaboration of drivers of these land-use changes and structuring in a cause-effect diagram. In a second meeting on 27 April 2016, participants (c) ranked drivers collected at the local level according to their importance for accelerating land-use change, discussed ranking differences and summed rank numbers as well as (d) related the connections between the drivers in an impact matrix.

We conducted a total of 14 interviews with farmers in the study villages from mid-April to the end of April 2016, covering the following topics: household characteristics, plot characteristics (incl. land tenure situation), sources of revenue, perception of well-being, and land-use change. In addition, we conducted four transect walks accompanied by local farmers, who explained land-use changes and the reasons and rationales for the changes on-site (see e.g. de Zeeuw & Wilbers, 2004).

Step 3: Validate cause-effect structure and define states

To validate the elaborated cause-effect structure, we organized the collected information in causal chains (Meyfroidt, 2016) and presented the most relevant chains one-by-one to both stakeholders of the platform and local farmers from November to mid-December 2016. We conducted one regional-level workshop and one workshop in each village. We also used the workshop discussions to define the nodes and states of the nodes used in the BN. All nodes are listed and defined in Appendix C.

Step 4: Basic parameterization of the Bayesian Network

Data collection for parameterization included a questionnaire with local farmers and an exercise that triggered imagination of decision situations. The questionnaire collected attributes of 71 households, including information about rice self-sufficiency, household characteristics, and strategic ideas for future development. In addition, we collected characteristics of the plots (=parcels), such as past, current and projected future land use, slope, and water availability (see questionnaire in Appendix F, $N = 173$). Each question used the BN node states as categories for response in order to be able to create 'case files' for parameter learning.

In an 'if-then' exercise, we defined crucial parts of the conditional probability tables by discussing 'if-then' situations with eleven members of the regional MSF. The exercise targeted one node at a time and was repeated three to five times changing settings of states (e.g. from 'high' to 'medium' to 'low', given a node with these states).

Step 5: Subjective validation of the Bayesian Network and re-calibration

As there was no past land-use data available satisfying needed precision to delineate our land-use categories, we opted for a subjective validation procedure (Celio et al., 2012). We conducted a workshop with farmers in each village in February 2018 to validate the location of land-use change (allocation), the number of parcels and the maximum amount of changing parcels, respectively (quantity), as well as the timing of the change (dynamics) (inspired by Pontius & Millones, 2011).

To carry out the subjective validation procedure, we conducted workshops in each village with 10 to 19 farmers (Fizono: 11, Mahalevona: 14, Beanana: 19, Morafeno: 10) to discuss uncertainties in the BN structure and open questions (see participants in Appendix F). We deepened our understanding regarding the effect of market prices fluctuations in the cash crop sector, the perception of tradition and identity, land tenure, and the perception of advantages and drawbacks of mixed agroforestry system versus dense clove plantations. In addition, we mapped zones of lacking water in a participatory manner. At the regional level, a similar 'dynamics' exercise was conducted. Participants of the MSF were split into groups of three to four people, pooling their expertise either in the northern or southern case study site and supported by a multiple-choice questionnaire (one per group; see Appendix F).

The outputs of the workshops allowed us to determine if our proposed land-use change trajectories were plausible. In case of diverging statements in workshops, we used several iterations to consolidate what most probable rationales are. By conducting a content analysis of the workshop transcripts (see Appendix F for transcripts), we then derived rules on how to modify the BN. Appendix B provides a detailed compilation of deduced rules and their effect on the further development of the BN parameterization.

Step 6: Final parameterization of the Bayesian network

We parameterized the BN in the following sequence:

- In a first step, all nodes including equations were turned to conditional probability tables ('clove income', 'need of money', 'rice production', 'value rice production', 'clove production', 'income clove production', 'vanilla production', 'yearly income other cash crops', 'other income', 'income', 'expenses', 'income statement', 'cash crop ratio', 'expense ratio').
- Secondly, the household questionnaire described in step 4 was used to populate the conditional probability tables of the nodes 'other yearly income', 'yearly income from other cash crops (such as coffee or vanilla)', 'clove price at farm gate', 'farmer's intention to change land use', 'rice self-sufficiency', 'revenue of rice per household', 'persons per household', 'water availability (precipitation and irrigation)', 'living costs', 'clove stands per household', and 'yield per clove stand'.
- Thirdly, the plot level information was used to populate the conditional probability tables of the following nodes: 'land use in t0', 'land use in t1', 'farmer's intention to change land use', 'slope', 'disturbance events', and 'protected area'.
- Global-local clove market relationship was implemented using trade data. See appendix B for further details.
- Finally, we applied the rules and adjustments described in Appendix B. All nodes are described in more details in Appendix C.

Table 2. Scenario specifications. 'Current water availability' is based on participatory mapping (spatially-explicit input); 'enough water for irrigation' refers to lack of water everywhere in the villages; 'lack of water for irrigation' refers to lack of water everywhere in the villages. Indications for prices and production are deduced from own observations and analysis of timeline data. Variations in time step t3 were built on a best-case development in t1 and t2. Each timestep represents a period of 5–7 years.

Time steps	Scenario	Water (irrigation)	Global clove price [US$/kg]	Green vanilla price [US$/kg]	Clove production [kg/household]	Vanilla production [kg/household]
t1, t2	Business-as-usual (BAU)	Current water availability	12.5	60.5	47.5	25
	Best-case	Enough water for irrigation	17.5	67.5	47.5	25
	Worst-case	Lack of water for irrigation	7.5	46.5	47.5	25
t3	(1) Price High	Enough water for irrigation	17.5	67.5	47.5	25
	(2) Price shock	Enough water for irrigation	7.5	46.5	47.5	25
	(3) No Clove	Enough water for irrigation	17.5	67.5	0	25
	(4) No Vanilla	Enough water for irrigation	17.5	67.5	47.5	0

Note: (1) best-case with continuing high prices, (2) price shock in clove and vanilla production, (3) No Clove = crop failure in clove cultivation, and (4) No Vanilla = crop failure in vanilla cultivation. Water is kept constant.

Step 7: Modelling of land-use change and village-level income under various scenarios

To discover alternative futures, we defined three scenarios for time step t1 (5–7 years from t0) and t2 (10–14 years from t0), tackling the influence of changes in irrigation water availability and potential harvest failures as well as cash crop prices on land-use change and farmer income. These variations and the duration of the time steps were motivated by discussions brought up by participants of our workshops. Durations of time steps reflect the time to mature for a clove seedling or a vanilla propagule. As no internal interaction mechanisms are present in the model, we refrained from calculating variations of variables over time (e.g. fluctuating prices). In addition, for time step 3 (15–21 years from t0), we defined variations of future prices and harvest quantity change given a best-case scenario in t1 and t2. We did not separate price signals of clove and vanilla as the ″no clove″ (clove price = 0) and 'no vanilla' (vanilla price = 0) scenarios are representing the extreme cases of all possible outcomes. Table 2 presents the parameters defining the scenarios, which were used to run the BN model (including price signal, production quantity, and irrigation water availability). Scenario names reflect farmers' perspective of good and bad situations for their farming.

The final BN structure presented in Appendix B (Figure A2, Figure A3) was used in gBay (Stritih et al., 2020) to connect the BN to geodata. We ran the model under the scenarios described in Table 2. The spatial resolution of the model raster output was 50 m × 50 m and sources of the input data are found in Appendix C.

To evaluate land-use scenario outputs, we calculated an income indicator within the BN by attaching an income indicator part (Appendix Figure 3) to the land-use BN (Appendix Figure 2). A similar idea of an income indicator was implemented by Hartje et al. (2018) using non-spatially-explicit big sample approach employing regression analysis. The income indicator representing the village income level was calculated subtracting operating expenses (e.g. living costs) from the gross revenue (value of rice production, income of clove production, income from other cash crops such as vanilla, other income from off-farm work) (cf. Food Canada and Statistics Canada, 2000) for each household and projected onto the area assumed to be managed by the household. In other words, the starting point is a $-value per raster cell. Using this raster file, we obtained the median of the probability distribution for each pixel. Next, we calculated the average of these medians within a village boundary. This average of medians is associated with an average evenness index per village and scenario. Thus, each grid cell represents the value of the income indicator for this spatial extent.

In the BN, the indicator was represented by a continuous node that was discretized. The indicator income statement was discretized in three positive and three negative states (expected income at disposal calculated over one year).

The BN was instantiated for two different land-use situations, knowing the land use at each pixel (certain situation), and using a land-use probability distribution at each pixel (uncertain situation). The BN was run under a best-case scenario until t2 (10 to 14 years from present), and subsequently, different potential future events were simulated: (1) best-case with continuing high prices, (2) price shock, (3) crop failure in clove cultivation, and (4) crop failure in vanilla cultivation. We used the BN once in an uncertainty perspective (blue circles, Figure 5), running the model from t0 to t3. Uncertainty is propagated in each time step to the next and hence, resulting probability distributions tend towards uniform distributions. In contrast in the 'no uncertainty' perspective (green circles, Figure 5), the BN was instantiated with the most probable land-use category for t2 (hard evidence, providing a certain land-use category assuming we know which land-use category is found in the future at a certain location). In other words, instead of using the complete probability distribution, we determined the land-use category with the highest probability and used this category only to continue the modelling.

We measured the level of uncertainty using the indicator 'evenness index' (EI). EI measures entropy in the posterior probability distribution. '0' depicts complete certainty and '1' denotes a uniform distribution (hence, maximum uncertainty) (Stritih et al., 2019, 2020).

We did not include capital gains or losses nor deprecation. Currency exchange rates were assumed to be constant in the next 10 years (assumed exchange rate of 1$ = 3400 Malagasy Ariary, given in 2017).

3. Results

3.1 Influence of market prices as well as changes in irrigation water availability and potential harvest failures on land-use change

Under all investigated scenarios (Figure 4), we observe a change towards mixed agroforestry. The global trade and local-regional trade dynamics presented in Appendix A, Figures 2, and 3 are reflected in the land-use dynamics. Even in the business-as-usual scenario, we observe a pronounced land-use change as this reflects the experiences of the past years. The land use change is particularly evident under high market prices for clove and vanilla and good irrigation water availability. Under low irrigation water availability and low market prices, we see more equally distributed land uses around all villages (worst case scenario in Figure 4). We also observe some village-specific characteristics. In comparison to Morafeno, agroforestry extension is constrained around Mahalevona due to the land-use restrictions of the park, but the site keeps paddy fields under all scenarios, due to the suitability of the area for paddy rice production. Interestingly, we observe a higher percentage of paddy rice cultivation even in the worst-case scenario in which we assume a lack of irrigation water and low prices. The model reflects the strong influence of the cash crop price signals, and, in the scenarios with low prices, the pressure to produce rice is high. In addition, in Mahalevona, upland rice cultivation is marginal, which would be a typical preceding land use type of agroforestry systems (observed in Morafeno).

3.2 Vulnerability of income to prices as well as changes in irrigation water availability and potential harvest failures

In order to assess changes in income due to market price fluctuations and changes in irrigation water availability and potential harvest failures, we instantiated the BN for two different starting land-use situations: an uncertain land use (BN outcome as probability distribution),

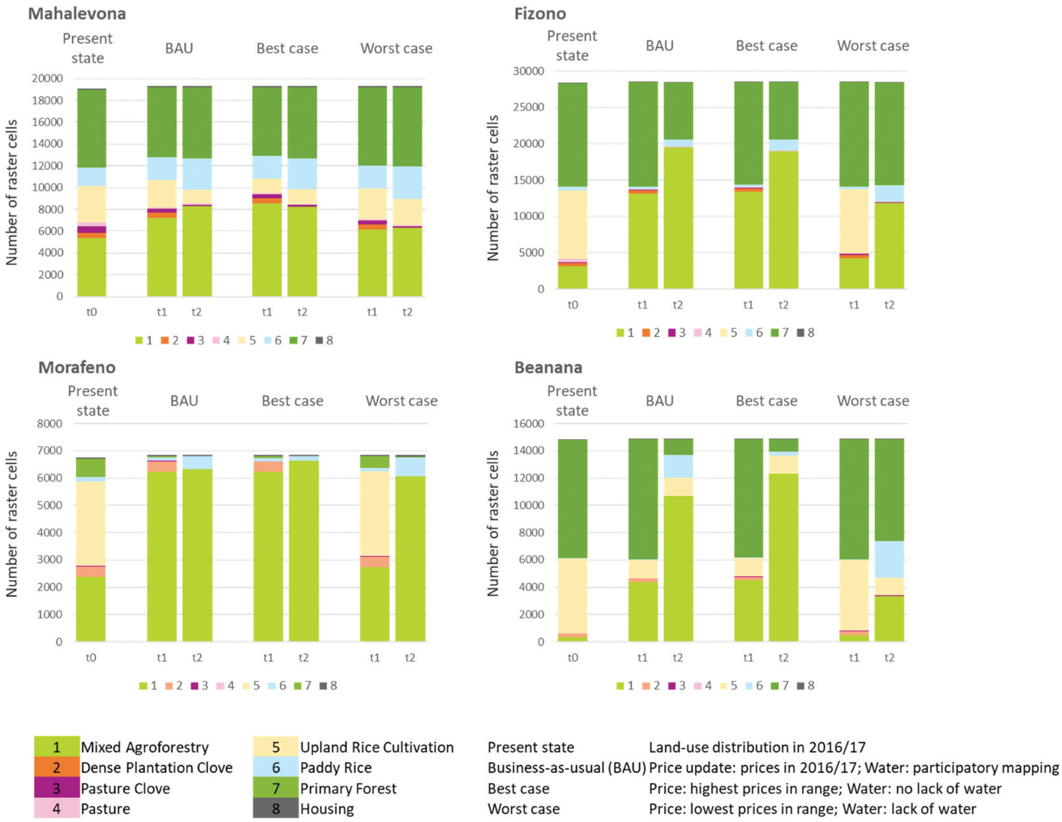

Figure 4. Land-use change pathways starting in t0 (2017) to t1 (2022–2024) and t2 (2027–2031). We vary price signals and irrigation water availability. Source: Bayesian network model outputs, elaborated using gBay.

and a certain land-use (no uncertainty; BN outcome as expected value or in other BN-terms, providing hard evidence). Figure 5 shows the vulnerability of income under four scenarios in t3: (1) best-case continues, (2) price shock, (3) crop failure in clove cultivation, and (4) crop failure in vanilla cultivation.

Under an uncertain land-use change situation, the income level at disposal is expected to become negative under all scenarios, highlighting the influence of uncertainty in future land-use change This does not mean no incomes are earned in the respective villages, but that there are large uncertainties in the system (Figure 5) For the price shock scenario, both perspectives (uncertainty and certainty) are similar and indicate a robust system regarding future uncertainty. In contrast, we observe for a no uncertainty perspective that income level could strongly increase when prices are high, independently of the clove production. Particularly, there is a high potential of large mixed agroforestry extension around the village of Morafeno and hence, a high potential for revenue creation. In addition, we observe that as soon as the vanilla production system is confronted with price shifts or harvest failures, income is reduced substantially. More concretely, under low market prices and in particular under vanilla crop failure, we observe negative income at disposal in all case study areas, albeit the uncertain land-use change situation. This highlights the importance of vanilla production today and shows that income related to clove production can only slightly buffer income losses. Assuming decent prices and productivity of vanilla, its cultivation substantially supports a better income.

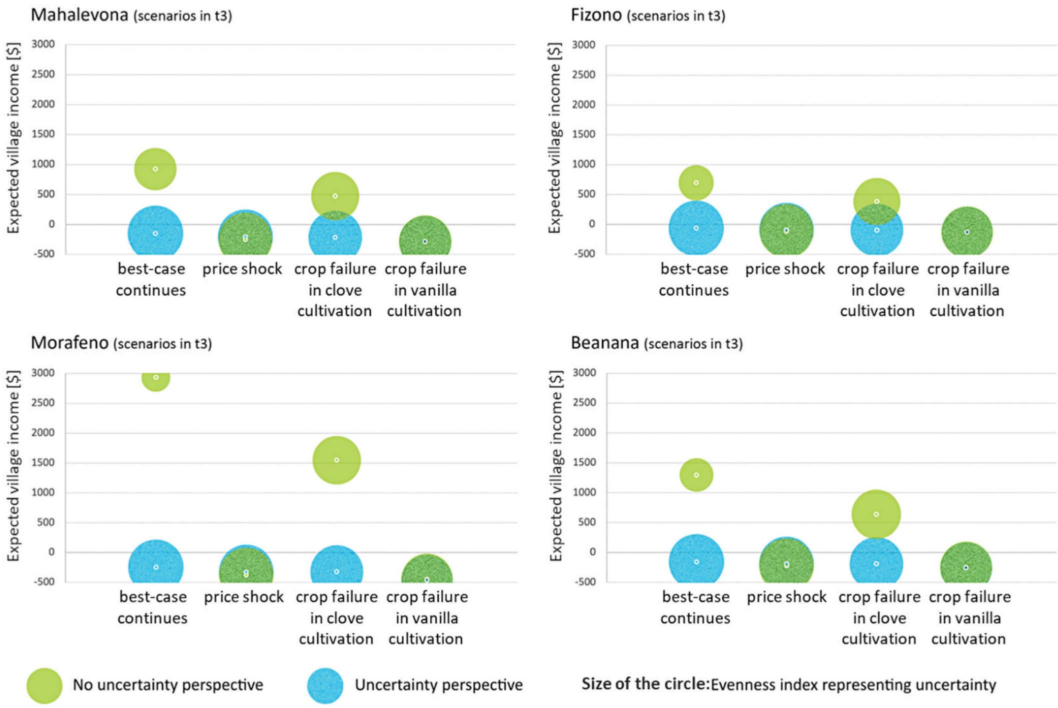

Figure 5. Expected income at disposal (median and evenness index) averaged across all villagers and normalized by agroforestry area under an uncertain (blue circles) and a certain land-use change situation (green circles). The size of the circle represents the evenness index, a measure of uncertainty (larger circles means higher uncertainty). The evenness index-values are varying between 0.88 (Fizono, best case continues, uncertainty perspective) and 0.23 (Morafeno, best case continues, certainty perspective). If circles are congruent, color tones are different.

3.3 Interaction of cash crop expansion with local rice production

We estimated the mean aggregated monetary gain/loss from additional/reduced clove, vanilla, and rice production per inhabitant comparing t0 with t2. The financial revenue consisted of the additional expected income at disposal from clove and vanilla, and was reduced by the amount equivalent to the cost of rice purchase due to converted rice plots.

For the four villages, overall rice production will be reduced in the next 10 to 14 years giving space for the expansion of other land uses (Figure 4). Especially upland rice cultivation is expected to diminish, while paddy will slightly increase. The increase of agroforestry will happen at the cost of forest and upland rice cultivation (in t1 less upland rice, in t2 less forest). The model suggested a reduction of upland rice cultivation by around 45.6 km^2 (representing 24% of the total area), and an increase of paddy rice by around 3.9 km^2 from t0 to t2 (next 10–14 years) (Appendix E, Table A2). In total, around 3’000 tonnes of rice (upland rice and paddy rice) per year are needed to keep today’s rice availability. If imported to the villages, this would amount to nearly 895,000 US$ in total per year (1000 Ar/kg rice; 3500Ar/US$) (Appendix E).

Comparing the reduced rice production to the revenue potential of cloves and vanilla, the per person revenue gain amounts to values between 209 US$ per person/year (Mahalevona) and 12’700 US$ (Beanana) (Table 3) (Appendix E, Tables A2 and A3). The case study areas around Mahalevona and Beanana represent, however, extreme cases and it is assumed that population remains constant. Mahalevona accommodates a very high population and limited potential to extend agroforestry area, while Beanana has a low population, but a high potential to extend agroforestry. A more balanced view is offered by the villages of Fizono and Morafeno with an income gain of 3188 and 1587 US$ per person/year, respectively. Compared to average living costs for a decent life of

Table 3. Expected income at disposal change related to increase of clove and vanilla production in mixed agroforestry systems at the cost of local rice cultivation (both, upland and paddy rice). All estimates based on the area change. 7 US$/kg for dried clove, 55 US$/kg for green vanilla, and 0.29 US$/kg rice (1000 Ariary/kg). Source 'number of inhabitants': Service de la population, District of Maroantsetra (most recent available data).

	Net income (clove vs. loss rice)	Net income (gains clove & vanilla vs. loss rice)	Number of inhabitants	Net income (clove vs. rice) per person	Net income (clove & vanilla vs. rice) per person
Village	[US$] (rounded)	[US$] (rounded)	[persons]	[US$/Pers]	[US$/Pers]
Mahalevona	252000	2051000	12559 (2020)	26	209
Fizono	1145000	12278000	4856 (2020)	297	3188
Morafeno	227000	2998000	1889 (2015)	120	1587
Beanana	992000	9157000	721 (2015)	1376	12700

approximately 5750 Euros/year[2] (about 6405 US$ in mid-2019) (Veldhuyzen, 2019), vanilla and clove production provide an important contribution.

Looking at the scenario that includes only gains from clove production, we investigated until which level clove prices may fall so that people still have a positive expected income at disposal. We observed that at a level of 3 US$/kg of clove, financial outcomes. More details regarding calculations may be found in Appendix E.

4. Discussion

Using a participatory land-use modelling approach, we assessed farmers' vulnerability to cash crop export economies in a case study in northeastern Madagascar. We observed a trend towards agroforestry in most of the considered scenarios, and could attribute a key role to vanilla production for farmers' livelihood situation. Comparing income gains from cash crop production with costs for buying rice to cover basic needs shows that farmers are better off when focusing on cash crop production if prices of cash crops are stable or increase. However, such a strategy was found to be highly risky if vanilla harvest fails (e.g. by destructions from cyclones or the occurrence of a plant disease), vanilla prices crash, or vanilla theft occurs. Hence, abandoning vanilla cultivation seems impossible once income from vanilla crosses a certain threshold. In other words, villages in our study sites find themselves locked-in in a vanilla trap.

4.1 Global markets and local land-use decisions

The modelled trend towards agroforestry (converting from upland rice) fits the changes observed in the years 1990–2017 (Llopis et al., 2019), thus well representing the current decision-making of local farmers. On the one hand, given that vanilla and clove need approximately 3–4 and 8–10 years (Chambers et al., 2019; Danthu et al., 2014; farmers reported rather 5–7 years for clove maturity), respectively, to mature and produce yield, short-term price fluctuations should be of lower importance to decision-makers. Farmers want to secure income for their children, and hence, planting a clove tree is an investment that may be inherited someday. In addition, upland rice cultivation seems to be more labor intensive than the cultivation of an agroforestry area (financial return on investment) (cf. Martin et al., 2022). To increase the share of land for commodity production is thus favorable in this respect. In addition, it is known that agroforestry generates less provisioning ecosystem services in vanilla agroforestry compared to fallow land while regulating ecosystem services, particularly carbon storage, increases with establishment of agroforestry systems (Martin et al., 2022; Soazafy et al., 2021). On the other hand, global vanilla price, which was high during many years, increased the interest of farmers to plant vanilla, leading to a new phenomenon in our case study region of monoculture-like vanilla plantations cultivated on former fallow plots (without shade trees).

However, farmers' high dependency on vanilla income requires a stable vanilla market (Andriamparany et al., 2021). The export diagrams (Figure 2) show a relatively stable export-import system (compared to the clove value chain) over the last decade, which might be a sign of a well-integrated market (Moser et al., 2009). However, the current price development in the Madagascar vanilla market has strongly changed. From an original price of about 300'000 Ar/kg (about 85 US$/kg, exchange rate in November 2018) green vanilla in 2018, price went down to approximately 35'000 Ar/kg (about 9 US$/kg, exchange rate in November 2021) green vanilla in 2021. Hence, expected incomes at disposal are diminishing, which drives farmers into poverty.

4.2 Market prices as well as changes in irrigation water availability and potential harvest failures

Compared to existing work on livelihood indicators (e.g. Knippenberg et al., 2019; Quandt, 2018), our study focused on the temporal development of farmers' income under various uncertain future changes. We are aware that expected income at disposal is only a fraction of what defines livelihood. Other factors to be considered would include e.g. nutrition, social life and traditions (Andriamparany et al., 2021; Osterhoudt, 2016). In addition, we based our analysis in t3 on a single, fairly positive development from t1 to t2. The goal was to investigate a 'safe' development with a following shock. The BN would allow to investigate further scenarios, assessing legacy effects and adaptation strategies, including the development of a shared understanding of the challenge, the definition of key decision points (Wise et al., 2014) and no regrets or co-benefit strategies (Butler et al., 2014).

While our results suggest that an increase in vanilla and clove production could lead to an economically favorable situation, the study focused on four villages without investigating neighborhood effects. Collaboration across villages could decrease the vulnerability to cash crop market fluctuations of single villages. Such collaboration would, however, have to come along with a learning and trust building process as well as with the creation of appropriate institutions (Sayer et al., 2013; Scoones, 1998).

Examining the differences between the certainty and uncertainty scenarios in t3, we observe the importance of vanilla in the modeled system. When adapting parts of the system that are independent of vanilla cultivation, differences may occur.

Only when adapting parts of the system that are independent of vanilla cultivation, differences between the certainty- and uncertainty-perspective may occur. Vanilla-dependent negative scenarios always lead to vanishing differences between the certainty and uncertainty perspective as vanilla carries huge shares of the income at disposal. When thinking of negative scenarios related to clove, in the uncertainty perspective also vanilla-related income at disposal is uncertain and adds to a negative outcome for income at disposal. Remarkably, even if clove cultivation fails, the system is able to compensate due to the presence of a functioning vanilla cultivation (see crop failure in clove cultivation in certainty-perspective, Figure 5).

At the individual household level, the ability to access and to control land resources is key and also provides a way to buffer vulnerability to global market prices (Quandt, 2018). A household with a lot of potential to expand its cash crop production has been shown to be less vulnerable due to the availability of reserves (Scoones, 1998). The high availability of labor force is known to lead to an increased capability to cope with risk (Ingxay et al., 2015). Additionally, from a labor force perspective, vanilla harvest in June fits well with the cultivation cycle of upland and paddy rice (in between the seasons, see Appendix D,Table A1, for a yearly cultivation cycle). Hence, a similar synergy like in the cases in Ghana (Yaro et al., 2017) and Senegal (Van Hoyweghen et al., 2018) could be established.

The advantages of vanilla cultivation will, however, put pressure on primary forests, as expansion of cash crop has been shown to take place also on forested plots, potentially, with an intermediate step of upland rice cultivation (Llopis et al., 2019). At the same time, Martin et al. (2021) shows for the neighboring SAVA region that 70% of vanilla agroforestry systems are derived from open-land (fallow) and only 30% from forests. Promoting clove and vanilla aiming at reducing deforestation has to be carefully reflected. Such incentives may increase attractivity of those cash crops and cash crops could be newly cultivated on a fallow previously used for upland rice. This could also lead to the displacement of upland rice cultivation onto new primary forest areas (Meyfroidt et al., 2013). In contrast, Moser (2008) shows reducing effects on deforestation by vanilla cultivation which is potentially also related to progression and/or intensification of vanilla cultivation Buffering negative effects on primary forests are possible if incentives to convert primary forests are balanced with incentives to value the same forests (e.g. by monetary incentives, intergenerational justice, mitigation of climate change effects).

4.3 Diversification to shape future pathways

Interestingly, the estimated gain from producing cash crops (considering lower rice production as well) (Table 3) lies in a similar range than the net present value of the opportunity costs of conservation restrictions (2,375 US$) (Poudyal et al., 2018). Poudyal et al. (2018) estimated that this net present value reflects '27% to 84% of the median total annual household income'.

Given farmers develop towards more market-oriented production (and less subsistence production), rice market dynamics become key and farmers need to be concerned about a diversified production (see also Andriamparany et al., 2021). Even if higher yields can be expected in paddy rice cultivation, this comes at the cost of higher needs for collaboration. We observed an increase of Madagascar rice imports from 2016 to 2017 by a factor of 2.7 (year of cyclone Enawo) (United Nations, 2022). This may lead to a situation of over-demand on the international market, rising prices (FEWS NET, 2018) and eventually to liquidity problems at the level of the households. In addition, prices in remote areas are higher than in the capital due to transport costs (Minten & Dorosh, 2006).

A follow-up study would need to shed light into the individual household situation under the different future scenarios and to figure out if strategies of diversification (of crops, over time and space, insurance) would help villagers become more resilient against price fluctuations (Scoones, 1998) and if there is potential to establish financial reserves. In addition, pursuing a short-term coping vs. long-term adaptation strategy to, e.g. fluctuating price signals frames the portfolio of reactions in a risk-prone situation (Toillier et al., 2011) and farmers would rather use coping as their capacity to invest is low. However, a more pro-active adaptation strategy would need a strategic future vision that is difficult to create in an environment that is politically and economically fast changing and driven by external forces. For instance, the need to guard the vanilla plantations due to the fear of thefts (Neimark, Osterhoudt, Blum, et al., 2019) or potential competitors in vanilla production from Indonesia, the Comoros, Uganda, or the Netherlands have to be taken into account (Hänke et al., 2019). However, the ability to act collectively has not been trained in the community, and the adaptability of the communities would have to be reviewed critically (May, 2019).

The parameterization of the BN was challenging as complex, sometimes heuristic decision-situations of farmers had to be structured and quantified. We used a mixed-method approach and relied on context knowledge for some parts. However, using the concept of causalities with a participatory BN is advantageous to discuss issues of decision-making and landscape development. While we modelled human agency using a decision-making model, the results show that, independently of farmers' decision-making, an overarching trend towards agroforestry exists. An institutional and political perspective would thus be helpful to better understand how to embed the individual decision-making into a more general transformation process to steer towards sustainable development. A connection between those who are able to incentivize via price signals and those who are receiving the signal has to become more balanced (cf. Neimark, Osterhoudt, Alter, et al., 2019).

Allocating all externalities to the consumers would increase producers' negotiation power and give them capacity to organize themselves (cf. Rapsomanikis, 2015 on cooperatives). This would not necessarily call for a strong state, but a regional coordination and self-empowerment. Such a system would be more suitable in countries with weak governments and may lead to qualitative (economic activity aligned with social and ecological growth) instead of quantitative growth. While we share the concerns that global forces need to be countered by a strong state, we advocate for a more nuanced perspective aiming at relatively short-term gains for farmers and common understandings. In this perspective, the government would need to secure value chains by providing transparent policy and market conditions. In addition, the income possibility of middlemen in trade chains is potentially relevant for the well-being of the local population. Governments should, of course, not prohibit or incentivize middlemen in value chains, as both may have adverse effects. However, incentivizing the creation of cooperatives provides a possibility to share revenues more equally and keep a locally based organization in place. In addition, potential insecurity due to thefts (Neimark, Osterhoudt, Blum, et al., 2019) could be reduced. Still, cooperatives are no panacea. To participate in international markets, continuity of supply and quality, food safety or quality requirements need to be fulfilled (Rapsomanikis, 2015).

Finally, to reduce vulnerability, an insurance system independent of the central government or insurance companies might be a way forward to reduce the above-described risks to livelihood (e.g. Giz, 2016; Raithatha & Priebe, 2020). A reinforced local banking system providing the possibility to save money on a small-scale, regular basis, would be an individual solution. Coupling such a saving system to the possibility to get credits for investments or harvest failures would complement an environment that supposedly leads to more stability for local actors.

5. Conclusions

To conclude, the modelled land-use scenarios showed a promising but risky pathway in the future when focusing on cash crop production. In addition, we highlighted the need to consider uncertainty when assessing future scenarios.

In our mixed-method approach, two aspects need to be considered. First, the scenarios are based on a participatory process and show trends for future land-use and are representing mental models of participating actors and stakeholders. Second, our rough estimation of a potential interaction of cash crop production with local rice production is an attempt to link model outputs with on-the-ground realities. Both, land-use scenarios and our estimate for the cash crop-rice interaction should facilitate the deliberation process to shape sustainable transformations.

The hypothesized 'vanilla lock-in' should be further researched to find ways how to balance subsistence and cash crop production. In addition, further research should be conducted to compare trajectories further north and south along the east coast to confirm the findings of this case study research.

Notes

1. Average farm size: 1.6 ha (Cadot et al., 2006), 1.3 ha (New Agriculturist, 2013), 0.8 ha in agricultural census 2004/2005,, 70% of the agriculture households below 1.5 ha (Rasoarahona et al., 2015).

   Average household size: 7.5 members (Harvey et al., 2014), 4.6 members (Institut National de la Statistique (INSTAT) [Madagascar] & ORC Macro, 2005), 4.7 members (United Nations, Department of Economic and Social Affairs, Population Division, 2017)
2. 'The cost of decent living for an average household is € 5750 per year (or € 3.75 per person per day), of which € 2,597 (45%) represent food costs.' (Fairtrade Living Income Reference Prices for Vanilla, Carla Veldhuyzen, November 2019).

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ORCID

Enrico Celio http://orcid.org/0000-0003-1316-1850
Adrienne Gret-Regamey http://orcid.org/0000-0001-8156-9503

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APPENDIX A

PRODUCTION

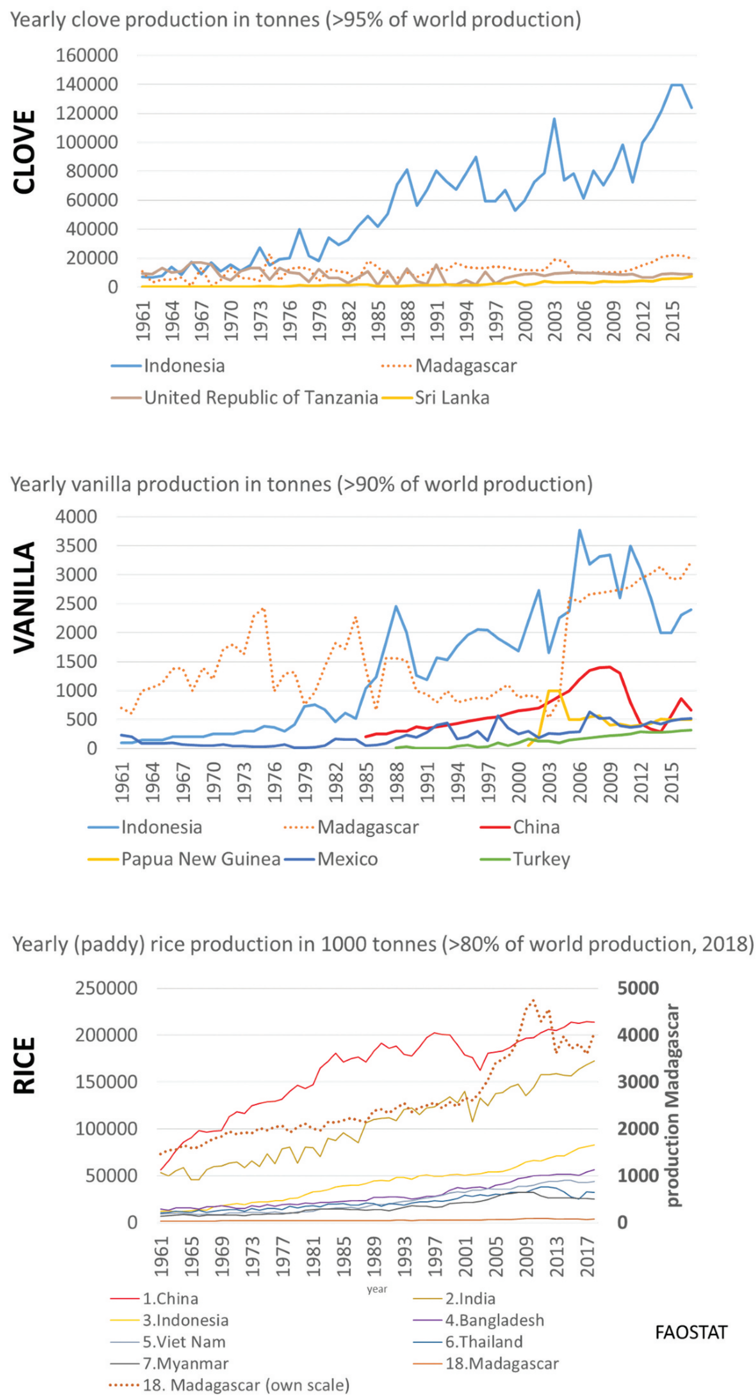

Figure A1. Production of clove, vanilla, and rice (in tonnes) of the major producing countries. Source: Food and Agriculture Organization of the United Nations (2021).

APPENDIX B

Indicators, and technical implementation of Bayesian network (BN)

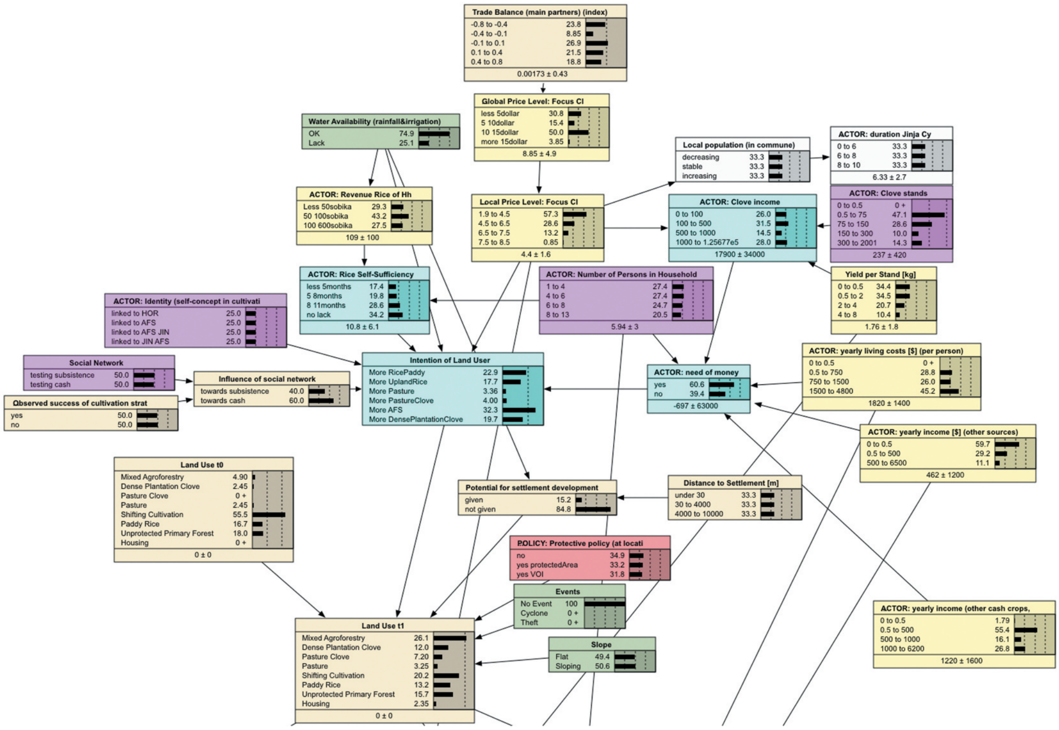

Figure A2. BN structure, nodes and states for land-use decision part. Color code: purple: local actor characteristics, yellow: economic characteristics, green: irrigation water availability, blue: intention, rice self-sufficiency, clove income, and need of money. Abbreviations: **Hh**: household, **Cl**: Clove, **Cy**: cycle, **Jinja** (**JIN**): upland rice cultivation, **Horaka** (**HOR**): paddy rice cultivation, **AFS**: Agroforestry systems.

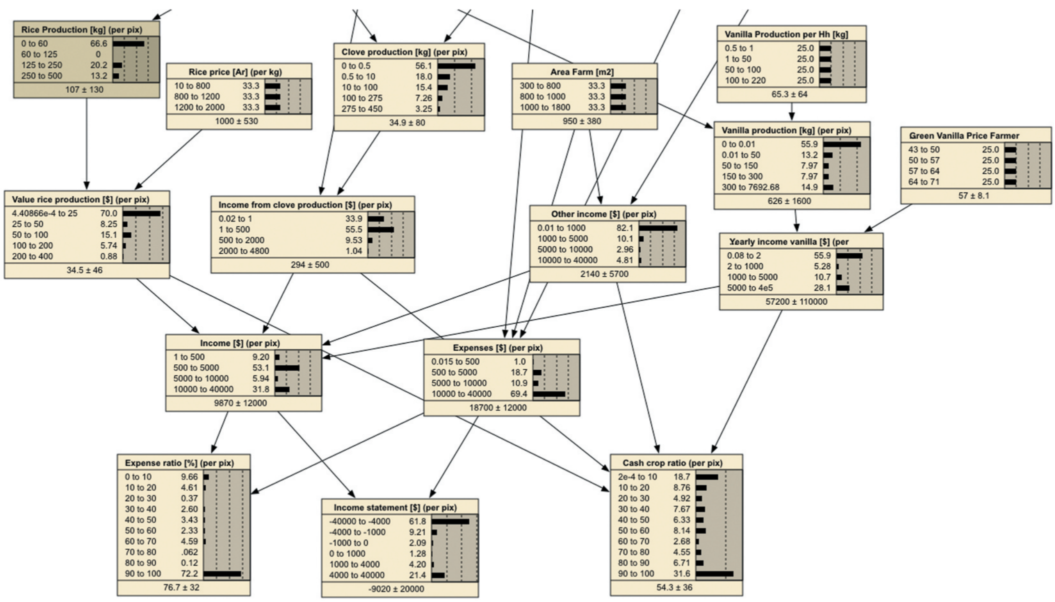

Figure A3. BN structure, nodes, and states of the income indicator part.

Two aspects of the technical implementation are provided under the following URLs:

(1) Geodata used: https://polybox.ethz.ch/index.php/s/qWAqs8kJibvrz0U

(2) Case files for parameter learning:
https://polybox.ethz.ch/index.php/s/qWAqs8kJibvrz0U

Rules for Bayesian network (BN) adaptations

To include the adjustments evoked in the subjective validation exercises, the conditional probability table (CPT) were set-up from scratch eliminating inconsistencies (overlaps to the former version). Starting point was the questionnaire data that served as basic parameterization. Due to the relatively small sample size given the large CPTs, some uniform or skewed distributions were observed. If probabilities were higher than 0.9, we transformed the probabilities for the specific combination of conditions to a uniform distribution. We found 5.7% of the all the conditional probabilities to fulfill this criterion in the intention node and in the land-use (LU) t1 node, 0.68% of all conditional probabilities were set to uniform distribution due to peaks higher than 0.9.

Participants in our workshops confirmed the general trend toward agroforestry systems and more specifically, that an agroforestry system (AFS) parcel would remain in this land-use category. In addition, they confirmed the high probability that upland rice changes to AFS independently of the price situation.

In both, the *intention* and the *LU t1* node, we adjusted five and seven causal mechanisms, respectively. In *intention*, we adjusted impact of price signal (interpolation in the price range and effect of high prices), impact of water availability, impact of identity, impact of social network, and impact of rice self-sufficiency. In *LU t1*, we adjusted for the presence of housing in t0, the fast conversion from upland rice to AFS, the impact of the distance to settlements, the conversion from pasture to paddy rice given a medium distance to the settlement, introduced the effect of protective policies, introduced path-dependency of land-use categories, and adapted the impact of slope.

In node "rice revenue", we adjusted the probabilities to reflect the influence of water (emphasized in the allocation and dynamics exercise). If water is lacking in an area, this would have a stronger in influence on the revenue (increased lowest state by 20% if water was lacking)

Node "intention"

ID	Construction step and rule to adjust BN	Empirical base for change
0	Expectation-maximization (EM) learning algorithm ($N = 71$)	Questionnaire data for each node
1	**Reason for changing**: Small sample size in the questionnaire. **Implemented change**: Probabilities higher than 0.9 without empirical foundation transformed to a uniform distribution.	Questionnaire analysis
2	**Reason for changing**: Lack of water was emphasized as strong reason to reinforce upland rice cultivation. **Implemented change**: Increased probabilities in intention for upland rice by 0.33.	'if-then' exercise
3	**Reason for changing**: Reflect importance of water for paddy rice production. Pasture turns to paddy rice if water situation is ok and at an intermediate distance from the village. Partly introduced in intention node, partly in LU_t1. **Implemented change**: Increase paddy rice probability by 0.2 if Water situation is 'OK'	Dynamic exercise (see step 5 in section 2.3), Gap Filling
4	**Reason for changing**: Paddy rice should not be sensitive to the price signal (alone) and stays unchanged as long as water situation is OK. Paddy rice turns to agroforestry systems if prices are high and water situation is not OK. Questionnaire data was available for today's price level (4.5–6.5$), hence other states need to be adapted. **Implemented change**: Given price signal is 4.5–6.5$ interpolate probabilities in intention: (1) Calculate mean from state 1 and 3 for state 4.5–6.5$. (2) add mean difference to state 7.5–8.5$ (of clove price) for intention 'More agroforestry systems'.	Allocation exercise Dynamics exercise
5	**Reason for changing**: Dense plantation stays the same if prices are low, it changes to AFS if prices are high (at least today's level). Pasture and Pasture & Clove turns to AFS or dense plantation if prices are high. Questionnaire data was available for today's price level (4.5–6.5$), hence other states need to be adapted. **Implemented change**: For high price levels (at least today's level) probabilities increase intention AFS and dense plantation: +0.3 ('6.5 to 7.5'); +0.6 ('7.5 to 8.5'); −0.2 ('1.9 to 4.5'), for dense plantation: +0.1 ('6.5 to 7.5'); +0.3 for ('7.5 to 8.5').	Dynamics exercise Allocation exercise (see step 5 in section 2.3)

(*Continued*)

(Continued).

ID	Construction step and rule to adjust BN	Empirical base for change
6	**Reason for changing**: Include village-based identity reflecting where the village's major cultivation expertise lays. **Implemented change**: Include a new node 'identity' (instead of 'tradition'). Identity = Reflects a farmer's self-concept in his actual cultivation. This is a village-based indicator and is implemented as follows: MAH favors paddy rice (implemented: +0.2 basis point in paddy rice given 'linked to paddy'), Fizono favors AFS (implemented: +0.2 basis point in AFS given linked to AFS"), MOR: favors AFS and upland rice (implemented: +.15 basis point in AFS and+0.1 basis point in upland rice given 'linked to upland and AFS') BEA favors upland rice and AFS (implemented: +0.15 basis point in upland rice and 0.1 basis point in AFS)	Gap Filling, questionnaire data analysis
7	**Reason for changing**: Introduce social network and connected to SN, 'observed success'. **Implemented change**: Include new node social network. Increases the respective cultivation types by 0.2 basis point (cash or subsistence). Pasture remains untouched in either case.	Gap filling
8	**Reason for changing**: Questionnaire data was not available for 'need of money' as this was critical to ask. Assumption: in a household with 'need of money', cash crops are given priority. **Implemented change**: +0.2 basis point in AFS and dense plantation given 'need of money'.	Causal chain exercise in FV3
9	After applying the adjustments, a normalization steps was calculated to get sum of all probabilities match 100%.	

Node "LU_t1"

ID	Construction step and rule to adjust BN	Empirical base
0	EM-learning algorithm ($N = 173$)	Questionnaire data for each node
1	**Reason for changing**: Small sample size in the questionnaire. **Implemented change**: Probabilities higher than 0.9 without empirical foundation transformed to a uniform distribution.	Questionnaire analysis
2	**Reason for changing**: Housing data was not available. **Implemented change**: Housing had to be included manually. If housing was given in t0 housing is set in t1.	Land-use data
3	**Reason for changing**: If LU t0 is located within a protected area, land-use in t1 should adjust. The real decision-making could not be grasped due to its highly political situation. An ideal case – from the policy maker perspective – is implemented to start discussions. **Implemented change**: Change LU t1 according to LU t0's overlap with a protected area. If LU t0 == forest then 100% forest; If LU t0 == shifting cultivation then 33% shifting, 33% AFS, and 33% forest. If LU t0 == AFS then 50% AFS and 50% forest. If LU t0 == pasture or pasture & clove or dense plantation or paddy rice or housing then 50% forest and 50% land use given in LU t0.	'if-then' exercise
4	**Reason for changing**: If LU t0 is located within a VOI area then LU t1 should adjust. The real decision-making could not be grasped due to its highly political situation. An ideal case – from the policy maker perspective – is implemented to start discussions. **Implemented change**: Change LU t1 according to LU t0's overlap with a VOI area. Copy-paste the probabilities from 'no protective policy' AND IF lu_t0==forest, increase probability for forest in LU t1 by 60%.	'If-then' exercise
5	**Reason for changing**: Upland rice changes to AFS independently of price situation. **Implemented change**: If LU t0 is upland rice then independently of intention (price), LU t1-AFS will be increased by 0.2.	Dynamics exercise

(*Continued*)

ID	Construction step and rule to adjust BN	Empirical base
6	**Reason for changing**: Paddy rice turns to housing if water situation is not ok and parcel is adjacent to the village. Paddy rice turns to agroforestry systems if water situation is not ok and not adjacent to village. **Implemented change**: Include a new node reflecting distance from settlement. Effect: (a) Given paddy rice up to a distance of 30 m from village and lack of water: increase probability of housing by 20%. (b) Given a distance of more than 4 km (potential settlement development not given), paddy rice will more likely turn to AFS (work efficiency) by 20%.	Allocation exercise
7	**Reason for changing**: Pasture turns to paddy rice if water situation is ok and at an intermediate distance from the village. **Implemented change**: Given pasture in LU t0, settlement potential is 'not given', add 20% to paddy.	Dynamic exercise
8	**Reason for changing**: path-dependency and the importance of farmers ideas should be reinforced. **Implemented change**: (a) The probability for LU t1 in a category was increased if the same land-use was present in LU t1. (b) In addition, for sloping areas a premium of 0.2 was given to AFS, upland rice, dense plantation, unprotected primary forest, and pasture & clove; for flat areas a prime of 0.2 was given to paddy. (c) Probability of intention state was reflected by increasing 0.2 at the respective land-use.	Causal chain exercise in FV3
9	After applying the adjustments, a normalization steps was calculated to get sum of all probabilities match 100%.	

Nodes "Local price level: Focus clove","Global price level: Focus clove", "Trade Balance (main partners) (index)

Trade Balance (main partners): Frequencies of categorized trade balance of Madagascar with maintrading partner for clove turned into percentages. Trade balance = export –import. Data used: Index Indonesia (<2010) and India (2010 to <2015).

Global price level: Focus clove: Frequencies turned into percentages of trade balance categoriescompared to market price (price global, price at exporter). Correlation(price_global; trade_balance): - 0.37609

Local price level: Focus clove: According to Duault (2008) in: Danthu et al. (2014): 58% of FOB remain with Farmer. According to own data: 3.25$ ofabout 10-12$ remain with farmer which is about 32.5 to 27.3 %. Mean usedfor appraisal: 29.5%. Rule 1: If mean and Duault (2008) and own data in samecategory: 0.9 for this category. Rule 2: If they split: Mean 0.5, neighboringcategories/states: 0.2.

APPENDIX C

List of nodes
https://polybox.ethz.ch/index.php/s/CPVDZsco7mHupPz

APPENDIX D

Table A1. Yearly cultivation cycle in northeastern Madagascar.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Source
Amount of precipitation (mm)	363	397	442	438	306	255	268	204	113	79	126	284	https://en.climate-data.org
Average temperature (°)	26.3	26.4	26	25.1	23.5	22	20.9	20.8	21.4	22.9	24.4	25.5	https://en.climate-data.org
Cyclone season	+	+	+										Tadross et al. (2008)
Jinja (upland rice)	Weeding		Weeding		Harvest	Harvest			Clearing	Clearing	Burn	sowing	Locatelli (2000). P. 148ff
Rice season Horaka (paddy)	Season I	Season I		Season II	Season II	Season II	Season II		Season I	Season I	Season I	Season I	Locatelli (2000)
Horaka I (paddy rice I)	Harvest I							Sowing I	Transplant I	Weeding			Locatelli (2000), p. 157
Horaka II (paddy rice II)	Transplant II				Harvest II	Harvest II				Sowing II	Sowing II	Transplant II	Locatelli (2000), p. 157
Jirofo (clove)										Harvest	Harvest	Harvest	Locatelli (2000), p. 170
Lavanila (vanilla)							Harvest	Harvest	Planting	Planting	Planting		https://en.climate-data.org
Kafe (coffee)							Harvest	Harvest					Locatelli (2000), p. 173

APPENDIX E

Calculating the rice loss and cash crop gains using the positive scenario.

Table A2. Model-induced rice production (upland and paddy rice) to estimate a loss in rice cultivation/harvest/revenue and a potential compensation to buy the respective rice quantity.

	Difference Upland rice t0-t2	Difference Paddy t0-t2	Difference Upland rice t0-t2	Difference Paddy t0-t2	Difference Upland rice t0-t2	Difference Paddy t0-t2	Difference Rice (total) t0-t2
Village	[ha]	[ha]	[t]	[t]	[US$]	[US$]	[US$]
Mahalevona	−505	255	−409	364	−116929	103981	−12948
Fizono	−2299	97	−1862	138	−531996	39529	−492467
Morafeno	−769	−5	−623	−8	−178026	−2145	−180171
Beanana	−989	48	−801	68	−228883	19509	−209374
TOTAL	**−4562**	**394**	**−3132**		**−894960**		
Factors used for calculation			0.81t/ha	1.43t/ha	1000 Ar/kg 3500Ar/$	1000 Ar/kg 3500Ar/$	

Table A3. Potential gains from the model-induced increase in agroforestry system (AFS) surface.

	Difference AFS	Difference Cloves	Difference Cloves	Difference Green Vanilla	Difference Green Vanilla
Village	[ha]	[t]	[US$]	[t]	[US$]
Mahalevona	654	38	264710	33	1799188
Fizono	4048	234	1637922	202	11132688
Morafeno	1008	58	407635	50	2770625
Beanana	2969	172	1201257	148	8164750
TOTAL	**8679**	**502**	**3511523**	**434**	**23867250**
Factors used for calculation		57.8 kg/ha	7 US$/kg	50 kg/ha	55 US$/kg

APPENDIX F

Validation methodology (EN): https://en.climate-data.org
Household and parcel questionnaire (EN): https://en.climate-data.org
Validation workshop participants (EN): https://en.climate-data.org
Validation workshop transcripts (Malagasy and FR): https://en.climate-data.org
Multiple-choice questionnaire (EN): https://en.climate-data.org