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Young Scientists Summer Program

Coupled dynamics of biodiversity loss and undernutrition in eastern Madagascar: a participatory agent-based model

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Approved by:

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Program: SI and BNR
Date: 30 September 2022

This report represents the work completed by the author during the IIASA Young Scientists Summer Program (YSSP) with approval from the YSSP mentor.

It was finished by Romain Clercq-Roques and has not been altered or revised since.

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ZVR 524808900

Abstract

Introduction

Undernutrition remains the primary cause of mortality in Madagascar, especially among poor rural communities, who rely to a large extent on subsistence agriculture and wild foods for their nutrition. Furthermore, Madagascar, a biodiversity hotspot, is registering rapidly diminishing levels of biodiversity, notably due to deforestation driven by shifting agriculture and unsustainable wild species harvesting. Biodiversity provides ecosystem services to farmers, sustaining agricultural production, and allows them to supplement their diets with wild foods. However, the impact of biodiversity loss on undernutrition in rural Madagascar remains largely unknown. The overarching aim of the study was to explore the links between biodiversity and nutrition in the context of eastern Madagascar. The specific objectives were to identify key social and ecological processes directly related to biodiversity and nutrition, represent them in an agent-based model, and observe whether and how the dynamic relationships between these processes reproduce empirical patterns of biodiversity loss and undernutrition in eastern Madagascar. In the agent-based model, alternative scenarios with varying impact on biodiversity were compared: a baseline scenario in which farming households resort to shifting agriculture and foraging to achieve their nutritional needs; a scenario introducing forest and wild species conservation, thus impacting agricultural expansion and foraging practices; and a scenario introducing a portfolio of agroecological practices adapted to the local context.

Methods

The study was conducted in two stages. First, a model design was developed based on empirical data gathered in eastern Madagascar as well as academic literature. This allowed to identify current dynamics as well as specific social and ecological processes and their links, and develop alternative scenarios. Second, a stylized agent-based model was developed to simulate the relationship between these processes and explore the impact of the alternative scenarios on biodiversity and nutrition. The model was developed in Netlogo based on interviews and role-playing games with local experts and farmers as well as academic literature. The model includes two types of agents: farming households, and land patches on a 2 dimensions grid. Farmers change land-use to produce food, which leads to changing patches biodiversity and landscape forest cover. Farmers also forage in forests, impacting wild edible species levels. Stochastic disruptions of yields represent fluctuating harvest losses due to climatic events and biotic pressure (pest, disease and weed pressure). The model simulated population growth and the adaptation of farmers to increasing land scarcity and changes in resource availability over 120 annual time steps.

Results

The baseline scenario exploring the traditional system of shifting agriculture - in which in which farmers cultivate specific plots for one year before shifting to new plots and letting the firsts fallowed for a long period - to be very sensitive to population density. At low population density shifting agriculture was sustainable but increasing population density led to collapse of both biodiversity and nutrition outcomes. Land scarcity forced households to reduce fallow lengths, generating a dynamic of self-reinforcing soil degradation, until the landscape became completely unproductive and barren. Deforestation and increasing foraging pressure to compensate for poor agricultural outputs quickly led to the disappearance of wild species, reducing diet diversity and leaving farmers vulnerable to declining yields and higher harvest losses. The second scenario introducing forest conservation measures further reinforced this dynamic by reducing land available to agriculture and failing to improve

ecosystem services due to lower tree cover and soil biodiversity on fallows. Nevertheless, improving fallows regeneration could mitigate trade-offs from forest conservation. Introducing foraging quotas protected wild species as long as the habitat was maintained but did not appear to provide notable nutritional benefits, as foraging amounts were insufficient for a growing population. The third scenario introduced a portfolio of agroecological practices: SALT 4 (Small Agrofruit Livelihood Technology) agroforestry, diverse home-gardens, and SRI paddies (System of Rice Intensification) with fish. This portfolio had large positive effects on biodiversity and nutrition outcomes, due to its much higher within-field biodiversity, significantly lower area required to sustain a household and significantly improved diet diversity provided by production diversity.

Discussion

The baseline scenario generated increasing biodiversity loss and undernutrition through interdependent social and ecological processes generating a reinforcing feedback loop worsening both, providing an explanation for the dynamics observed in rural eastern Madagascar. The second scenario of forest conservation protected wild biodiversity but, when implemented without additional measures, generated nutritional trade-offs that require further consideration. The third scenario suggested that agroecological practices could generate large synergies for biodiversity and nutrition. Current model outputs are not definitive, and uncertainties remain, however. The second scenario requires further calibration and exploration of alternative assumptions about forest ecosystem services. The model will be used as a focal object in a dialogue with national stakeholders and iteratively developed based on this dialogue. It will be revised and extended, calibrated further, formally analysed and finally validated based upon both stakeholder perceptions and the ability of the model to reproduce empirical patterns based on evidence-based micro-level processes

About the author

Romain Clercq-Roques is currently a 2nd year PhD student in public health and policy at the London School of Hygiene and Tropical Medicine, exploring the social-ecological dynamics linking biodiversity loss and undernutrition for smallholder farmers of rural eastern Madagascar. He obtained a Master of public health at King's College London and a Master of international law at Pantheon-Assas University. Romain worked eight years with the International Committee of the Red Cross, as a legal advisor and humanitarian worker. His main research interest is planetary health, and specifically identifying policies co-benefiting health and biodiversity. (Contact: romain.clercq-roques@lshtm.ac.uk)

Acknowledgments

I would like to thank my IIASA mentors Katya Perez-Guzman and Marta Kozicka for their important contributions to the design and development of the agent-based model and this report. My LSHTM supervisors Kristine Belesova and Paul Wilkinson for their important guidance for this research. Martin Jung and Christian Folberth from IIASA as well as Zaid Chalabi from LSHTM for their suggestions to improve the design of the model. The organisations l'homme et l'environnement and Cétamada as well as Herizo Randriambanona from the CNRE for their assistance in conducting fieldwork in Madagascar.

Introduction

Madagascar is among the three countries with the highest prevalence of undernutrition (Abbafati et al., 2020). Notably due to chronically insufficient intakes, protein-energy undernutrition and micronutrient deficiencies are rife. 43 percent of rural children under five are thought to be stunted, and 27 percent are underweight (Asgari et al., 2015). Adults are also at risk, with 26 percent of women thought to be underweight, and 88 percent having an insufficiently diverse diet, (Instat, 2010) causing micronutrient-deficiencies and associated health issues such as iron-deficiency anaemia. The traditional rice centric diet is associated with high micronutrient deficiencies (Moursi et al, 2008; Ravaorisa et al, 2018). A recent study found that vitamin A, B12, D, E and calcium intakes were highly insufficient in a rural community (Golden et al., 2019), and 52 percent of infants are thought to be vitamin A deficient (Stevens, 2015). In addition, rural populations are highly vulnerable to natural disasters such as cyclones and droughts, which cause frequent food security crisis, especially in the semi-arid south-west (Harvey et al, 2014). Undernutrition remains the primary morbidity and mortality factor in Madagascar (Powell et al., 2015). Epidemiological studies have explored social determinants of undernutrition in Madagascar (see, e.g. Hirotsugu et al., 2019), but ecological determinants remain largely unexplored, despite most of the population relying on self-production and wild foods for their nutrition.

80 percent of the population lives of agriculture, mostly of subsistence and mixed small-scale family farming, with less than 1ha per farm (Osborne et al., 2016; Instat 2019). Shifting agriculture, mostly of rice, cassava or maize using slash-and-burn, is the main agricultural practice for most farming families, with extensive cattle ranching also common in the drier western regions. Wild ecosystems are also important food sources for remote rural communities. Forests are commonly used to gather wild tubers, wild honey, green leafy vegetables, fruits, and a variety of insects, mammals, and birds, while rivers and coastal waters are important sources of fish and crustaceans (Borgerson et al., 2018 and 2019). Wild foods provide important sources of protein, lipids and key micronutrients, especially to poorer households (Golden et al. 2011b and 2019) and their disappearance would increase micronutrient deficiencies (Golden 2011a). Forests also provide important products for rural families such as traditional remedies, construction material, fibres, fuelwood and charcoal. Additionally, wild ecosystems also provide ecosystem services to local farmers (Randrianarivony et al., 2016). Forests host important pollinators and regulate regional weather patterns, water flows, microclimates, pest pressure, maintain soil health (notably soil conservation and nutrient cycles) (Bodin, 2016; Dudley et al., 2017; Kihara et al., 2020). Forests, mangroves and coral reefs also mitigate extreme weather events (Ferrario et al., 2018; Menendez et al., 2020). In Madagascar and other tropical contexts, trees and natural vegetation in farms are increasingly recognised to provide similar ecosystem services by regulating micro-climate, improving soil fertility and hosting beneficials species (Rosenstok et al, 2019). Soil biodiversity, and positive relationships between above-ground and below-ground diversity, have been found to be important factors in farm productivity and resilience against climate extremes and pest pressure, by improving physical, chemical and biological soil parameters as well as crop health (Mujtar et al., 2019; Kihara et al., 2020).

Crop and livestock diversity in farm have also been found to improve ecosystem services and to be correlated to improvements in nutritional outcomes of smallholder farmers, through numerous pathways (Smith et al., 2008; Jones et al., 2017; Tamburini et al., 2020). Crop diversity at genetic, varietal and species level can improve the nutritional content of crops, crop adequacy to the local context, and resistance to climate extremes and pests and diseases (Holt-Gimenez et al., 2002). Production diversity can also provide additional income and protect farmers against environmental and market fluctuations (Holt-Giménez 2002, Jones, 2017, Duffy et al., 2021). Biodiversity in farms and forest thus has multiple influences on agricultural and wild foods on which smallholder farmers rely for their nutrition.

Madagascar is also a biodiversity hotspot, a denomination reserved to areas with both the highest global biodiversity and rates of biodiversity loss. Madagascar's biodiversity is found in its spiny, dry and humid tropical forests, as well as in its mangroves and coral reefs (Neugarten et al., 2016). All these habitats are facing rapid degradation and destruction, however. Since the 1950s, Madagascar is thought to have lost half of its forest cover (Vieilledent et al., 2018). Deforestation is mostly caused by the conversion of forests into fields and pastures. Additionally, unsustainable agricultural and pastoral practices, such as slash and burn with short fallow length, cause soil degradation, which shifts vegetation states from forests to grasslands or barren soil (Styger et al., 2007 and 2009). These lands in turn become agriculturally unproductive and support limited biodiversity. Both deforestation and degradation are increasing, with currently a third of agricultural land in Madagascar thought to be degraded. In remaining wild ecosystems, useful forests and marine species are being harvested at increasingly unsustainable rates, causing local extirpations, with potentially many more species impacted through trophic cascades caused by losses of keystone species (Borgerson, 2019).

While it appears that rural populations in eastern Madagascar are dependent on biodiversity in agricultural and wild ecosystems for their food intakes, the impact biodiversity loss may have on undernutrition remains largely unexplored. The relationship between biodiversity and health is mediated by biodiversity-supported ecosystem processes, contributing to creating ecosystem services. Additionally, farmer practices and their adaptation to environmental changes may mediate the relationship between biodiversity and nutrition, as they may impact biodiversity to various degree and thus support or hinder ecosystem services (Diaz et al., 2015). To understand these relationships, it is thus necessary to account for both ecological processes and social processes, specifically agricultural and foraging practices that impact biodiversity levels and the choices farming households make when confronted to changes in agricultural and wild food availability. Local landscapes can be framed as complex social-ecological systems in which system level outcomes of biodiversity loss and undernutrition emerge from micro-level social and ecological processes (Folke et al., 2016; Diaz et al., 2015). These emergent outcomes, in turn, shape social processes through farmer adaptation to a changing environment, which may generate reinforcing feedback loops or balancing feedback loops, that would contribute to either destabilising or stabilising the system. This micro-macro interplay generates complex dynamics that are hard to predict. Agent-based models (ABM) are valuable tools to explore these complex dynamics as they represent both macro and micro level processes and can be spatially explicit, allowing to explore the outcomes of interacting social and ecological processes at the landscape scale.

The overarching aim of the study was to explore the links between biodiversity and nutrition in the context of eastern Madagascar. The specific objectives were to identify key social and ecological processes directly related to biodiversity and nutrition, represent them in an agent-based model, and observe whether and how the dynamic relationships between these processes reproduce empirical patterns of biodiversity loss and undernutrition in eastern Madagascar. The focus was on agricultural and foraging practices, as they directly impact biodiversity levels in farms and forests, and ecosystem services as they link biodiversity to food production. Other indirect connections between biodiversity and nutrition, for example through emerging infectious diseases, fuelwood or income generation from natural resources use were excluded, as well as other existing causes of undernutrition not directly related to biodiversity, such as income and education levels. In the agent-based model, alternative scenarios with varying impact on biodiversity were compared: a baseline scenario in which farming households resort to shifting agriculture and foraging to achieve their nutritional needs; a scenario introducing forest and wild species conservation, thus impacting agricultural expansion and foraging practices; and a scenario introducing a portfolio of agroecological practices adapted to the local context: SALT 4 (Small Agrofruit Livelihood Technology) agroforestry, diverse home-gardens, and the SRI paddies (System of Rice Intensification) with fish. Based on the concept of social-ecological trap, which focuses on the interdependency of social and ecological systems in situations of reinforcing environmental degradation and worsening social outcomes such as poverty (Haider et al., 2018; Eriksson et al., 2021), the baseline scenario was hypothesised to generate a reinforcing feedback loop between biodiversity loss and undernutrition, through processes to be identified. Conversely, the alternatives scenarios were hypothesised to improve biodiversity and nutrition by maintaining biodiversity and ecosystem services, preventing this reinforcing feedback loop from emerging. The ABM was developed using the companion modelling approach, consisting of iterative rounds of development and revision based on a structured dialogue between researchers and stakeholders.

Materials and methods

1) Context and study area

The study focuses on eastern Madagascar. Madagascar is a low-income tropical country off the south-eastern coast of Africa with diverse geographical regions. The eastern region is composed of a narrow lowland followed by a steep escarpment reaching the central highlands at an elevation of about 1000m. It receives large amount of rainfall brought by eastern winds, notably during the seasonal tropical storms and cyclones. Until recently completely covered in rainforest, the region is seeing rapid deforestation (figure 1), mostly due to agricultural expansion. The population is mostly rural and lives of subsistence and mixed agriculture. The traditional agricultural practices in eastern Madagascar are centred around upland rice produced using slash and burn, a type of shifting agriculture in which farmers cut and burn the vegetation on a first plot to cultivate it for a short period, usually one or two years, before shifting to a new plot and letting the first plot fallow for a long period. Farmers thus cycle between numerous plots, cultivating only a limited surface at a time. This system can include cassava as a secondary crop, cultivated the second year before fallowing. Some farmers also cultivate cash crops, notably cloves, but the proportion remains low and fluctuates over time depending on State incentives and

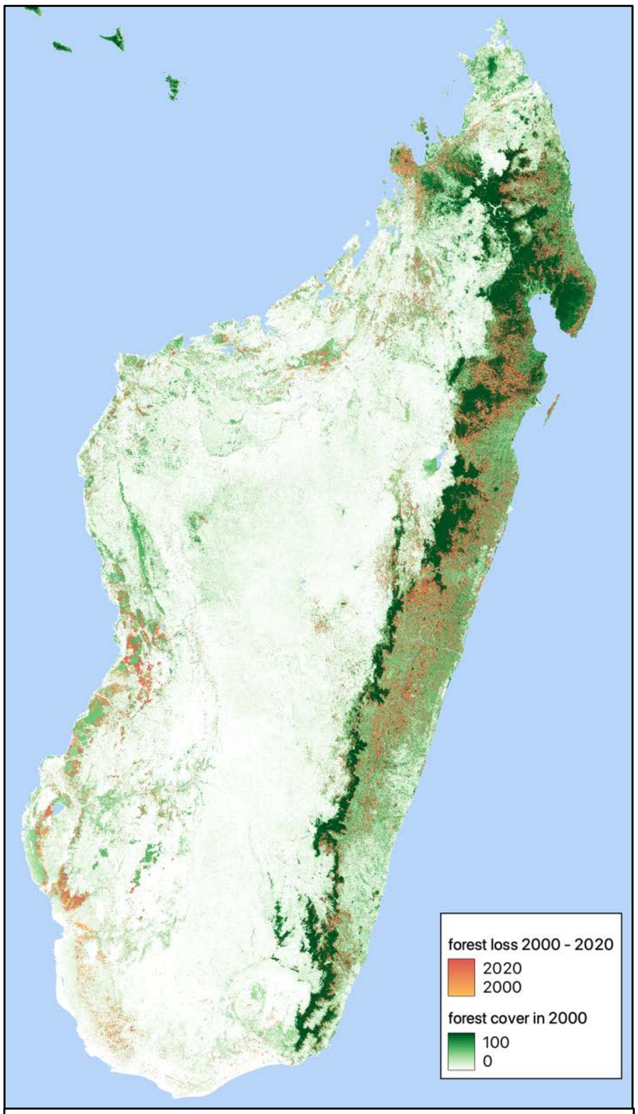


Figure 1: forest cover and forest loss in Madagascar. Forest cover is in percentage of canopy density. Forest loss colour gradient indicates the year forest cover was lost

international market prices. Farming households more commonly maintain some fruit trees, such as banana, mango, avocado, papaya, citrus or pineapple, usually in very numbers around homes. Data collection was conducted in two field locations: in the settlements around Vohimana - a small forest protected by the local NGO l'homme et l'environnement, and located in the vicinity of two national parks; as well as in southern Sainte Marie, an island of the eastern coast, where agriculture is complemented by fishing. Additionally, national experts and stakeholders were consulted in Antananarivo, the capital city.

2) Research process and data sources

This study adopted the companion modelling approach, a participatory research process in which a computer model is developed and revised iteratively based on a structured dialogue between researchers and stakeholders (Barreteau et al., 2014). This approach is meant to bridge science and policy in a co-learning process especially relevant for complex problems which tend to escape a simple and consensual definition. By gathering stakeholders from different sectors, it fosters dialogue among them and facilitates the definition of a common understanding of system dynamics and ways to address them. Additionally, by involving local stakeholders it improves research relevance and impact. The study was conducted in two main stages. First, a model design was developed based on empirical data gathered in eastern Madagascar as well as academic literature. This allowed to identify current dynamics as well as specific social and ecological processes and their links, and develop relevant alternative scenarios. Second, the agent-based model was developed to simulate the relationship between these processes and explore the impact of the alternative scenarios. The research process is iterative, based an ongoing dialogue with national stakeholders and experts in biodiversity conservation, agriculture and public health nutrition. This dialogue will continue, and the model will be revised and extended based on stakeholder feedback.

In early 2022, smallholder farmers and national stakeholders from the biodiversity conservation, agriculture and public health nutrition sectors were interviewed. Initial interviews with stakeholders notably allowed to prepare focus-group discussions and role-playing games that were then conducted with farmers in Vohimana and Sainte Marie, along with field walks to gain a better understanding of local landscapes. Focus-group discussions were designed to gather information about changes observed by farmers in their landscape during the past decades, notably in terms of biodiversity and ecosystem services, changes in their foraging and agricultural practices and agricultural outcomes, as well as diets and nutritional outcomes. A board game was designed to elicit information about farmer choices when confronted to a changing environment. Land scarcity due to population growth, deforestation and loss of wild species and natural disasters were represented to capture their choices, as well as discuss hypotheses about system dynamics. The overall aim of the role-playing game was to guide the design of the agent-based model, especially to inform the local choices of farmers, later represented as agents. Additionally, academic and grey literature about Madagascar and other low-income tropical countries was scoped to gather relevant information about the role of biodiversity in ecosystems and ecosystem services, shifting agriculture, agroecology, and wild forest foods. Biodiversity and agriculture experts were finally consulted to refine the model design.

3) ABM design

The model description follows the Overview, Design concepts, Details (ODD) protocol for describing individual- and agent-based models (Grimm et al. 2006), as updated by Grimm et al. (2020). The last part of the protocol, Details, is not included in this report to maintain brevity.

Overview

1 purpose and patterns

The main purpose of the model is to simulate the dynamic relationships between key social and ecological processes directly related to biodiversity and nutrition, and observe whether dynamics of biodiversity loss and undernutrition emerge, as seen in eastern Madagascar. The model has two higher level purposes: explanation and social learning. It is being developed based on a dialogue with stakeholders to develop a shared understanding of the dynamics of biodiversity loss and undernutrition in rural eastern Madagascar, and of possible interventions that would improve both.

2 entities, state variables, temporal and spatial scales

In the model biodiversity is divided in distinct categories identified as directly relevant from a preliminary scoping of the literature: wild foods and production diversity for their direct role in providing food and associated agrobiodiversity, which includes all organisms providing ecosystem services to agriculture such as pollinators, pest predators, decomposers and others (Jackson et al. 2007). The model divided associated agrobiodiversity into below ground diversity (soil biodiversity) and above ground diversity, captured using tree cover at both the plot and the landscape scale. Nutrition was captured using annual individual energy intakes, as well as food groups consumed, using the 10 food groups of the Minimum Dietary Diversity for Women of Reproductive Age indicator (MDD-W) which has been validated as an indicator of micronutrient intakes (FAO and FHI 360, 2016). The consumption of 5 groups or more is a predictor of sufficient micronutrients intake, at community level.

The model is composed of two entities: farming households and landscape cells. Farming households are of three kinds, depending on the crops cultivated (upland rice and cassava using shifting agriculture, lowland rice paddies, or diverse crops), and their main attributes are age, household size and thus energy needs, owned and cultivated plots, and finally energy and food groups obtained from self-production and foraging. Landscape cells are of seven kinds (forest, fallow, slash-and-burn, paddy, paddy using SRI and fish, SALT agroforest, home-garden) and their main attributes are related to biodiversity (table 1), ecosystem services (soil fertility, biotic and abiotic disruptions regulation and pollination), and agricultural output: expected energy production, which is the yearly production that could be expected without any biotic or abiotic disruption, and achieved energy production, after losses to disruptions. Additionally, wild species diversity is represented by a global variable tied to emergent properties: landscape vegetation cover and foraging pressure.

Table 1: agricultural plot types and current biodiversity parameter values

Household type	Plot type	Production diversity	Tree cover	Soil biodiversity
Shifting agriculture	Cultivated upland	2	0	Dynamic
	Fallow		Dynamic	Dynamic
Rice paddy	Lowland rice paddy	1	0	0.6
Agroecology	SALT agroforestry	4	0.5	0.9
	Home-garden	6-8	0.7	0.9
	SRI rice & fish	2	0.2	0.7

The model is composed of a two-dimensional grid of 4331 discrete spatial units, each representing 0.1 ha for a total of 433.1 ha. The model runs over 120 annual time steps. Spatial and temporal scales have been chosen to allow key dynamics to emerge, and notably observe the influence of increasing population density and the loss of ecosystem services over several decades.

3 process overview and scheduling

During each time step, seven processes run in sequence. First, global variables are updated. They notably include a biotic and an abiotic disruption value, both randomly generated each time from an exponential distribution with a mean value that can be modified by the user (30 by default), as well as landscape forest cover and vegetation cover, and wild species diversity. These variables will then be used to compute cell-level ecosystem services and farmers' food availability. Second, demographic variables are updated. Household members age and have children. After 18 years these children leave to create their own households, and their parents share a third of their land with them. Household members over the age of 64 die, simplistically reproducing average life expectancy. Third, households plan land-use. The process is different for the three types of household. Household relying on the traditional shifting cultivation practices rotate between upland rice or cassava and fallow, and an internal model determines fallow length and expansion over forested land based on their nutritional needs and preferences. Household cultivating rice paddies simply decide about the surface they need based on household size. Similarly, agroecological households decide of the surface they need but cultivate diverse plots: paddy rice using the system of rice intensification and fish, SALT agroforestry and diverse home gardens. Fourth, plots are harvested. Energy outputs are function of both plot-scale and landscape-scale biodiversity and ecosystem services levels. Fifth, farmers forage in remaining forests. Energy and diversity obtained is function of wild species levels, and foraging intensity increases when agricultural outputs are insufficient to meet energy needs. Sixth, fallows variables are updated. Soil biodiversity and vegetation cover regenerate at a pace influenced by plot degradation level. Finally, farmer nutrition variables are updated.

Design concepts

The model explores the relationship between micro-level social and ecological processes and system-level outcomes of biodiversity loss and undernutrition. It is hypothesised that undernutrition (both insufficient energy intakes and diet diversity) emerges from a reinforcing feedback loop between changes in the state of the environment (land scarcity and biodiversity levels) and farmers adaptive actions. It is further hypothesised that changes in social processes might generate improved nutrition and biodiversity outcomes. Farming households aim to maintain sufficient nutrition by achieving adequate energy intake and diet diversity. They use a strategy relying on subsistence agriculture supplemented by wild foods. Energy intakes are modelled using direct objective seeking. Farmers assess their energy needs and make resource use decisions based upon them. Diet diversity is modelled using indirect objective seeking, by reproducing observed behaviours of farming households, and thus households do not have a diet diversity target. Farmers make land-use decisions based on household energy needs and expected energy output of their cultivated patches. Farmers are aware of their own energy needs and of some environmental variables: forest patches available for expansion, wild food availability, fallow age and expected energy production of cultivated patches. The core of the model is in the interactions between patches and farmers. Farmers change land use and thus biodiversity levels. Patches provide farmers with energy and diet diversity. The model also represents interaction between patches, as ecosystem services at patch-level are impacted by biodiversity at patch and landscape levels. Interactions between farmers occur only indirectly, through competition for land and wild foods. Stochasticity is used to initialize the model (randomizing farmers and plots location), to randomise agent actions order, avoiding hierarchisation between them, to model foraging outcomes, as amount captured is variable in practice, and finally to model disruptions of agricultural production, representing the natural climate fluctuations and unpredictable extreme weather events and crop pest & disease outbreaks.

Results

Model structure

Social processes

The focus group discussions and role-playing games allowed to identify key social processes and represent them in the model. Three types of processes were identified as potentially central: demographic processes leading to population growth and intra-family land sharing, land-use processes driving agricultural expansion and intensification, and foraging processes driving changes in wild species levels and diet diversity (Figure 2). They were simplified and stylized in the agent-based model.

In the model, households only have 2 children rather than 4 as Malagasy households currently have on average. This is because each child in the model will create a new household and thus contribute twice to population growth. This is a simplification made to improve clarity in interpreting model outputs that does not affect result in term of population dynamics. Population growth can be restricted to a ceiling by model users, which prevents households from having more children and allows to explore model behaviour at different stable population densities.

Land-use processes are central as they determine whether households choose to expand or intensify cultivation, and thus the area owned, the proportion cultivated, fallow length, and biodiversity levels. An important design decision was the order of preference of households between various land types. Each year, people have to choose between cultivating a new plot, a fallowed plot, or a plot cultivated the previous year. To reproduce observed patterns of semi-stable cycles between mature fallows, farmers have to prioritise them over either forest or younger fallows. Farmers can decide whether fallows are mature enough based on either age or their vegetation state, providing an indication of both the amount of organic matter that will be added through burning or mulching and soil fertility. Based on interviews it was decided to base farmer decisions on vegetation regrowth rather than fallow age. It is both simpler to manage in practice for farmers and a better indicator of soil fertility. In the model, the preferred fallow vegetation regrowth is a variable that can be modified by users in NetLogo user interface, allowing experiments. The actual decision made by households depends on the preferred vegetation state as well as land availability. With a growing household, and as long as some forest remains, people have to choose between expanding and reducing fallow length. Nevertheless, interviews and role-playing games revealed that people valued forest conservation for both cultural and practical reasons (notably as a source of timber, fuelwood, wild foods and remedies). The games revealed that people tended to reduce fallow length before forest disappeared entirely, but with varying individual preferences. This is reproduced in the model by introducing a ‘preferred forest cover’ variable. The maximum value can be modified by users in NetLogo user interface, with each household level being randomly drawn. A final factor that determines land use choice is the household energy target. Households have energy needs that vary with their size and may decide to produce less than they need in situations of land scarcity, to limit land use intensification. This was added after early results showed that a household behaviour aiming to rigidly achieve energy targets would lead to a dramatic system collapse, as explained later in this paper. An adaptive process was thus added, allowing farmers to reduce their energy target to protect soil fertility. Practically, this means that households leave a greater proportion of their plots to fallow, rather than putting them into production. The land-use and foraging decisions made by individual households impact biodiversity levels in their plots and in the landscape. These changes in biodiversity levels in turn impact ecosystem services and thus the amount of energy provided by cultivated patches.

Finally, households can obtain wild foods from the landscape. Farmers noted in focus group discussions that wild foods used to amount for around a quarter of their foods but that they progressively disappeared. The model thus represented a baseline routine foraging behaviour that would provide a similar amount with large forest cover. In rural Madagascar, wild foods are also used as a resilience mechanism during the "lean season" and against crop failure, notably caused by droughts or cyclones. In these cases, wild foods consumption increases to compensate decrease in agricultural production (see e.g. Hanke et al., 2017; Golden et al., 2019). Recent literature has highlighted the significant role of wild foods to the nutrition of rural populations in low-income tropical countries (Rowland et al., 2017). In the model, foraging frequency increases when agricultural production does not cover household nutritional needs. Households will forage up to 10 times.

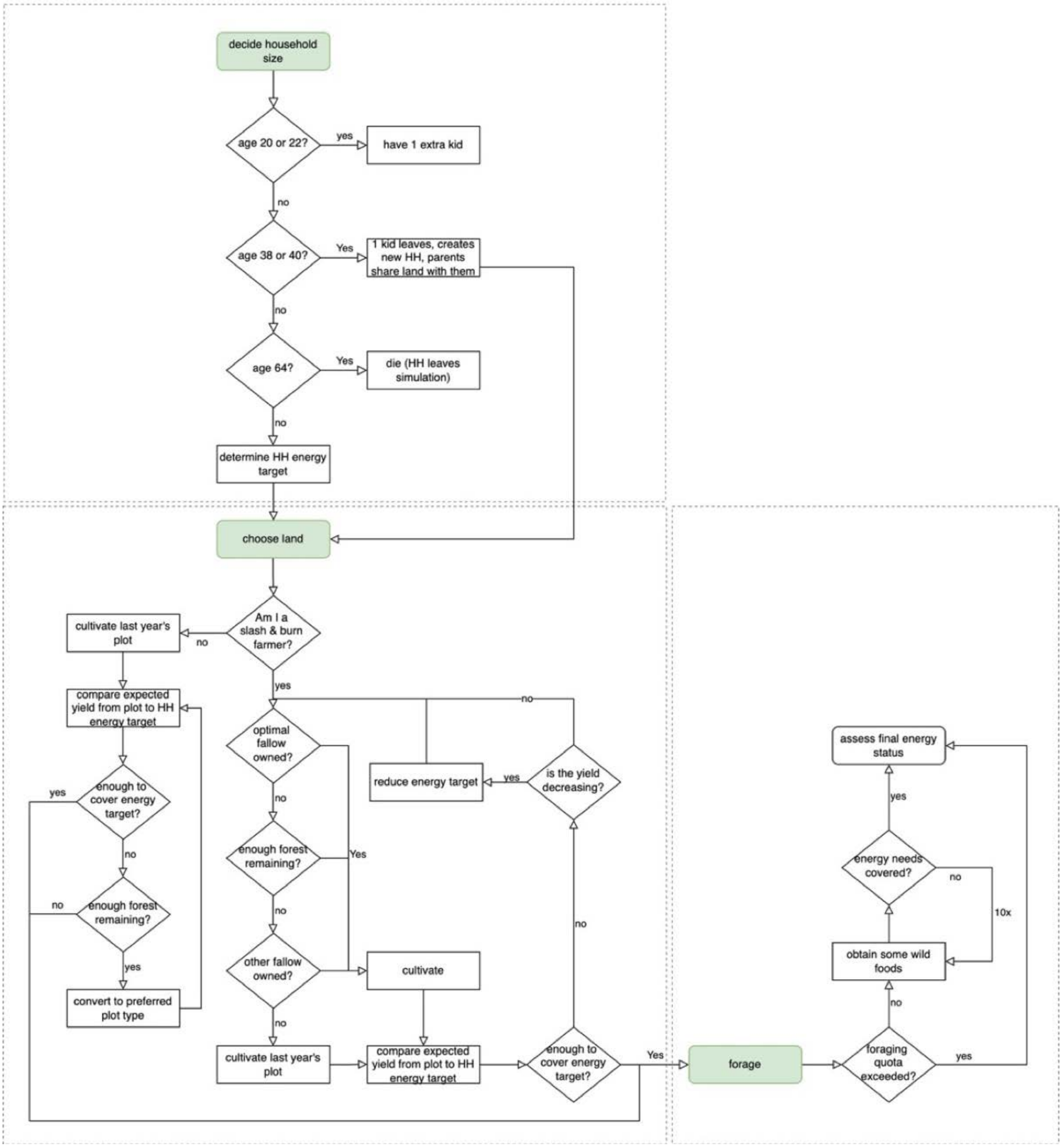


Figure 2: social processes represented in the agent-based model

Ecological processes

The causal links between specific biodiversity variables, ecosystem services and yield are represented in figure 3. The ABM is stylized and meant to capture the salient processes, based on literature scoping and expert knowledge. As such, the causal structure and equations in the model greatly simplified and abstracted the complex causal relationships between biodiversity and ecosystem services. During interviews, farmers also indicated observing a connection between forest cover and abiotic disruptions, notably precipitations, droughts and floods. In the model, landscape vegetation cover, rather than forest cover is used as an indicator of associated agrobiodiversity in the landscape, and impacts pollination and biotic and abiotic disruptions regulation. Fallows, while not primary forest, may also have significant vegetation cover and host significant biodiversity at landscape scale, and may thus contribute to ecosystem services (Klanderud et al., 2010). Similarly, agricultural plots with significant tree cover, such as agroforestry and complex home gardens also contribute to landscape scale ecosystem services (Rosenstock et al., 2019, Andreas Martin et al., 2021). Vegetation cover on a specific patch also impacts the same ecosystem services of pollination and biotic and abiotic disruptions regulation at patch scale, representing a stronger impact due to proximity. Soil biodiversity on a specific patch impacts biotic and abiotic disruptions mitigation as well as soil fertility. Biotic and abiotic disruption regulation occurs both through micro-environment modification and through improved crop health (Mujta et al., 2019; Bender et al., 2016). Finally, production diversity impacts biotic disruptions regulation and soil fertility (Tamburini et al., 2020). All biodiversity variables are percentages, assuming a maximum value in forests. Land use decision change them by a fixed amount, assuming that a percentage of biodiversity is lost in converting plots. Biodiversity values then linearly and additively impact ecosystem services values. For example, plot level abiotic disruption regulation is the sum of the values of patch vegetation cover, landscape vegetation cover and soil biodiversity, divided by 3. Soil fertility is slightly different, with soil biodiversity having an impact twice as large as production diversity. The amount of energy produced by a specific patch is computed in two steps. First, an expected yield is computed from the maximum energy achievable for a land-use type, multiplied by the sum of soil fertility and pollination levels. The achieved yield is obtained by subtracting the percentage lost to the remaining biotic and abiotic disruptions. Cultivating a plot through shifting agriculture removes all tree cover and divides biodiversity by two. Each year fallowed will allow both variables to recover linearly. By default, vegetation will recover over 20 years and soil biodiversity over 10, but this rate is reduced by a degradation variable. Cultivation-fallow cycles over 10 years will add 0.03, and cycles of 10 years and less will add between 0.1 and 1. These values were chosen to reproduce results from empirical studies of fallow dynamics conducted in that region (Pfund, 2001; Styger et al., 2007; Klanderud et al., 2010; Van Vliet et al., 2012).

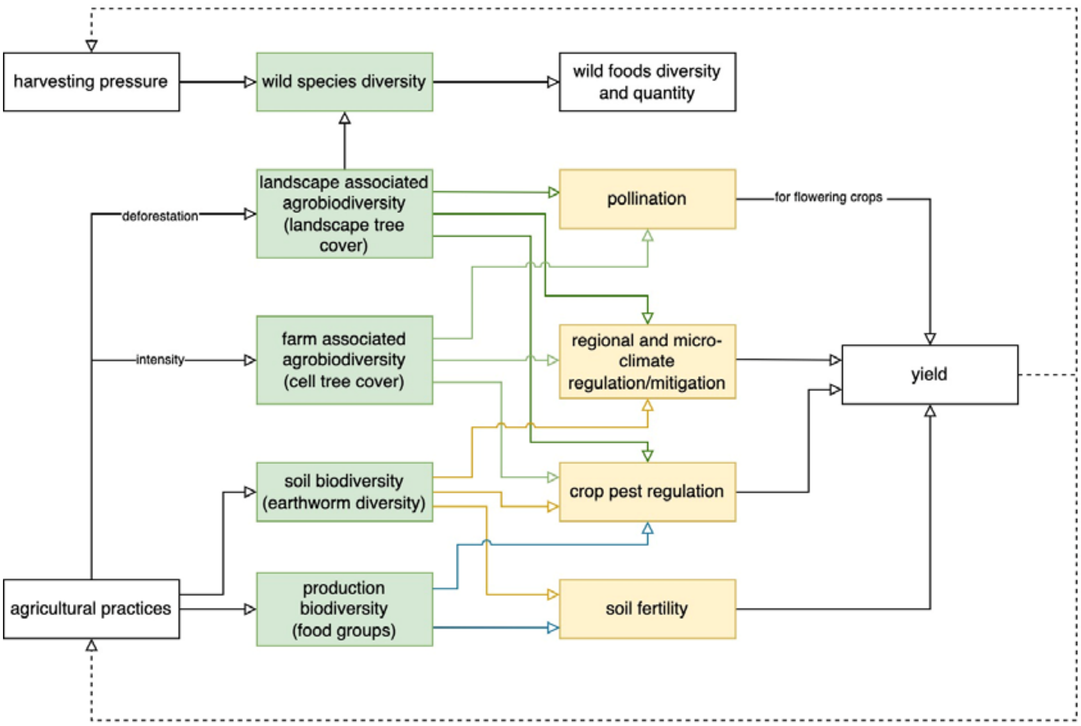


Figure 3: ecological processes in the agent-based model

Model behaviour

Impact of shifting cultivation at different population density

As stated in the objectives, the general hypothesis was that a reinforcing feedback loop between biodiversity loss and undernutrition might emerge with decreasing food availability driving people to resort to increasingly biodiversity damaging practices. To better understand current dynamics in rural eastern Madagascar, the model was first explored with a baseline scenario in which households resort exclusively to shifting agriculture, the traditional practice in this region. Population density levels, preferred fallow length, forest preference, and adaptation to decreasing yields were manipulated to assess their impact on biodiversity and undernutrition levels and the system dynamics more generally.

The model showed two distinct behaviours. With a low population density, a short period of expansion and forest cover loss was followed by a stable rotation among existing fallows, with stable and high nutrition and biodiversity outcomes, as long fallow length maintained soil fertility and vegetation cover, and good agricultural production limited foraging pressure on wild species. With a slightly higher population density however, the system quickly collapsed when land scarcity forced households to reduce fallow length (figure 4). Plots under shorter fallow cycles had lower mean vegetation and soil biodiversity value, but also became increasingly degraded, reducing their ability to recover. This created a dynamic of decreasing soil fertility and yields, even with a stable population. Because yields dropped, households had to put an increasingly large number of plots in production to cover their energy needs, further reinforcing this dynamic. This also reduced landscape-scale vegetation cover. The combination of increasing undernutrition and vegetation loss led to a quick loss of wild species and thus of diet diversity. When a population density threshold was exceeded, the system collapsed, and maintaining a stable population or allowing the population to grow had a marginal impact on biodiversity and nutrition outcomes. As such, the reinforcing process of soil degradation appeared to be a central causal process in this dynamic of biodiversity loss and undernutrition.

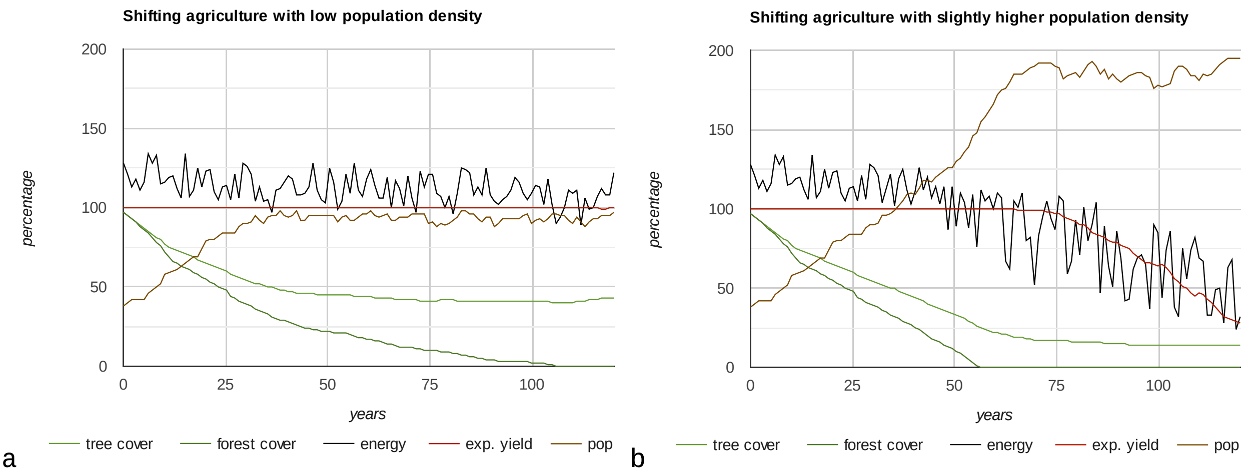


Figure 4: main outcomes with a population of 100 and 200 people practicing shifting agriculture.

Manipulating the preferred fallow length (i.e., the vegetation cover on fallows) with a low population density unsurprisingly affected the forest cover, as people cycled on smaller surfaces with shorter fallow length. Shorter fallows maintained the forest cover over a longer period, but had limited impact on landscape vegetation cover, as shorter rotations implied less vegetation regrowth on fallowed plots. Even with varying preferences the mean fallow length tended to increase to a similar value over time. Because shorter fallow length reduced yields, people progressively acquired new plots to achieve their nutritional targets, which then allowed them to increase fallow length. The system stabilised with fallows slightly above 10 years, which ensured adequate soil biodiversity regeneration. With a greater population density, preferred fallow length had no significant impact as household preferences were quickly constrained by land scarcity and trapped in the reinforcing dynamic of soil degradation.

Manipulating the preferred forest cover, that is the proportion of forest cover under which households would switch from expanding to reducing fallow lengths, led to a more gradual forest loss, maintaining forest cover over a longer period. This came at the cost of increased land-use intensity on agricultural land however, and the greater forest cover was negatively compensated by lower vegetation covers on fallows, leading to a limited improvement of landscape vegetation cover. This increased land-use intensity negatively impacted yields, which dropped earlier and worsened nutrition outcomes. Aiming to maintain forest cover under population growth thus appeared to come at the cost of agricultural outcomes and was eventually defeated by other households with lower preferred forest cover.

Manipulating fallow recovery pace had a large effect on biodiversity and nutrition outcomes. The default pace saw soil biodiversity recover over 10 years and vegetation completely recover over 20 years. Doubling or even quadrupling recovery pace significantly improved biodiversity and nutrition outcomes by reducing the area required by shifting agriculture and improving vegetation cover. This greatly reduced deforestation and wild species loss, while maintaining soil fertility. Improved agricultural production and vegetation cover also reduced pressure on wild species which helped maintain wild species in the landscape, thus also improving diet diversity.

Impact of forest conservation on biodiversity and nutrition

The model also aimed to assess whether conserving forested area and wild species might offer benefits to agricultural production through improved ecosystem services and improved energy and micronutrient intakes through a sustainable supply of wild foods. In the model, manipulating forest cover logically improved forest cover, as well as landscape-scale vegetation cover. Nevertheless, sparing land for forest reduced land for agriculture. Results discussed before highlighted the central role of land scarcity in the model, and increasing forest cover reduced the population density over which the reinforcing dynamic of soil degradation emerged. As a result, and contrary to expectations, ecosystem services were not improved. While vegetation cover was higher, soil biodiversity was degraded by increased land-use intensification, with an overall negative impact on soil fertility and a neutral impact on abiotic and biotic disruption regulation. Overall, nutrition outcomes worsened with increases in forest cover, due to the high sensitivity of the model to land scarcity (figure 5a). The negative impact of forest protection on nutrition could be mitigated by manipulating fallow recovery pace (figure 5b). Improving fallows reduced land constraints and additionally improved vegetation cover, thus improving ecosystem services. Intervening on forests and fallows in parallel might thus provide benefits to both biodiversity and nutrition. Without wild species protection forest conservation increased foraging pressure and led to the disappearance of wild foods, due to lower agricultural production.

Manipulating wild species foraging through quotas (i.e., allowing foraging only when wild species diversity was above a given value) was efficient in conserving wild species, as long as vegetation cover in forests or fallows remained, which only occurred with low population densities or with externally imposed forest protection. However, quotas had no significant nutritional impact on either energy intakes or diet diversity. While quotas maintained wild species and allowed some sustainable foraging, the quantities extracted were insufficient to provide significant benefits to a growing population (figure 5a). With a very low population quotas were unnecessary as high vegetation cover was maintained and sufficient agricultural production limited foraging pressure. The results related to forest conservation and wild species are based on fairly simplified mechanisms and parameter values and future model version will explore more realistic mechanisms and the impact of changing parameter values.

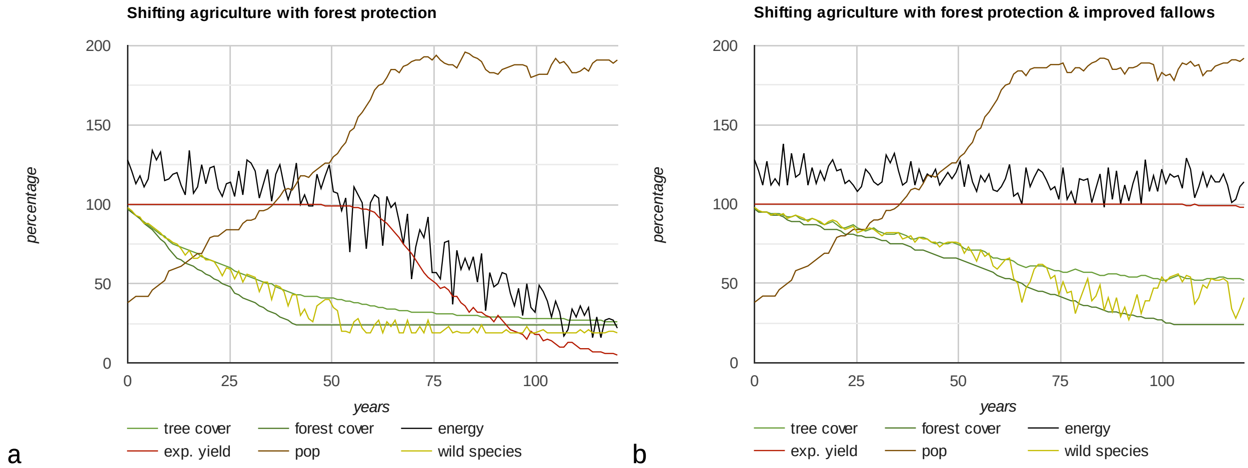


Figure 5: main outcomes with a population of 200 and 25% forest conservation & 20% foraging quotas, without (a) and with (b) improved fallows

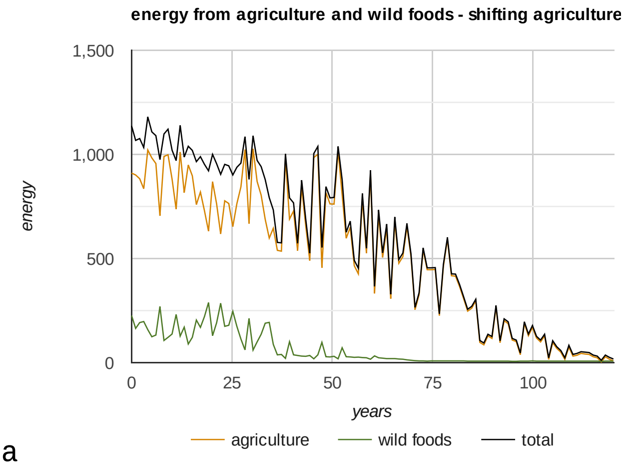
Impact of agroecological practices on biodiversity and nutrition

Finally, the model aimed to assess the impact of biodiversity-based improved agricultural practices on biodiversity and nutrition. Specifically, the model assessed the outcomes of a portfolio of SALT agroforestry, diverse home gardens, and rice paddies under the System of Rice Intensification (SRI) with fish, compared to a more traditional rice paddy monoculture. SALT agroforestry and diverse home-gardens have high production diversity and tree cover (Tasio, 1993; Mattson et al., 2018). They also have, as SRI, high soil biodiversity. SRI notably reduces flooding and seedling density, reducing anaerobic conditions and improving soil biodiversity (Stoop, 2011). These practices have been developed for low-income tropical smallholders, notably on slopped land, and where thus directly relevant for this model. The specific crops included in these portfolios (upland rice, cassava, peanuts, pineapple and banana for SALT; sweet potato, cassava, pigeon pea, avocado, chicken, and various vegetables for home-gardens; lowland rice and tilapia for SRI) are all commonly cultivated in eastern Madagascar. Thanks to their high soil diversity, production diversity and tree cover these practices have the potential to provide multiple benefits: improved diet diversity, improved ecosystem services and productivity, and improved biodiversity conservation (Thakur & Uphoff, 2017; Rosenstock et al. 2019; Galhena, Dissanayake & Maredia, 2021). The yields for all crops in the model were calibrated based on studies conducted in either Madagascar or other tropical countries. Average yields observed in field studies were selected, rather than maximum yields achievable under optimal management.

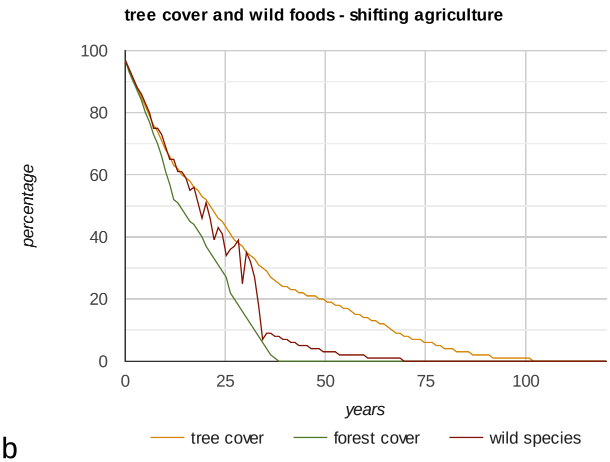
The model showed large improvements for all biodiversity and nutrition variables when farmers adopted these practices rather than shifting agriculture. Due to the strategic choice of crops in the portfolio, such a peanuts, sweet potatoes and bananas, and improved biodiversity values, energy productivity per ha cultivated was quadrupled compared to no-input upland rice under shifting agriculture, and without fallowed area households could produce sufficient food for their family on a greatly reduced surface. Whereas shifting cultivation of upland rice required 0.23ha of cultivated land and 2ha of fallow per capita to be sustainable, the agroecological portfolio only required 0.1ha per capita. Consequently, the landscape could accommodate a much larger population. These values are not surprising considering the large surface required for non-improved fallows and the very low baseline productivity of upland rice in eastern Madagascar. Forest cover could thus be retained despite a growing rural population. In addition, the large tree cover in agroforests and home-gardens provided ecosystems-services at both field and landscape-scale. These and the high soil biodiversity ensured a high and stable agricultural production, largely shielding it from both pest pressure and climatic fluctuations and ensuring adequate nutritional outcomes even when calibrating the model to large average disruptions (figure 6c and 6d).

The paddy rice only scenario could accommodate a similarly large population, households requiring 0.13ha per capita in the model. However, the model showed different behaviours at low and high population densities. At high population density, the lower soil biodiversity and the lack of production diversity and tree cover provided much lower ecosystem services, and generated much more volatile agricultural production, leaving households undernourished most years (figure 6e and 6f). At low population density, ecosystem services provided by forests and wild foods mitigated paddy production fluctuations and ensured adequate nutrition. The lower values of biodiversity in fields made paddy rice more dependent upon ecosystem services provided by forests, whereas the agroecological portfolio was more internally resilient thanks to high within-field biodiversity.

The agroecological portfolio also significantly improved diet diversity, for two reasons. Its vastly improved productivity, stability and vegetation cover allowed to maintain higher level of habitat and reduced foraging pressure, thus maintaining wild foods availability at higher population density. More importantly, the large production diversity ensured a stable and high diet diversity to households at all population density. Shifting agriculture and a paddy rice monoculture both have low production diversity and failed to maintain sufficient diet diversity with a growing population (figure 7).



a



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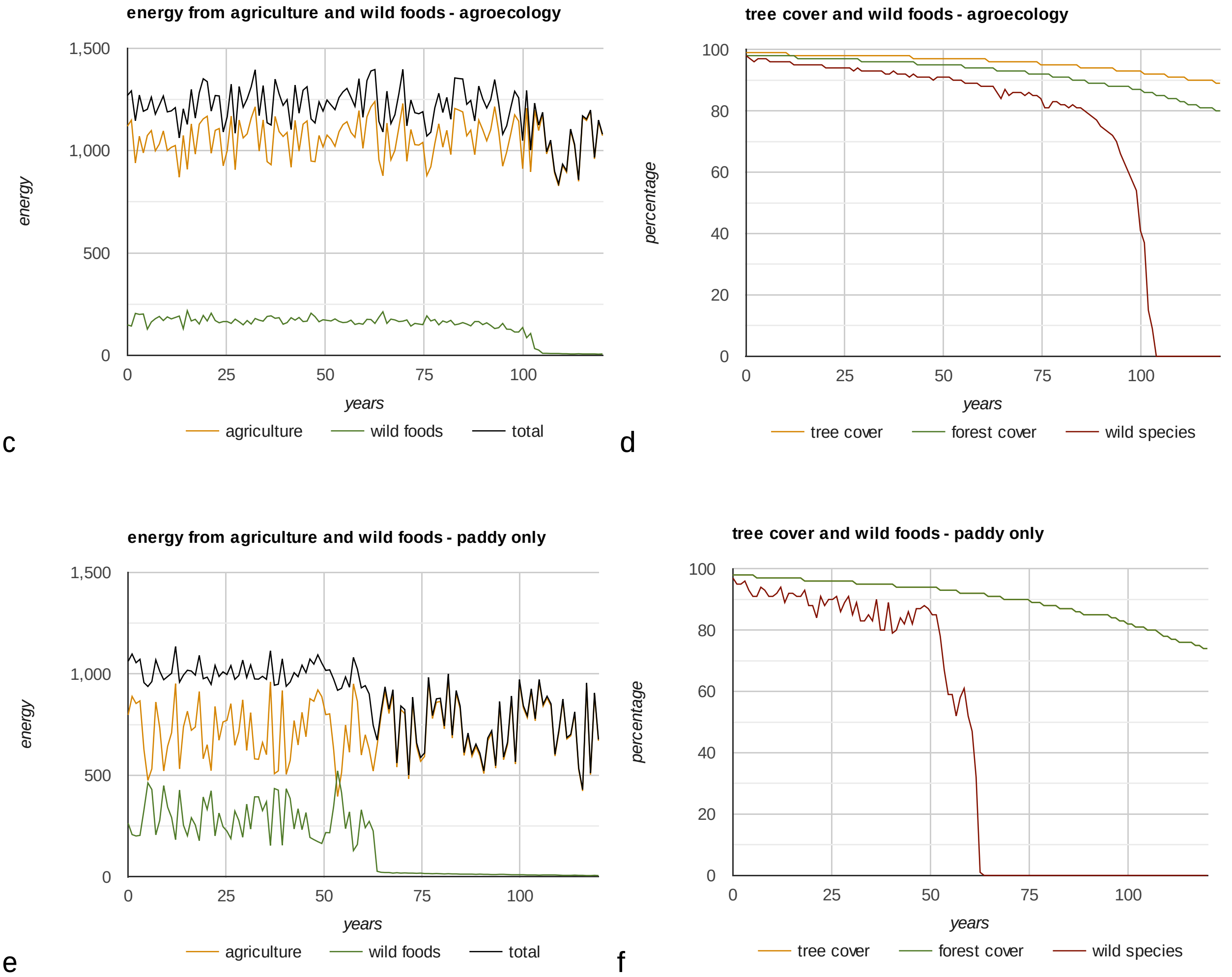

Figure 6: model results with a population growing from 40 to 840, and average biotic and abiotic disruption at 30% each. Energy is in thousand kcal; individual needs were defined at 876 (2400kcal*365). On graph f, tree cover and forest cover have the same value, thus only one line is visible.

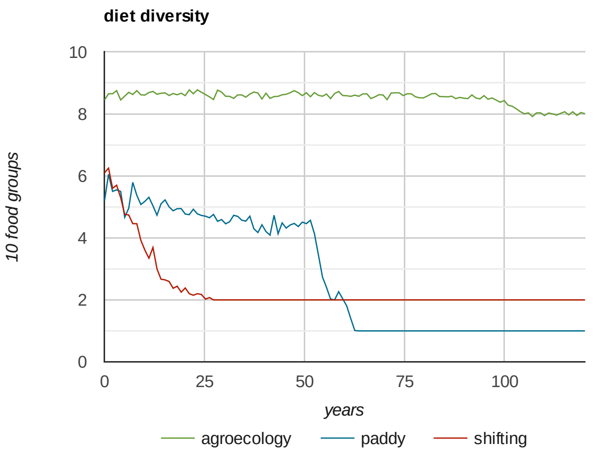

Figure 7: diet diversity under the three agricultural practices, with a 40 to 840 population.

Discussion

Interpretation of results

The model identified key social and ecological factors relating biodiversity and nutrition in eastern Madagascar and explored their dynamics, suggesting a potential explanation for the current dynamics of biodiversity loss and undernutrition in this context. As long as population density remained low, shifting agriculture ensured stable biodiversity and nutritional outcomes. With a growing population however, shifting agriculture quickly collapses due to the very large surface required for long fallows and the inability of the traditional system of shifting agriculture to function under diminishing fallow length. A pattern of reinforcing soil degradation emerges, generating large biodiversity loss and undernutrition, and leaving a barren, degraded, landscape. Wild foods quickly disappear due to falling agricultural outputs driving overharvesting and habitat loss. These results tie together and logically articulate the changes experienced by farmers interviewed, who noted a constant decrease in farmed area due to population growth and their great concern for increasing soil degradation and dramatically decreasing yields, which they linked to deforestation and decreasing fallow length. These results are in line with previous studies that noted that shifting agriculture was sustainable at low population density but environmentally damaging in higher population contexts (Van Vliet et al., 2012; Hauser & Norgrove, 2013; Mukul & Herbohn, 2016) and suggest mechanisms at play in this context: land scarcity locks smallholder farmers in a cycle of increasing intensification and soil degradation which causes both biodiversity loss and undernutrition by eroding ecosystem services.

Model results suggest the existence of a density tipping point that leads to system collapse when overreached, however the threshold depends on farmers' practices (preferred fallow length, adaptation to decreasing yields) and environmental conditions (soil fertility, fallow recovery pace) and contextual heterogeneity should thus be expected. These results suggest that, with the current high population growth Madagascar is experiencing, traditional rural food systems are threatened, with their loss of productivity possibly further increasing undernutrition. Farmer interviews and previous studies (Hanke et al, 2017) suggest that farmers are aware of this dynamic but lack social and financial resources to implement adaptive measures that would prevent or reverse this cycle of social and ecological degradation.

With a growing population, manipulating farmers behaviour in the model (preferred fallow length, preferred forest cover, adaptation to diminishing yields) only had limited impact on biodiversity and nutrition outcomes, suggesting a limited potential for interventions based on education in this context. Results suggest that maintaining fallow length or improving their regeneration could keep shifting agriculture functional at somewhat higher population density, helping to protect biodiversity and nutrition. In this context of low to no external input, soil fertility is a major limitation (Barret & Bevis, 2015; Sanchez, 2019) and improving fallow recovery pace had a large impact. Planting woody species that rapidly create biomass and regenerate soil fertility, such as legume trees and shrubs, may have significant impact while requiring limited practice change, thus potentially facilitating adoption. Improved fallows have shown good empirical results in other contexts (Partley et al., 2017; Mamuye et al., 2020).

While it was hypothesised that protecting forests and creating foraging quotas could improve both biodiversity and nutrition by increasing ecosystem services (Karp et al., 2013; Isbell et al., 2017; Dainese et al., 2019) and providing a sustainable source of diverse foods, current model results showed worsening nutritional outcomes with increased forest cover. The large sensitivity of the model to land scarcity meant that sparing land for forest forced triggered the dynamic of reinforcing soil degradation at lower population density. The loss of soil biodiversity negatively balanced the positive impact of increased forest on biotic and abiotic disruptions regulation and worsened soil fertility, negatively impacting yields. Previous studies suggested a positive impact on yield of maintaining some forest cover (Dainese et al., 2019; Garibaldi et al. 2021). They did not consider shifting agriculture however, and the problem of soil degradation central to this system. Future model versions will explore the impact of forest cover on agriculture in more detail and with more realistic and spatially explicit ecological processes. The calibration of the impact of foraging pressure and habitat loss on wild foods remains tentative due to limited data. The model also assumes a linear decrease in ecosystem services with decreasing forest cover, whereas the literature suggests that biodiversity might be non-linearly related to habitat size (Mitchel et al., 2014; Yang et al., 2020). Biodiversity and ecosystem services provision also appear to be related to landscape structure, i.e. the relative location of agricultural and forest patches, their size and their connectivity (Arroyo-Rodriguez et al., 2020). Including these processes could lead to different results and will be explored in future model versions. Additionally, the model has a fairly small spatial scale and higher spatial scales may not show trade-offs between food production and forest protection, especially on marginal land.

The agroecological intervention, due to its much higher productivity, resilience, and within-field biodiversity, provided great benefits to both biodiversity and nutrition, echoing a growing body of evidence on agroforestry, home gardens, SRI and agroecological practices more generally (Thakur & Uphoff, 2017; Rosnstock et al. 2019; Galhena, Dissanayake & Maredia, 2021). It was the only scenario that ensured high and stable energy and diet diversity. Rice paddy monoculture was also significantly more productive than shifting agriculture, but its lower within-field biodiversity made it significantly more vulnerable to biotic and abiotic pressure and thus agricultural production was much more volatile, generating some undernutrition. During focus-groups discussions, farmers also highlighted the particular vulnerability of rice paddies to climate shocks. The scenario with rice paddies only also led to poor diet diversity due to the rapid loss of wild species and the low production diversity.

Limitations and way forward

The results in this study reflect outputs of a non-finalized agent-based model. The model will be revised and extended based on the ongoing dialogue with stakeholders and experts. The stylized model reproduced the broad dynamics of biodiversity loss and undernutrition observed in eastern Madagascar but stakeholder validation would be needed to ensure that the model does so for the right reasons, and that the effect sizes are realistic. Further model calibration and analysis are also required to obtain rigorous results. Ecological processes in the current model are greatly simplified and the model will be revised to assess the impact of non-linear relationships between habitat loss and biodiversity loss, and spatially heterogeneous impact of ecosystem services, reflecting the limited range of species delivering those services. Trade-offs of forest conservation as well as dynamics of wild species and the impact of foraging quotas in the current model are especially uncertain and require further calibration, the exploration of alternative assumptions and mechanisms, and sensitivity analysis.

The large benefits provided by the agroecological portfolio appear less uncertain, notably as there is already a large body of literature demonstrating empirical benefits of the practices included. Nevertheless, these practices rely in great part on tree crops, which often take years to become productive, a delay not considered in the model. The model also does not explore the ability of these practices to work on already degraded soils, an important point to assess its practical usefulness in eastern Madagascar, and that should be explored in future model extensions. Another limitation is the absence of consideration of land tenure, labour and financial costs as well as access to planting material and technical knowledge, all known to be important adoption constraints (Meijer et al., 2015).

Another important limitation is the lack of economic aspects in the model. Focus-group discussions with farmers revealed that loss of wild foods and agricultural productivity was partly compensated by market foods, which are not represented in this model and would be necessary to fully assess nutritional status. They may also give rise to further complexity, as households might then have to resort to other environmentally damaging practices, such as illegal timber extraction, charcoal production, forest clearing for the benefit of external actors, or commercial wild meat poaching to buy foods (Helmut, Geist & Lambin, 2002, Hanke et al., 2017). The agroecological portfolio also only consider self-subsistence, even though cash crop production has been shown to have the potential to improve nutrition outcomes and are often integrated into agroforestry and home-gardens (Mohri et al., 2013, Rosenstock et al. 2019). Coffee, cocoa, vanilla and pepper are example of high-value shaded crops that could be added to such the intervention in the current model, for example intercropped with avocado and banana trees, and provide additional benefits.

While the model requires further development to contribute to the scientific literature, by articulating issues and processes related to biodiversity conservation, ecosystem services management, agriculture and nutrition, the model should already prove a useful tool for intersectoral dialogue with national stakeholders on the biodiversity-nutrition nexus, and contribute to the development of a common understanding of the problem and identification of synergetic solutions. The ongoing dialogue with stakeholders will contribute to the iterative model development. The model will be revised and extended, calibrated further, formally analysed and finally validated based upon both stakeholder perceptions and the ability of the model to reproduce empirical patterns based on evidence-based micro-level processes.

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