**ODD protocol for an agent-based model exploring the biodiversity-agriculture-nutrition nexus in Eastern Madagascar.**

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The model description follows the ODD (Overview, Design concepts, Details) protocol for describing individual- and agent-based models (Grimm et al. 2006), as updated by Grimm et al. (2020).

* Grimm, V., Berger, U., Bastiansen, F., Eliassen, S., Ginot, V., Giske, J., Goss-Custard, J., Grand, T., Heinz, S. K., Huse, G., Huth, A., Jepsen, J. U., Jørgensen, C., Mooij, W. M., Müller, B., Pe’er, G., Piou, C., Railsback, S. F., Robbins, A. M., … DeAngelis, D. L. (2006). A standard protocol for describing individual-based and agent-based models. *Ecological Modelling*, *198*(1–2), 115–126. https://doi.org/10.1016/j.ecolmodel.2006.04.023
* Grimm, V., Railsback, S. F., Vincenot, C. E., Berger, U., Gallagher, C., Deangelis, D. L., Edmonds, B., Ge, J., Giske, J., Groeneveld, J., Johnston, A. S. A., Milles, A., Nabe-Nielsen, J., Polhill, J. G., Radchuk, V., Rohwäder, M. S., Stillman, R. A., Thiele, J. C., & Ayllón, D. (2020). The ODD protocol for describing agent-based and other simulation models: A second update to improve clarity, replication, and structural realism. *Jasss*, *23*(2). https://doi.org/10.18564/jasss.4259

**1. Purpose**

The model investigates how different land uses affect synergies and trade-offs between food security, agricultural production, and biodiversity in a forest–agriculture mosaic landscape representing a prototypical rural landscape in Eastern Madagascar. It aims to simulate the interactions between land-use decisions by heterogeneous farming households (agents), forest conservation, ecological feedbacks, and demographic dynamics over time, under stochastic environmental conditions.

**2. Entities, State Variables, and Scales**

**Entities**:

* **Turtles (Households)**: Represent smallholder farming households.
  + Breeds:
    - tavy-producers (shifting agriculture),
    - paddy-producers (lowland rice monoculture),
    - diverse-producers (agroforestry).
* **Patches**: Represent 0.1-ha land parcels (grid cells) with defined land-use and ecological characteristics.

**Household Variables (turtles-own)** include:

* Demographic: age, children-number
* Energy metrics: energy-target, production-target, production, energy-from-plots, energy-from-forest, energy-from-conservation, food-stock
* Diet diversity: food-groups
* Behaviour: forest-desired

**Patch Variables (patches-own)** include:

* Land-use type: forest, S&B, paddy, garden, agroforest, fallow, degraded (agroforest and garden are 2 land uses for the broader agroforestry land use, allowing to divide crops between 2 different plots, ensuring realistic crop diversity levels)
* Ecological: soil-biodiversity, perennial-cover, pollination-service, climate-regulation, pest-regulation, production-diversity, soil-fertility
* Yield: expected-yield, achieved-yield

**Temporal and Spatial Scales**:

* Time step: 1 year
* Spatial extent: 5070 cells of 0.1-ha patches (5.07km2)
* Simulation duration: up to 120 years

**User interface**:

Une image contenant texte, capture d’écran, diagramme, carte

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**3. Process Overview and Scheduling**

At each annual time step, the following processes occur in sequence:

1. **Update global variables**
2. **Demographic dynamics** (population growth, household succession)
3. **Ecosystem payments** for forest conservation
4. **Determination of production targets**
5. **Land-use planning**: permanent agriculture (paddy, agroforest/garden)
6. **Shifting cultivation decisions**: plot reuse or forest conversion
7. **Harvesting and yield loss computation**
8. **Farmer movement** (for visualization)
9. **Foraging**: opportunistic and purposeful
10. **Fallow recovery and degradation**
11. **Farmer-level outcomes**: energy-per-capita, nutrition status

Optional emergency clearing (if starvation) and stop condition are also defined.

**4. Design Concepts**

**Basic Principles**:

* Captures trade-offs between conservation, production, and nutrition.
* Pathways between biodiversity levels in forest and agricultural patches, ecosystem services (climate regulation, pest regulation, pollination, soil fertility), and yields.
* Households respond adaptively to food insecurity via additional forest clearing, land-use intensification or foraging.

**Emergence**:

* Forest cover decline, foraged species diversity, land degradation, food insecurity, and dietary diversity emerge from household decisions and ecosystem feedbacks.

**Adaptation**:

* Households adjust plot numbers, fallow lengths, and foraging frequency in response to production shortfalls and conservation incentives.

**Objectives**:

* Maintain appropriate household energy intake per capita
* Maintain desired forest cover (if possible)
* Optimize fallow length and cultivated plot number to balance yearly production and long-term soil degradation

**Learning**:

* Not explicitly modeled; decision-making is rule-based with stochasticity.

**Prediction**:

* Households estimate energy targets using anticipated yield losses from biotic and abiotic disruption (sensing the average climate and pest regulation in their plots, simulating average losses farmer can expect without knowledge of the specific yearly level of disruption) and average soil fertility (simulating farmer knowledge of soil fertility in their plots from previous harvest).

**Sensing**:

* Households assess local land-use types, their own plots, and forest cover.

**Interaction**:

* Indirect via shared forest and biodiversity resources, and via changes in ecosystem services from landscape-level changes in biodiversity levels
* Foraging by one agent reduces wild food availability for others

**Stochasticity**:

* Climate and pest disruptions (optional stochastic distributions)
* Demographic variables (initial age, childbearing)
* Patch selection (randomized among options, e.g. farmers cultivate one of their plots with maximal fallow length)

**Collectives**:

* Farmers are grouped by production type but do not act as collectives, i.e. they act independently.

**Observation**:

* Key outputs: forest cover, vegetation cover, biodiversity, per-capita energy, food groups, yield, fallow recovery, etc.

**5. Initialization**

* Entire landscape starts as forest.
* Initial households of each type (tavy, paddy, diverse, depending on simulation configuration) are created at random locations.
* Global variables such as energy-needs, max-yield, and land-equivalent-ratio are set using empirical parameters.
* Patches are initialized with forest characteristics (high biodiversity, perennial cover, etc.).

**6. Input Data**

* No external input data are used during runtime.
* Initialization relies on empirical values embedded in the code (e.g., kcal needs, yields, forest-BD-loss-threshold).

**7. Submodels**

**7. Submodels (Detailed)**

**7.1. Update Globals (update-globals)**

This submodel updates global landscape and ecological state variables at the beginning of each time step:

* **Forest cover** (forest-cover): Fraction of patches with land-use = "forest".
* **Vegetation cover** (vegetation-cover): Mean perennial-cover across all patches.
* **Forest biodiversity** (forest-biodiversity): Determined by a non-linear threshold model:
  + If forest cover drops below a dynamic fc\_threshold (dependent on mean-tree-cover of non-forest patches), biodiversity drops rapidly.
  + Above the threshold, it declines slowly.
* **Disruption levels**: Stochastic or deterministic abiotic and biotic disturbance levels (abiotic-disruption, biotic-disruption), capped at a combined 100%.

**7.2. Demographic Dynamics (grow-population, have-kids, create-household)**

* Each household ages annually.
* At age 35, agents create a child household, generating population growth.
* Land is shared: ~50% of a household’s plots are allocated to the child via create-household, using spatial checks to prevent misallocation.
* At age ≥ 64, the original household becomes the 2nd child (simulating mortality and land sharing via a simplified process avoiding the destruction and creation of agents).
* The whole submodel 7.2 can be deactivated or capped at a specific population density level from the user interface, allowing to observe the impact of stable versus increasing population numbers.

**7.3. Conservation Payments (attribute-conservation-benefits)**

Implements **Payments for Ecosystem Services (PES)**:

* Global conservation benefit (conservation-benefits) scales with remaining forest cover.
* Divided proportionally among households by size (adults + children).

**7.4. Production target determination**

* Households set production targets based on their energy needs.
* Households reduce their production targets based on PES income.
* If climate-regulation decreases, production targets are raised to hedge against expected average losses.

**7.5. Land-Use Planning**

**a) Permanent Farmers, i.e. rice paddies and agroforestry (plan-permanent-land-use)**

* Includes paddy-producers and diverse-producers.
* Already-owned plots are cultivated first using cultivate-diverse.
* If expected yield is below target, new plots are cleared (nearest forest patches), until energy-from-plots ≥ production-target or forest conservation constraints are reached.
* If forest cover is below individual desired forest cover or landscape-scale forest protection %, farmers do not clear any forest patch.

**b) Shifting Cultivators (plan-shifting-land-use)**

* Attempt to reuse owned S&B plots (years-cultivated < desired-years-cultivated).
* If production is insufficient, they:
  1. Attempt to cultivate optimal fallows first (perennial-cover ≥ desired-fallow-state).
  2. If needed, clear forest or suboptimal fallows via choose-plots and choose-other-plot.
* If yield decreases, farmers adjust production target downward based on prior yield loss (yield-drop × yield-drop-adaptation). This allows farmers to balance energy needs and soil degradation (driven by short fallows) by accepting lower production levels to maintain longer fallows.

**7.6. Plot Cultivation**

**a) Permanent Agriculture, i.e. rice paddies and agroforestry (cultivate-diverse)**

* Updates:
  + land-use to "paddy", "agroforest", or "garden"
  + Ecosystem services: soil-fertility, pollination-service, pest & climate regulation
  + Biodiversity metrics: soil-biodiversity, perennial-cover, production-diversity
* Yield depends on:
  + Maximum yield (max-paddy-yield, etc.)
  + Soil fertility
  + Pollination services (only in agroforestry)
  + Land equivalent ratio for agroforestry

**b) Shifting Cultivation (cultivate)**

* Clears tree cover (perennial-cover = tree-cover-after-clearing).
* Soil biodiversity (soil-biodiversity) decreases by a proportion (soil-BD-loss-pace).
* Expected yield = max-S&B-yield × soil-fertility
* Ecosystem services depend on current biodiversity in each plot and the landscape (forest biodiversity)
* Color of patch is scaled by yield to visualize degradation.

**7.7. Harvesting (harvest)**

* **Yield losses** calculated:
  + plot-abiotic-impact = abiotic-disruption × (1 - climate-regulation)
  + plot-biotic-impact = biotic-disruption × (1 - pest-regulation)
* **Achieved yield** = expected-yield × (1 - (biotic + abiotic impact)/100)
* **Food stock management**: Food stocks serve as household-level buffers against temporal variability in agricultural yields and environmental disruptions. They are updated annually as follows:
  + **Stock accumulation**: When harvests exceed household energy needs, surplus energy is added to food-stock after accounting for post-harvest losses (food-stock-loss), simulating spoilage and non-food uses.
  + **Stock depletion**: When harvests fall short of needs, households draw from their food-stock to meet their energy requirements:
    - If stock fully covers the deficit, it is reduced accordingly.
    - If the deficit exceeds the stock, the stock is depleted and the household remains partially food-insecure.
  + **Impact on food security**: Food stocks stabilize consumption across years and prevent immediate undernourishment from single-year shocks.
* **Food group score** assigned based on household type and energy security:
  + tavy/paddy: up to 3
  + diverse: up to 6

**7.8. Foraging (forage)**

* Two types of foraging are implemented. Farmers forage only if edible-species-diversity remain > 0 and > foraging-quota (activated optionally from the user interface).
* **Opportunistic foraging**: All households obtain energy from foraging wild species depending on edible-species-diversity. Reduces edible-species-diversity by species-loss-per-foraging.
* **Purposeful foraging**: Triggered when total energy (from plots + PES + forest) is insufficient:
  + Repeated up to 8 times per year, but with only a third of benefits and impact of the opportunistic foraging, allowing for more granularity.
  + Reduces edible-species-diversity by 1/3 of species-loss-per-foraging.
  + Energy target drops with each iteration to simulate increasing foraging pressure from deeper food insecurity.
* **Food groups** increase from foraging:
  + tavy/paddy gain more (up to +4)
  + diverse gain less (up to +2) as they already cultivate most food groups
* **Wild food recovery** is density-dependent (faster recovery at higher diversity) and bounded by forest-biodiversity. This simulates the impact of foraging pressure and deforestation on wild species diversity.

**7.9. Fallow Recovery (recover-fallows)**

* **If degradation ≥ 0.7** → Patch is irreversibly degraded.
* **Else**:
  + soil-biodiversity recovery begins after 3 years fallow (soil-BD-recovery-delay)
  + Recovery speed depends on degradation and improved-fallow-rate.
  + perennial-cover increases continuously with a sigmoid growth function.
  + Yield potential increases as soil recovers.

**7.10. Nutritional Assessment (update-farmer-variables)**

* Calculates:
  + energy-per-capita
  + cultivated-plots and fallowed-plots
  + Color codes agents: (used for visual diagnostic)
    - Green: >95% energy needs met
    - Orange: 50–95%
    - Red: <50%

**7.11. Emergency Forest Clearance (clear-protected-patch)**

* Activated optionally via the interface.
* If energy-per-capita / energy-needs < 0.33, one forest patch is cleared (nearest), even if it violates forest conservation constraints.