FNNR ABM – ODD PROTOCOL

The ODD (Overview, Design concepts, & Details) Protocol for an agent-based model is a standardized document which outlines a model's purpose, variables, framework, schedule, and data. The format was conceptualized by a team of twenty-eight authors who had previously published or worked with agent-based models, and serves as a universal set of guidelines for describing a model (Grimm et al. 2006; Grimm et al. 2010).

1. Purpose

This agent-based model serves a variety of inter-connected purposes:

a) To simulate the demographic changes of humans living in the FNNR, including births, deaths, marriages, out-migration and re-migration. These changes are modeled on the existing human data gathered from the FNNR. Heads of household are also designated. Various other statistics, such as income level and education level, are projected as well. Finally, human age structures are recorded.
b) To simulate GGM movement within the FNNR in a movement sub-model, which follows seasonal patterns of migration to a mating area and avoids human settlements or low elevations. Movement is also weighted according to the nearby vegetation: monkeys are more likely to move to vegetation that they are modeled to favor.
c) To simulate human resource collection in the movement sub-model, which may impact the movement of humans upon GGM habitat.
d) To simulate Green-to-Grain Program (GTGP) enrollment or dis-enrollment and GTGP land conversion, which is based on factors such as current income and types of land owned.
e) To simulate the demographic changes of the Guizhou Golden Monkey (referred to henceforth as GGM) of the Fanjingshan National Nature Reserve (referred to henceforth as FNNR) over time, including births, deaths, formation of new families from a large group or of all-male groups, and mating behavior. Monkey demographic (age and gender) structures are also recorded.

2. Entities, State Variables, & Scales

Time - Each time-step of the model represents approximately 5 days. Therefore, every 73 steps of the model, the model "advances" one year. Individual processes such as birth, death, and adulthood are continuous, and may occur at any time-step once conditions are met. While not an entity in itself, the passage of time will trigger events, such as birth or the formation of new groups.

Table A.1 – Entities, State Variables, & Scales

Entity	State Variables & Attributes	Spatiotemporal Scales & Extents
Guizhou Golden Monkey (individual	Unique ID Age	Spatial: One pixel represents a family group of 20-50 monkeys,

agents in mostly-stacked collective) Monkeys are defined by families in the visualization submodel and by individuals in the population submodel.	Age Category Gender Birth Interval Family ID Family Size Mother ID Current Position Past Position Family Type Split Flag (if families grow too large)	which move together. Temporal: Monkeys have a lifespan of approximately 30 years. At 8 years, they become adults and can begin to mate.
Human (stacked collective, single moving agents) In the movement model, only heads of households move to collect resources.	Unique ID Age Gender Education Work Status Marriage Status Household ID Past HH ID (if migrated) Home Location Migration Status # of Migrated Years Migration Network Migration Remittances Resource Location Resource Frequency Current Position GTGP Participation (Household) GTGP Area (mu, Household) Off-Farm Income (Household)	Spatial: One pixel represents a non-moving household, each of which has zero or one human agents who is a fuelwood collector and a varying number of total human agents within it. Any human agents that travel will always return to their household pixel. Temporal: Like monkeys, humans age, sometimes reproduce, and die. Their lifespan and other variables are set in the model.
Environment (grid cell) Potential Subtype:	Elevation Vegetation Type	Spatial: The extent of the FNNR. Elevation is adapted from 30m raster DEMs, scaled down by 10

Household, Farm, PES, (Managed) Forest		to create a manageable grid. The sq. area of the rectangular grid containing the FNNR extent—that is, not the FNNR itself—is approximately 640 sq. km. One environmental grid cell represents approximately 275m in diameter, or 0.075 sq. km in area. Temporal: None, though the agents interact with the environment by avoiding areas of low or high elevations.
Land (GTGP Area; not shown in movement model)	Unique ID Household ID GTGP Participation GTGP Land Area (mu) GTGP Net Income (yuan) Total Land Income Head-of-Household Age, Gender, & Education Level Land Type (rice or dry) Land Travel Time Plant Type Household Size GTGP Dry Land Area (mu) GTGP Paddy Land Area (mu) Total Dry Area (mu) Total Rice Area (mu) Non-GTGP Output (yuan) Pre-GTGP Output (yuan) Non-GTGP Area (mu) Unit Compensation	Spatial: None Temporal: Every step, there is a small chance GTGP conversion will be checked. If it is checked, then there is a chance that a land parcel may convert to a GTGP or non-GTGP land parcel, which will affect household-level variables such as income or land type. This chance is based on a regression formula that includes factors such as land type, current household income, and unit compensation.

3. Process Overview & Scheduling

All agents move in a random order, which does not affect the processes within each step. The processes are carried out in the same order for every agent; for example, for individual monkey agents, the death check always occurs at the end of every step. Possible agent actions, which may be restricted by certain agent attributes such as gender or age, are as follows:

Model (Step 0 only): Create GGM family agents, monkey agents belonging to each family, human agents, land agents that refer to household-level lists that humans access, resource agents, and environmental grids

Land Parcels (each step, land submodel only): simulate GTGP conversion, update household income, update GTGP area changes from conversion

Humans (each step, movement/visualization submodel only): Head to resources, gather resources, head back to house, and randomly select another resource to gather

GGM Family (each step, movement submodel only): Avoid humans if paths cross, avoid areas of low or high elevation (seasonally), move to Yangaoping (breeding site), move away from Yangaoping, and move to neighboring cells according to a correlated random-walk (path determined by vegetation and elevation) as described by Ahearn et al. (2006).

GGM Individual (each step, population submodel only): Age, possibly give birth (if female and of age), possibly out-migrate to another group (depending on age, gender, and current group size—male monkeys may defect to an all-male group, and large families can split into smaller groups), and die

Human Individual (each step, population submodel only): Age, possibly give birth (if female and of age), possibly marry, possibly out-migrate (sometimes in a special case due to college, where they typically do not re-migrate from) and re-migrate, gain education levels, change work status, possibly change head-of-household status, and die

4. Design Concepts

Discussed here are the eleven design concepts of the ODD protocol: basic principles, emergence, adaptation, objectives, learning, prediction, sensing, interaction, stochasticity, collectives, and observation (Railsback & Grimm 2005).

Basic principles

Visualization submodel – This assumes spatial patterns among all GGM families, such as yearly migration to Yangaoping; movement patterns are also calibrated according to movement needs as determined by known travel speeds, vegetation preferences, and behavior around humans from the literature (Grimm and Railsback 2005, Yang, Lei, & Yang 2002). Because the model input is directly based on observations from a field study, the default output—a showcase of movement over ten years—is expected to be fairly predictable. What is new about this model is the comparison of its output—a point density map of its movements—to a Maxent model through Cohen's Kappa, and a discussion of how different versions of this model—based on

configuration settings such as GTGP unit compensation—may differ through a similar comparison.

Population submodel – This confirms GGM population structure observations from Yang et al.'s field study (Yang et al. 2002) by modeling changes to the population over ten years based on birth, mortality, and birth-interval rates per age category. It does not consider intermediate factors that are not currently well-understood by the literature, such as low genetic diversity and the impact of this phenomenon on birth defects or miscarriages, or whether or not closely-related monkeys can breed. However, it considers the observed patterns of male departure from groups and refreshed fertility after a recent loss of an infant. The population submodel also assumes a stable human age demographic, stable migration, and consistent birth, death, and marriage rates in relation to China's national averages.

GTGP conversion submodel – This assumes that households will enroll in GTGP given that they meet a certain threshold as determined by the regression formula, and that they are likely to revert after a number of years without compensation after the program ends.

Emergence

Visualization submodel – Avoidance of humans and human settlements may have more or less of an impact than expected; vegetation weights may more or less than an impact than expected.

Population submodel – Fertility "recovery" after loss of an infant may have more or less of an impact than expected.

GTGP conversion submodel – GTGP unit compensation may have more or less of an impact than expected; the model also does not account for any land area changes as a result of GTGP enrollment in the visualization submodel.

Adaptation

Visualization submodel – Family agents avoid less-desirable cells with human settlements and lower elevations, and choose their neighboring cell by weights determined by vegetation type.

Population submodel – Fertility "recovery" or the lessening of between-birth intervals, after the loss of an infant is an adaptive trait that female individuals may have.

GTGP conversion submodel – GTGP enrollment affects income and GTGP land area, which plays a role in future GTGP enrollment.

Objectives

Visualization submodel – GGM Family agents primarily avoid humans, move to ideal vegetation, and visit Yangaoping for breeding and giving birth. The human agents' only objective is to gather resources and return to their homes.

Population submodel – Adaptations—and therefore objectives—are more chance-based rather than individual-objective based. For example, human and GGM agents have a small chance of dying every step, which cumulates to a yearly mortality rate every 73 steps.

GTGP conversion submodel – Adaptations—and therefore objectives—are more chance-based rather than individual-objective based. For example, land parcels have a chance of conversion and adjusting household income every step.

Learning

This model does not have agents change their traits responsively as part of its process, but can be modified to do so using "self" variables. The closest feature it has is using the outputs of processes, such as increased income from GTGP conversion, to inform other future decisions.

Prediction

Agents do not estimate future consequences of decisions; decisions made are based on information available at the time, and often impact current decisions immediately thereafter, or on a cumulative basis.

Sensing

Visualization submodel – GGM Family agents sense the presence of humans gathering resources and human settlements, and will move so as not to overlap them. They also "sense" the vegetation and elevation around them.

Population submodel – Female monkey agents give birth at the correct ages, and if male, may migrate to other groups.

GTGP conversion submodel – Income and land parcel interaction affect each other, so higher temporary income may result in lower GTGP enrollment, which creates a negative feedback loop (lower GTGP enrollment may also temporarily lower income).

Interaction

Visualization submodel – Humans gather resources, but otherwise do not interact with GGMs. The model may be changed later, e.g. to implement a poaching behavior.

GGMs avoid humans, and will not move to occupy the same or sometimes even an adjacent pixel (each pixel is a 300-meter space) as a human agent.

Population submodel – if any monkey infant dies, its mother may give birth again the following year (a "recovery" of fertility), even though the normal birth interval rate is 3 years. Humans will gather resources less efficiently if they are marked as a resource-gathering household, but the head of the household/workers of age are currently migrated or die without a replacement.

GTGP conversion submodel – increased household income from GTGP conversion may result in higher out-migration rates; the end of the PES program will cause some households to revert their GTGP-enrolled land parcels.

Stochasticity

Visualization submodel – GGM agents move to their 8-cell (diagonal and adjacent) neighbors according to a weighted choice, which in turn is informed by the vegetation type of each neighbor. Males can also travel between groups or form an all-male group when of a sufficient age.

Population submodel – For both monkey and human agents, births and deaths are random chances determined by a birth-interval rate or yearly rate.

GTGP conversion submodel – A weighted-probability-based formula decides whether or not a land parcel converts to GTGP, which in turn affects human household income.

Collectives

In both the movement and population submodels, GGM individuals belong to a family; occasionally, all-male families can break off.

Land parcels belong to a household collective, which humans also belong to; the collective is accessed via lists, so there are no household agents.

Observation

The output of the movement model is a .csv file of all points that individual agents traveled to, from which a heatmap or point density map may be generated.

The output of the population submodel are .csv files tracking changes in the population and age/sex structure over time.

The output of the GTGP conversion submodel is a .csv file of non-GTGP and GTGP land parcel counts, areas, and household income tracking.

5. Initialization

All initial values for humans and GGMs are either taken from Yang et al.'s 2002 field study of the GGMs (in the case of population structure rates), or from data which was gathered as part of the greater FNNR project (in the case of environmental, resource, or human household data).

Visualization submodel – Initial settings (number of years the model runs for, number of monkey families, GTGP compensation structure, PES program span, etc.) are set by the user in fnnr_config_file.py before running the model.

Population submodel – Each family group contains 25-45 agents, and in total, there are between 600-900 monkeys in the reserve (very likely 650-750).

GTGP conversion submodel – Income is determined at the start by current land income and off-farm income combined. Some land parcels are already enrolled in GTGP.

6. Input data

Table A.2. – Input Data Sources for Each Variable

Entity	Input Data	Data Source
Guizhou Golden Monkey	Seasonal movement behavior (qualitative), birth rates, death rates, birth-interval rates, group-migration or infant-loss behavior (qualitative)	Field study (Yang et al. 2002), other literature
Humans	Household locations, birth rates, death rates, marriage rates, education rates, regression factors for migration probability, income levels, age/work status/gender/education levels for current FNNR residents	FNNR Project at SDSU
Resources	Resource location Resource type	FNNR Project at SDSU
Environment	Vegetation map DEM (digital elevation model)	FNNR Project at SDSU; vegetation categories map and DEM processed by Cindy Tsai (2017)
Land Parcel	Regression factors for GTGP conversion, current area/land type/land travel time for current FNNR land parcels	FNNR Project at SDSU

7. Submodels

The processes for the three submodels are outlined here.

Step 0 – all agent and environment types (families, individual monkeys, humans, resources, land parcels, environment) are parametrized and created.

Visualization submodel ordered priorities for GGM family agents:

1. Avoid humans and human settlement buffers (cannot enter certain occupied cells or face lower random odds of entering weighted cell).

2. Head to or from Yangaoping if it is directly before, during, or after mating season or birthing season (e.g. September, or steps 46-55 in a year of 73 steps).

3. Avoid certain low or high elevations. If traveling to or from Yangaoping, they may temporarily pass through those cells.

4. Move to neighboring cells (usually 5-10 times in a step to match the distances covered over five days, or one step, as noted in the literature) based on a random choice affected by weights assigned to each neighbor, which in turn is determined by one of nine vegetation types: mixed, broadleaf, deciduous, conifer, bamboo, shrublands, lichen, clouds (usually random; artifact from classification process), or farmland.

Visualization submodel ordered priorities for human agents:

1. If at home, choose a random resource from an imported list of resources their household gathers, and head towards the resource in a shortest-distance path.

2. Once at the resource, head back home to deposit the resource, and repeat the process.

Since humans gather resources faster than the time resolution of the model (one time-step represents 5 days), the visualization will show human agents "jumping" back and forth between resources up to each step; however, the coordinates traveled along the paths are recorded.

Population submodel for GGM individuals:

1. Face a low-level mortality rate each five-day step (slightly less than the yearly mortality rate divided by 73, since 73 * 5 = 365 days in one year, because of compounding probability). Mortality rates differ by age category.

2. If female and of age, birth interval increases every step; if it exceeds 3 (with no recent infant loss), give birth. If it exceeds 1 (recent infant loss), also give birth. Once a female has given birth, their birth interval resets to 0, and builds up again over time.

3. If male and of age, and if enough are "flagged" by a low-level chance once they reach of age, an all-male group may break off, and males will change families.

4. Each step, population dynamics are recorded (in some versions of the model; other versions only record the first and last step), and at the final step (ten years = 730 steps; twenty years =

1460 steps), a .csv file is generated. This file includes the starting/ending population and average age/sex structure of the population.

Population submodel for Human individuals:

1. Face a low-level mortality rate each five-day step (slightly less than the yearly mortality rate divided by 73, since 73 * 5 = 365 days in one year, because of compounding probability).

2. Every step, there is a low chance a new baby will be born. If that chance is met, a random married female who has not given birth in the last two years will be selected to bear a child, and the household size will increase. Once a female has given birth, their birth interval resets to 0, and builds up again over time.

3. If single and of age, there is a low chance of marriage occurring every step. Divorce is not accounted for in the model.

4. Miscellaneous variables such as education and work status update semi-randomly depending on other weighted factors such as the person's age.

5. Humans may migrate out or re-migrate back if they have migrated. These are based on regression formulas that consider gender, age, income, migration networks, ratio of land owned to laborers in the household, and education level.

6. Migration changes who is designated as the head of the household, which may in turn impact resource gathering (alternative heads of households, especially if not of age, may gather resources more slowly).

7. Each step, population dynamics are recorded (in some versions of the model; other versions only record the first and last step), and at the final step (ten years = 730 steps; twenty years = 1460 steps), a .csv file is generated. This file includes the starting/ending population and average age/sex structure of the population.

GTGP conversion submodel:

1. Each step, a small probability for GTGP enrollment or dis-enrollment is evaluated for each land parcel. This is based off a formula that considers the head of the land parcel's household's gender, age, education, and income. It also considers the time taken to travel to the parcel from the household, the land type, and the number of humans in the household (household size).

2. Non-GTGP land area, GTGP land area, and household income (for all land parcels of that household) are updated to reflect changes from GTGP enrollment.

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