Supplementary material

Appendix I - ODD Protocol

Overview

Purpose

The main goal of this model is to simulate the dispersal process of three species of marsupials with specific perceptual range and movement parameters (Didelphis aurita, Philander frenatus, Marmosa paraguayana). We expect to comprehend how these factors influence dispersal using empirical movement parameters from each species. Besides, we also look for the impact of landscape composition, such as habitat amount and fragmentation ("clumpiness"), and the presence of stepping stones, as small fragments and scattered trees, to functional connectivity.

Entities, state variables, and scales

The landscape

The environment is composed of fragmented landscapes that consist of habitat patches, stepping stones (small patches and scattered trees), and a matrix of pasture (non-habitat). We used 100 simulated landscapes consisted of a cell grid of 1024 x 1024 (-512,+512), and each cell size representing $10m^2$. Landscape composition varies by the percentage of habitat amount, from 5 to 70%, and "clumpiness" (degree of clustering, opposite of fragmentation), from 15 to 100%. We classified the types of cover by their size: habitat patches, which are fragments bigger than 5 hectares, small patches (5ha < $20m^2$), and scattered trees ($20m^2$ - 2 cells). Then, we generated four different landscape scenarios: habitat patches only (HAB), habitat patches and small patches (HAB_SP), habitat patches and scattered trees (HAB_ST), and habitat patches, small patches and scattered trees (HAB_SP_ST). We also generate layers of identification of all forest covers (habitat patches, small patches and scattered trees) and distance of each point of the matrix to the near forest remnant. Each patch (pixel) is characterized by cover type, identification (ID), distance from others forest patches (DIST). We generated the layers used in the simulation at GRASS GIS (Neteler et al. 2012) as ASCII format, and import these to the Netlogo environment.

The patches are characterized by the following state variables:

- *Cover* - referring to the type of cover of each patch. The values were defines as following: Habitat patches = 1, Small patches = 2, Scattered trees = 3, Matrix = 0.
- *Distance (DIST)* - referring to the distance value of each patch from the near forest edge. The value is positive on the matrix and negative within the forest patch. This value of distance was calculated separated for habitat patches, small patches and scattered trees. For each type of cover, we imported one layer with DIST values.
- *Identity (ID)* - referring to the identification of each habitat patch, small patch, and scattered tree. For each type of cover, we imported one layer with ID values.

The following patch-sets were created:

- *Fragment set* - all patches with cover = 1;
- *Border_patches* - all matrix patches (cover = 0) on the edge of habitat patches (cover = 1).
- *Border_ss* - all matrix patches (cover = 0) on the edge of small patches (cover = 2).
- *Initial_border_patches* - all matrix patches (cover = 0) and distance from habitat patches greater than agents perceptual range value. In cases which the landscape has too much habitat cover, there was no way to create the *initial_border_patches. In these cases,* we just create a patch-set with at most 10000 patches with the greatest distances from the habitat patches.

The agents

Each marsupial agents is characterized by the following state variables:

- *Identity (turtle)* - identification of each individual;
- *Specie* - referring to the specie name
- *Life* - if the individual is alive (1) or dead (0);
- *Perceptual range (PR)* - referring to the radius (meters) of the circular area around the individual, where it can perceive elements of landscape and became oriented to that element. The perceptual range values are species-specific and were defined by values obtained empirically by Forero-Medina and Vieira (2009);
- *Source* - referring to the fragment where the individual came from to start a movement across the matrix. That fragment is the near habitat patch of the agent defined after place each individual on a random patch from the patch-set initial_border_patches*;*
- *Actual cover* - the cover of the patch where the agent is located;
- *Location (x and y coordinate)* - spatial location of the individual, which is variable on time;
- *Oriented (type of movement)* - if the agent movement is oriented towards any patch or tree (value 1), or non-oriented (value 0). Each movement is based on distinct parameters from Uzeda (2017), and it is species-specific;
- *Turning angle* - referring to the previous turning angle used to calculate next location;
- *Absolut angle* - referring to the absolute angle realized on the previous movement step;
- *Step length (l)* - referring to the previous step length used to calculate the next location;
- *Distance total* - referring to total distance realized by each agent across the landscape;
- *Mortality distance* - as explained later on the sub-model **To mortality**, after each 100m realized by an agent, is calculated its chance of mortality. This distance variable is calculated until complete more than 100m, then the chance of mortality is calculated. If the individual survived, the Mortality distance discount 100m from its value, and keep counting as the agent moves;
- *Count mortality* - referring to the total times each agent has a mortality chance tested;
- *End fragment* - the final habitat patch reached by an agent after a successful dispersal movement across the matrix;

- *ID* - Identification value defined at each time the agent reach one of forest elements (habitat patches, small patches or scattered trees). This value is defined by the ID of the forest element reached;
- *Prev_ID* - Identification value of previous forest element encountered by each agent.

Process overview and scheduling

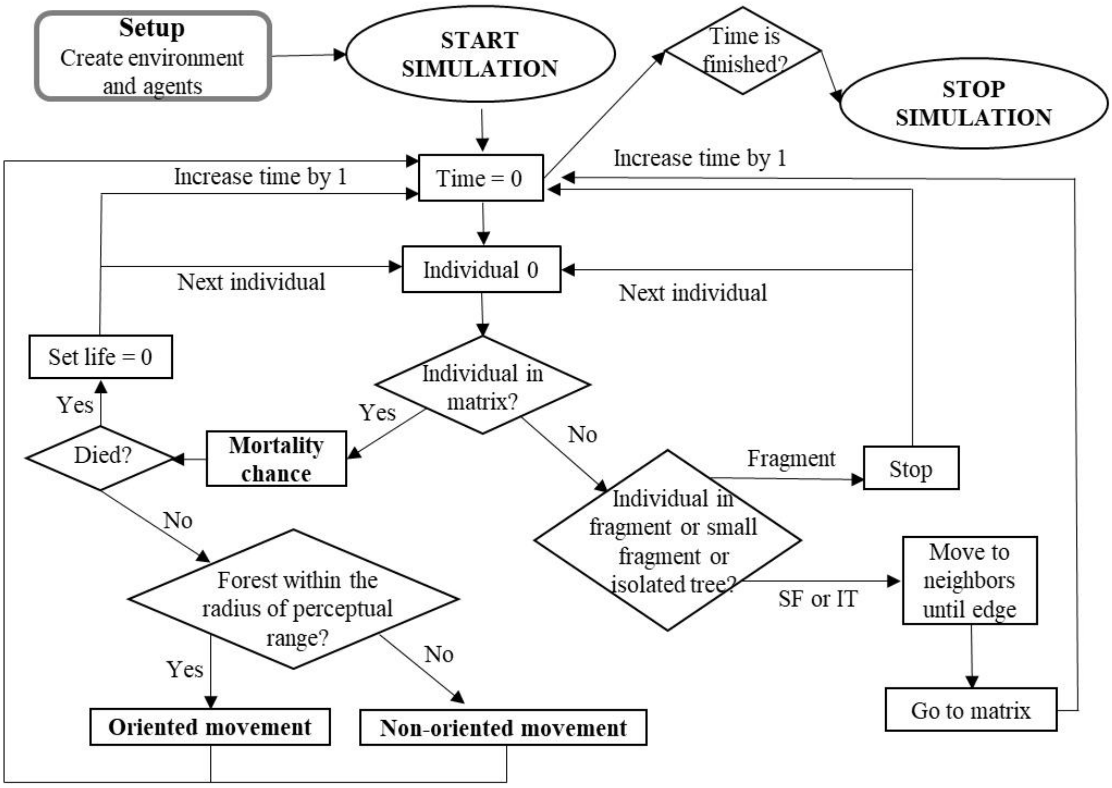

Figure 1: Flow diagram of the model.

The flow diagrams in Figure 1 details the model processes and its schedule:

1. The 'setup' create the environment and the agents;
2. The simulation starts with t = 0;
3. Within matrix agents' new locations are calculated by their step length and turning angle distributions. The distributions are specific to an oriented and non-oriented movement. If there is a forest within the radius of perceptual range, then the movement is oriented; if there is not, the movement is non-oriented;
4. In the oriented movement, if the near forest is a small patch, then the movement is oriented until the agent arrived at the small patch. After that, it moves to neighbour cells, until reaching the edge of the patch. Then, he moves to the matrix and keeps dispersing;

5. If the near forest is a scattered tree, then the agent moves directly to it. After that, it moves to a matrix location at a specific distance to avoid a return, then he starts again the movement across the matrix;

6. If the near forest is the source fragment, then the individual move to matrix again. If that occurs after agent move a distance > 1km then he concludes the dispersal movement. If it is a different habitat patch, then agent stop movement regardless of the distance realized;

7. Each agent movement stops only if they arrived in a fragment and establish. However, the simulation stops after 10000 ticks, and if the individual hasn't arrived at any fragment, he dies.

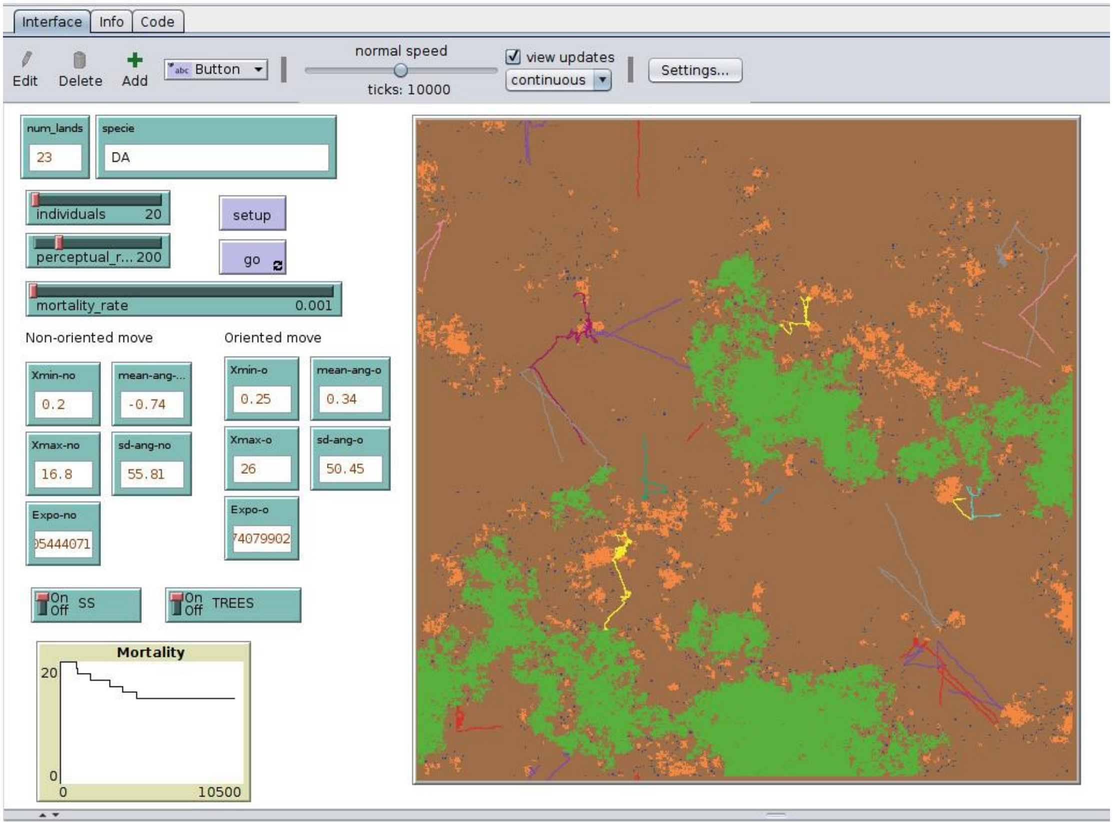

Figure 2: A simulation example in NetLogo. The landscape is composed of matrix (brown), scattered trees (purple), small patches (orange) and habitat patches (green). The model allow the user to fill each box with all the information needed, such as specie, landscape, parameters of movement, and presence of stepping stones and scattered trees. The color lines represent trajectories of each individual. The graph shows how many individuals died during the simulation.

Design concepts

Basic principles

The model intends to understand factors that may influence the success of dispersal across wide fragmented landscapes. The dispersal movement is a result of the animal's ability to move across a landscape and its responses to the landscape composition, configuration and its elements. The movement ability of animals is specie specific and its influenced by several characteristics. The individual makes many decisions during the dispersal movements, which are influenced by what the organism perceives about the landscape. Therefore, in this model, beyond the variety of movement patterns among species, we have considered the perceptual range as one essential individual factor which affects the dispersal success. Besides, the dispersal success depends on the animal's responses to the landscape, which influences on the habitat availability, mortality risks, clues to movement, and other factors. Moreover, this model aims to simulate the interactions among these factors and comprehend its effects on the dispersal process.

Emergence

The parameters implemented to simulate short movements allow the forethought about movement patterns in long-distance movement across the landscape, such as dispersal. The movement patterns and dispersal success are the main emerging result of the individual behavioural responses to the landscape composition, configuration and its elements, such as stepping stones and scattered trees.

Adaptation

Marsupial agents' decision-making about where to move is related to the landscape and its elements, change their movement parameter, or direction. Its decision-making is influenced by the specie's perceptual range, which is the distance where it can perceive elements of the landscape. Besides, when the agents perceive any landscape elements, such as scattered trees, stepping stones or habitat patches, they become oriented towards the elements to avoid the higher mortality risk within the matrix.

Objectives

The main objective of an individual is to complete the dispersal movement by reaching another habitat patch to settle. At short term, the goal of the agents is to move across the landscape been oriented by its elements and by using these elements, therefore, reduce mortality risks faced in the matrix.

Learning

The marsupials can remember the identification of the last element (scattered trees, small patch or habitat patch) and consequently avoid to return to it soon after leaving it. Also, the individuals avoid settling on the same fragment source, where they initiated the movement. That is consistent with the premise that the individual is searching for a new habitat to establish. However, in some cases, the fragment source is a large patch. Then, the individual stops avoid the fragment source after it moves more than 1km (explanation is presented on the paper).

Prediction

The implemented decision-makings are based only on the orientation throughout the movement. The agents are not able to estimate the future consequences of their decisions.

Sensing

Agents can identify habitat patches, stepping stones and scattered trees within their perceptual range radius. The individuals are also able to identify what type of cover is the patches within its perceptual range.

Interaction

Interaction among individual was not implemented on this model. Each agent moves independently others.

Stochasticity

The model has probabilistic events (for instance, mortality), and also, the initial locations are random, and the composition of the landscape is also random. Besides, the movement result from a behaviour response to the landscape brings more stochasticity to the model.

Collectives

As the agents are independent for each other, no aggregation or collectives is implemented on this model.

Observation

The focus of that model is on analyzing the factors that influence the success of dispersal and the patterns of dispersal movement. To reach that, the output gathered by simulations includes trajectories for each individual, total distance realized, type of movement (oriented or non-oriented), step length, turning angle and absolute angles, and success of dispersal by knowing how many individuals survived and reached a new fragment.

Details

Initialization

At time 0, agents are placed randomly at a forest patch and save their coordinates as 'start-patch', and the fragment identification as 'source'. Then, they are moved to a random location within the matrix with distance bigger than its perceptual range, to avoid an immediate return to fragment source. The landscape may present any combination of the cover types, such as matrix, habitat patches, small patches and scattered trees. The presence of each of these landscape elements is dependent on the scenario chosen.

Input data

The movement data, including parameters for step length and turning angle distributions, was obtained by (Uzeda 2017) and perceptual range values were obtained with fieldwork by (Forero-Medina and Vieira 2009). The simulated landscapes were generated using the QRULE program (Gardner and Urban 2007)

<u>Sub-models</u>

Setup

To create the environment, three types of files are uploaded. The first type of file defined the cover of each patch (matrix (0), habitat patches (1), and stepping stones - small patches (2), scattered trees (3)). The second type defined the identification of each forest patch and is composed by three layers, each one related with the identification (ID) of each type of cover (ID of all fragments, ID of all small fragments and ID of all scattered trees). The third type of file defined the distance of each location within the matrix to the forest patches (DIST) and it also is composed by three layers (a distance of habitat patches, small patches, and scattered trees). Then, each patch has also a value of cover, ID, and DIST of each of forest patches. To create agents, locations are randomly chosen, the perceptual range value is already defined by species.

Move

The movement is classified in oriented and non-oriented: oriented if there is any forest patch within the perceptual range radius; non-oriented otherwise. The parameters used to define the movement rules are based on step length and turning angle distributions. The first one, follows a Pareto truncated distribution, with three parameters: the maximum step length (l_max), the minimum step length (l_min) and power-law exponent (μ). The second distribution follows a Gaussian distribution with two parameters: standard deviation (Sd) and mean. All parameters were estimated empirically by Uzeda (2017).

At each step, values of step length (l) and turning angle (θ) are collected by those distributions, and a new coordinate is calculated, the x value is defined by the multiplication of step length (l) and sine of an absolute angle (ang = previous angle + θ) added to previous x value (xcor + (l * sin(ang))) and y values are defined by the multiplication of step length (l) and cosine of the absolute angle (ang) added to previous y value (ycor + (l * cos(ang))). Values of step length obtained by the distribution is in meters and considering that each cell at the simulation represents 10m, the value of l must be divided by 10, to allow the calculation of the new coordinates. At the end of each step, if the mortality distance > 100m, then mortality is tested (explained in the next topic).

Mortality

Individuals calculate a mortality distance, that is calculated by adding each step realized. When that distance is more than 100m, a random number between 0 and

1 is sorted, and if that number is less than the mortality rate, then the individual die. If the random number is larger than the mortality rate, the agent keeps moving. After that, 100 is subtracted from the mortality distance, and it starts to add values again. Agents face mortality only in the matrix. We defined mortality rate as 0.01.

In fragment (habitat patch)

When an agent arrives at a habitat patch (>5 ha), if the ID of the patch is different from the ID of source fragment, or if the agent already realized a distance > 1km, then he should stop the dispersal. If the ID is similar to the ID of source fragment and distance realized < 1km, then he comes back to matrix e keep dispersing.

In small patch

When an agent arrives at a small patch (< 5ha), the cover is defined as 2, and mortality distance is 0. The agent moves to neighbour cells until reach the edge. Then it is placed in a location within the matrix at a specific distance from the small patch used. That is done to avoid an immediate return to the previous location and allow the agent to start to move in the matrix. That distance to be placed within the matrix again is counted for calculating mortality distance.

In trees

When an agent arrives at a scattered tree, the cover is defined as 3, and the distance to calculate mortality is defined as 0 and starts to count again. After that, the agent is placed again in the matrix.

References

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