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ENHANCING ECOLOGICAL EDUCATION: UTILIZING AGENT-BASED MODELING TO SIMPLIFY THE IMPACTS OF DEFORESTATION ON AMPHIBIANS

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Abstract. Understanding how deforestation and changes in habitat boundaries affect biodiversity is essential for developing conservation solutions. These topics are central to biology and ecology programs, where students learn to apply their knowledge in real-world conservation efforts. Higher education plays a crucial role in strengthening this understanding, particularly in life sciences programs. Given the complexity of ecological processes in altered landscapes, agent-based modeling provides an interactive and engaging way to simplify and visualize the effects of land use changes. In this study, we integrate Amazonian anurans, highly sensitive to temperature and humidity fluctuations, with an Agent-based model to simulate the impacts of deforestation, habitat restoration, and land abandonment on species survival and movement. Their ectothermic nature and dependence on pulmocutaneous respiration make them especially vulnerable to the drier and more variable conditions caused by deforestation. Integrating this model into conservation biology courses has enhanced learning by encouraging independent exploration, both in and out of the classroom. This tool, an agent-based model, is particularly suited for university-level ecology and conservation courses, and can also serve as an effective awareness tool in environmental education and decision-making workshops, highlighting the negative effects of human-made habitat changes on biodiversity.

Key words: Agent-based modeling, landscape transformation, education classroom, edge effect.

Introduction

Habitat loss is one of the leading causes of species extinctions worldwide (Arroyo-Rodríguez et al., 2020; Didham et al., 2012; Tscharntke et al., 2012). When native forest is cleared for agriculture or other human activities, the newly formed forest edges expose species to novel environmental conditions for which they may not be adapted (Ries et al., 2004). These edge effects result in an ecotone between agricultural land and the remaining native forest patches, characterized by abrupt changes in temperature, humidity, and light that can significantly alter species distributions and abundances (Harper et al. 2005). The severity of edge effects depends on several factors, including the age and contrast of the forest edge—determined by the degree of structural difference between the native forest and adjacent human-modified areas—as well as the shape and size of the remaining forest patch (Ries et al., 2004). These complex interactions require careful study due to the high number of spatiotemporal variables involved.

Amphibians, particularly small-bodied species, are especially vulnerable to habitat loss and the creation of forest edges, largely due to their high dehydration rates and limited dispersal ability (Pfeifer et al., 2017; Schneider-Maunoury et al., 2016). In fragmented landscapes, larger-bodied amphibians may be able to disperse between forest patches through anthropogenic matrices such as pastures, while smaller forest specialists often become isolated in remnant patches (Pfeifer et al., 2021; Zabala-Forero and Urbina-Cardona 2021). Over time, natural regeneration of abandoned lands or active ecological restoration can help restore amphibian populations, but movement between patches remains limited for species with low dispersal capacity (Díaz-García et al., 2017; Hernández-Ordóñez et al., 2015).

The impact of anthropogenic landscape transformation on biodiversity are inherently complex, particularly because they involve numerous environmental, structural, and biotic interactions that are difficult to fully convey in classroom settings without field-based experiential learning (Tscharntke et al., 2012). Furthermore, scientific research on this topic is often published in specialized journals, which may be inaccessible or not easily interpreted by non-specialists, such as students, policymakers, or rural people (Ferraz et al., 2021; Redford et al., 2012). This underscores the need for simplified, interactive tools that synthesize these complex processes and foster

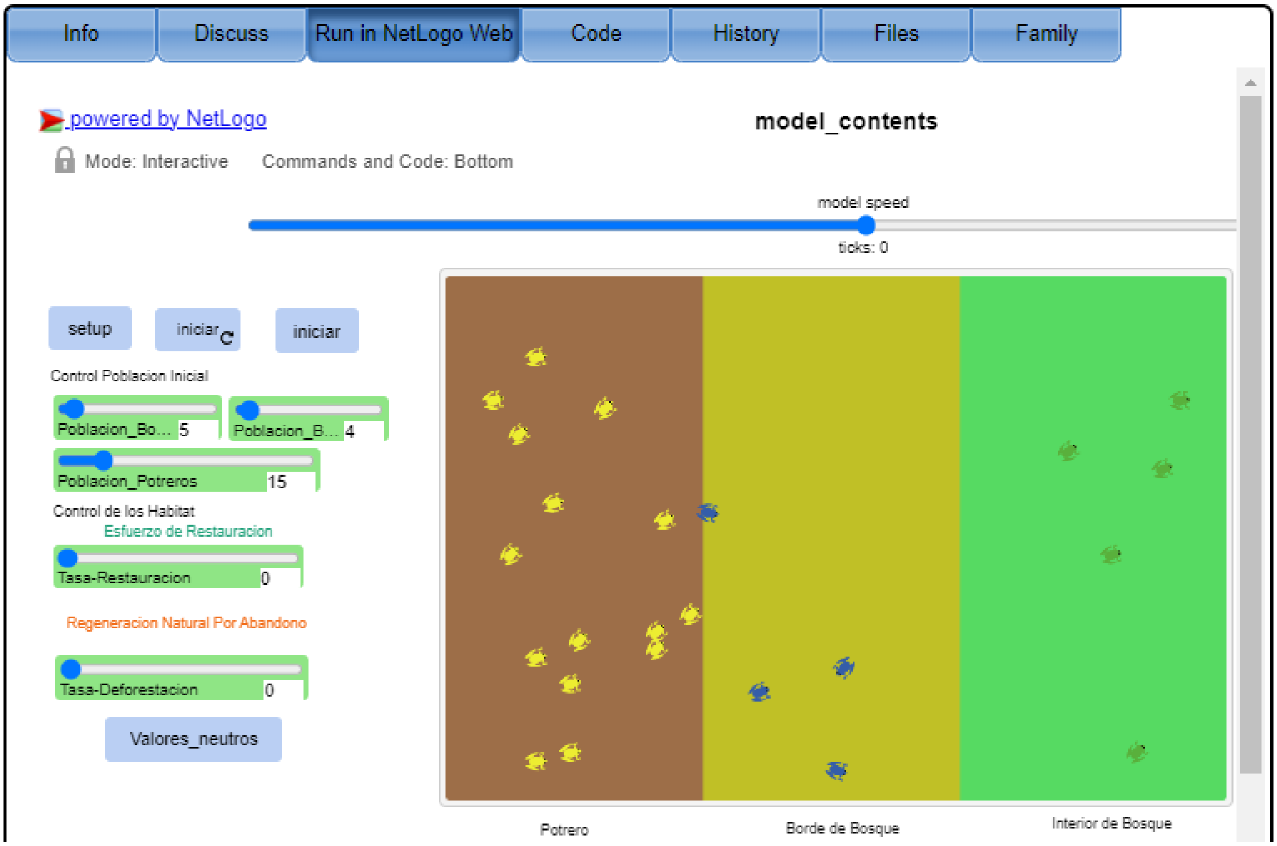

Figure 1. Netlogo Web Model with description of the tabs and buttons.

collaborative learning environments.

Agent-based models (ABMs) provide a valuable approach to illustrating environmental interactions that are difficult to observe directly in nature, making it an effective tool for communicating complex ecological concepts in educational settings (Carey and Gougis 2017; Farrell and Cayelan, 2018). ABMs are computational simulations that represent individual agents (animals, plants, or humans) within an environment, allowing them to interact according to defined behavioral rules. ABMs help simulate complex systems by modeling the interactions between agents and their environments. For example, ABMs have been used to study the impact of agricultural practices on biodiversity by simulating the behavior of species in response to changes in land use, such as deforestation or reforestation efforts (Chopin et al., 2019), and are increasingly integrated into classroom e-learning to reinforce concepts that traditionally require fieldwork (Brewer, 2006; Murphy et al., 2020).

Here we developed an interactive, user-friendly ABM to illustrate the influence of edge effects on the distribution and abundance of native amphibian species in the Amazon ecosystem of Colombia. We delineated specific behavioral patterns and energy consumption of species in pasture, forest edge, and interior habitats, organizing this information within a user interface designed for educational purposes. This model simplifies the complexities of species movement and reproduction in response to deforestation, restoration, and habitat fragmentation, providing a visual and engaging way to communicate ecological concepts to students.

Methods

Agent-Based Model description

The model was made in the programming language and integrated development environment NetLogo (Tisue and Wilensky, 2004). The model was described in depth using the Overview, Design Concepts, and Detail (ODD) protocol proposed by Grimm (2010), as it has been used to organize and explain models so that they are understandable to the public and replicable by other researchers. The full ODD can be found in the Appendix 1.

The user configures the transition parameters in land use type of pasture, rainforest edge, or interior from a panel with icons that can be slid to set the scenario (Figure 1). In each tick, as the simulation runs, results can be observed on a board with patches representing different habitats (represented by different colored pixels) and on which the different types of anurans are scattered and reproduced. In which a tick is a count of times the code has been read, the processes have been accomplished and don't represent real-time. However, processes like reproduction are linked to the ticks to show that reproduction is a discrete process. A patch is a stationary agent, the space in which the processes happen, and it can have its variables. This area does not have real measurements.

Classification of anuran species by forest edge response

The mobile agents are the anura (frogs) and were configured based on the field abundances of the amphibian species registered by Palomino-Cuellar (2019) in 90 linear transects of 15m in length along a distance gradient from 120 m into the pastures and 400 m into the Amazon rainforest interior. The field phase for amphibian sampling was carried out between November 2018 and February 2019 for a total effort of 240 person-hours (for more detail of the study area look for Appendix 2).

Within the amphibian assemblage, species were identified that showed changes in their abundance between the pasture, forest edge, and the forest interior habitats and were classified into three types of response to the edge (Schneider-Maunoury et al., 2016), as follows: 1) Mathiasson's Treefrog (*Dendropsophus mathiassoni*) affine for the pasture habitat; 2) Tiny Tree Toad (*Amazophrynella minuta*), and Variable Robber Frog (*Pristimantis variabilis*) affine for the forest edge habitat; and 3*) Peters' Dwarf Frog* (*Engystomops petersi*), Canelos Robber Frog (*P. acuminatus*), and Chirping Robber Frog (*P. conspicillatus*) affine for the forest interior habitat. Two and three species represented the border edge (from 0 to 50m) and forest interior habitat (beyond 100m from the forest edge), respectively, as each species has a small number of individuals, so we grouped them to maximize the information on environmental variables and functional (morphological and natural history) traits per habitat. There were two criteria to group species: 1) similar leg/weight ratio, 2) similar reproductive behavior.

Agents, patches, and variables

The board was divided into three habitats for the initial model: Pastures, rainforest edge, and rainforest interior. Each of these habitats has initial values from the average values of the environmental variables (temperature, relative humidity, and canopy cover) measured at the site where each of the individuals of the species was found by Palomino-Cuellar (2019) (Table 1). These three habitats change according to a rate set with a slider by the user, allowing to see faster or slower processes of spatio-temporal change. The user can determine in the model the changes in land use and land cover adjacent to the remaining native forest with transitions such as ecological restoration, deforestation, or natural regeneration after land abandonment. Every time a patch changes, it acquires a random new number for environmental temperature, canopy cover, and relative humidity within the range of the neighbors and the values observed in the field for each variable in each habitat (Table 1)

Each amphibian species was assigned a categorical value of dispersal capacity, reproduction, and a limited supply of energy to accomplish survival. In this sense, each agent in the model can die from a differential lack of energy (exhaustion), and so, depending on natural history traits, like parental care, seasonality in reproduction, number of eggs, type of nest, between other factors (Vitt and Caldwell 2013), a species´ group could consume more or less energy when reproducing (Table 2). Specifically, the relative energy consumption in reproduction is used in

Table 1. Environmental variables that characterize the habitat of the anuran species group from temperature, relative humidity, and canopy cover. These data were taken from the field measurements made by Palomino-Cuellar (2019).

Species	Environmental dimension	Minimum	Maximum	Average
Dendropsophus mathiassoni(15)	Temperature	22.70	28.50	26.54
	Relative humidity	84.50	94.80	90.36
	Canopy	0.00	7.54	0.90
Pristimantis variabilis (1), Amazophrynella minuta (3)	Temperature	26.70	33.20	30.22
	Relative humidity	67.20	88.20	75.70
	Canopy	81.90	88.14	85.97
Engystomops petersi (2), P. conspicillatus (1), P. acuminatus (1)	Temperature	24.40	28.20	26.26
	Relative humidity	91.20	100.00	94.00
	Canopy	82.42	88.66	85.23

Table 2. Morphological and reproductive values per anuran species inhabiting the rainforest in the Caquetá Department. The categorical value of relative energy consumption in reproduction ranges from 1 to 5, in which one would represent low energy consumption a

Species	Number of individuals	Relative energy consumption in reproduction (1-5)	Reproduction	Snout-vent length	Leg-weight ratio	Movement in model	Response group to forest edge
Dendropsophus mathiassoni	15	3		21.00	1.5	3.4	Pasture
Amazophrynella minuta	3	4	Seasonal	18.04	1.3	3.9	Edge
Pristimantis variabilis	1	2		16.47	0.9	5.5	Edge
Engystomops petersi	2	5	Seasonal	27.37	4.6	1.1	Forest interior
Pristimantis acuminatus	1	3		23.15	3.2	1.5	Forest interior
P. conspicillatus	1	2		34.62	5.6	0.9	Forest interior

the model as the rate at which a new amphibian is hatched per species group.

The relative energy consumption values assigned to each species group during reproduction are based on a combination of natural history traits, such as reproductive seasonality, number of eggs, type of nest, and parental care, which are known to influence energy expenditure in anurans (Vitt and Caldwell, 2013). For example, species with high reproductive seasonality and larger clutch sizes (e.g., *E. petersi* and *A. minuta*) are assigned higher energy consumption values (categories 4-5), reflecting their significant investment in reproduction within a constrained time frame. In contrast, species with lower reproductive frequency or smaller clutch sizes (e.g., *P. conspicillatus*) have moderate energy consumption values (categories 2-3). These categorizations allow the model to simulate differential energy expenditure based on species-specific reproductive strategies, which are well-documented in herpetological literature (Toledo et al., 2009).

The leg-weight ratio was calculated as

$$\left(\frac{biomass \times 100}{leg\ size}\right)$$

and indicates how capable is a frog to move their body, meaning that a lower number shows that the legs are longer or the frog´s body is smaller. Then, all the results were standardized and multiplied by

$$5\left(\frac{1}{Leg - Weight\ ratio} \times 5\right)$$

A value of 5 would reflect the maximum ability of an individual to explore his environment at a maximum of 5 pixels around the game board. For the model, the average between the individuals of the species in the same group was used (Table 2).

Processes within the model

Firstly, this configuration assumes that changes in the environment´s structure will affect reproduction chances (Cayuela et al., 2014). Likewise, we assumed that the edge effect acted in a set boundary, when in reality it´s impact varies within variables and distance. At the beginning of the simulation, the three groups of species (pasture, forest edge, or forest interior affine frogs) are distributed within their habitat at random (pasture, forest edge, and interior) (Figure 2). Still, they may become locally extinct depending on changes in the parameters made by the user. The user can modify the change rate with the provided sliders, adjusting levels of deforestation and restoration (Figure 3). All agents are assumed to be adults with reproductive capacity. When the user sets up the simulation, the patches acquire established values for the variables (Table 1). All anuran individuals have a base movement, meaning that they are never still and always consume at least 1 unit of energy per tick.

Subsequently, when the simulation starts, the agents check their surroundings in a radius ranging from 1 to 5 pixels depending on their leg-weight ratio (Table 2), the individuals inspect if the variables are within their suitable range to a greater or lesser number of pixels in the surrounding area. The frog will “run” facing the nearest suitable patch if they’re not within their range. The leg-weight ratio and available energy determine running, and thus, if energy is 0, the frog dies and disappears from the board (Figure 4).

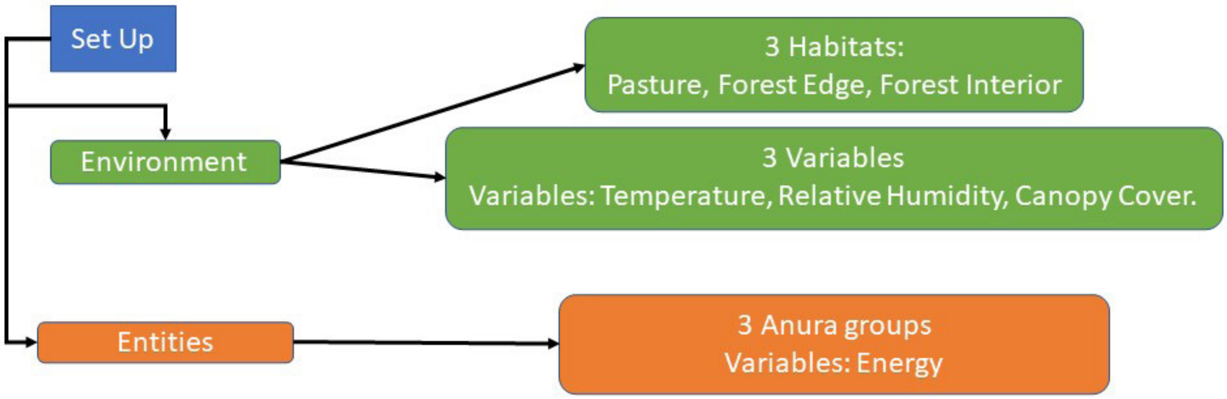

Figure 2. At setup, the code first creates the environment with each variable on each habitat. Then, it creates the agents, locates them in the previously created environment, and gives values to their variables.

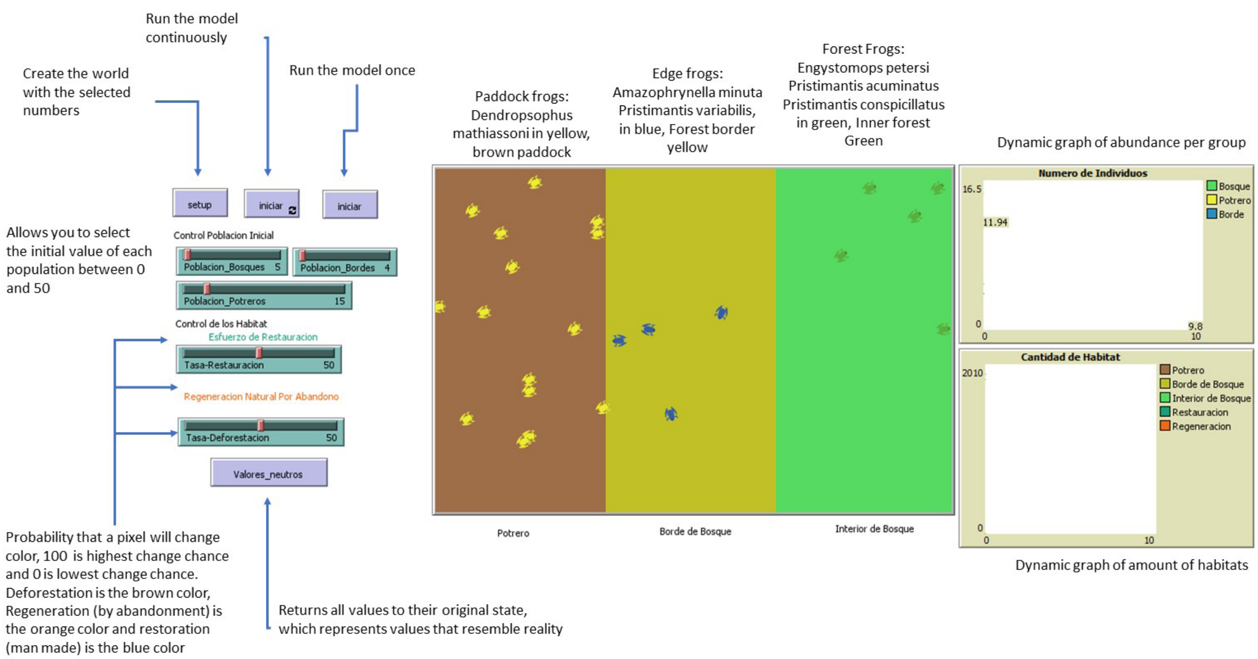

Figure 3. Illustration of the initial default settings of the agent-based model. Each habitat is proportional at set up, having 30 x 60 pixels. In brown, we have the pasture; in yellow, we have the forest edge; in green, we have the forest interior. Anuran individuals have the shape of frogs, representing one of the three species groups mentioned: yellow species are affine for pasture; blue is affine for forest edge; and green is affine for forest interior. At go, patches would turn orange to represent natural regeneration, blue, to represent restoration or brown, to represent deforestation.

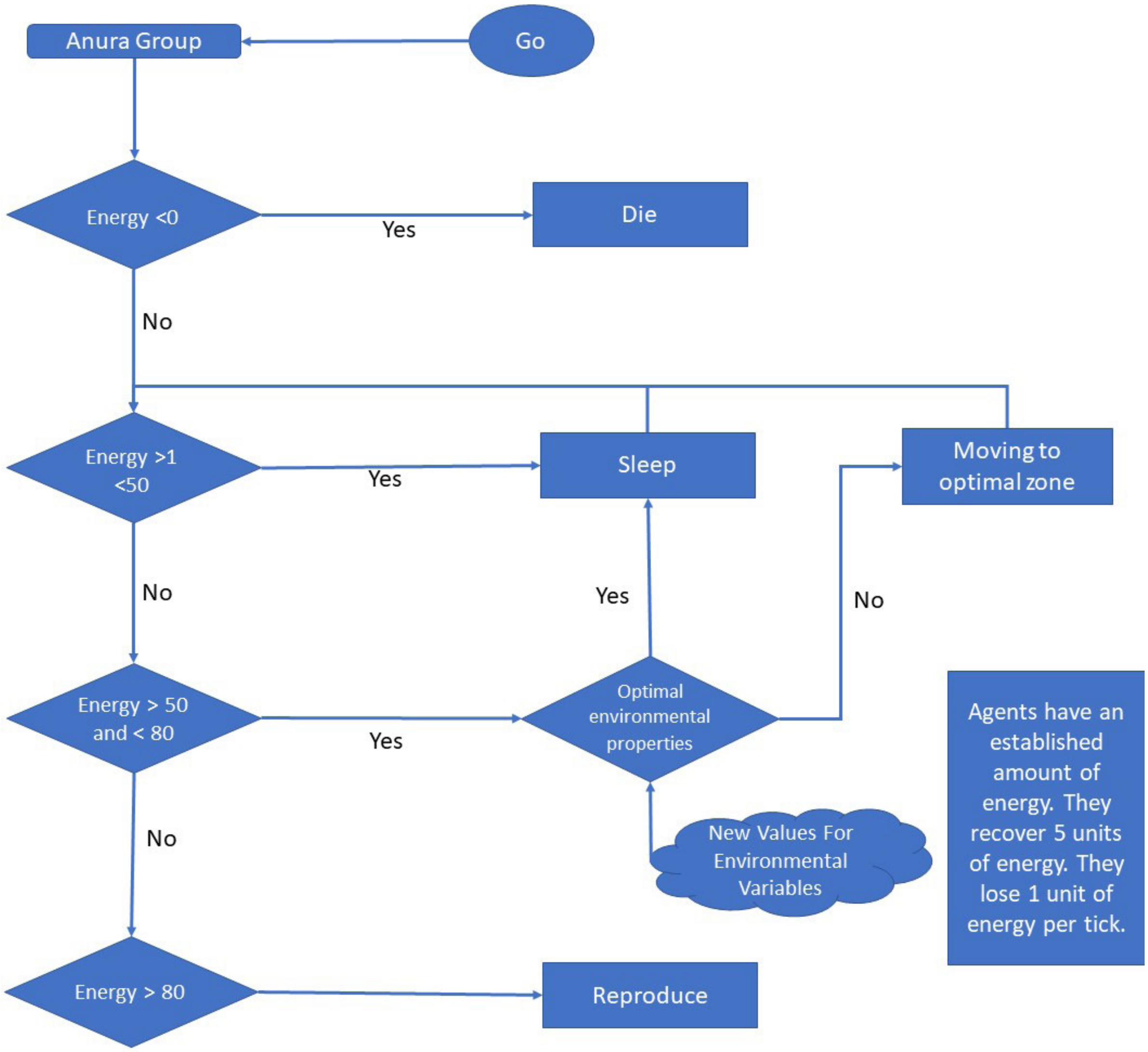

Figure 4. Flowchart of the decision-making of anuran species in the model. The cloud represents a connection with Figure 5.

In this sense, the values used in the simulation for energy thresholds and their corresponding behaviors (sleep, dispersal, reproduction, or death) are based on physiological principles observed in anurans. As ectotherms, anurans' energy consumption is highly influenced by environmental conditions such as temperature and humidity (Feder and Burggren, 1992; Hillman et al., 2009;). During periods of low energy, anurans reduce their activity to conserve resources, which is reflected in the model when energy levels are between 1 and 50. This is consistent with studies that show anurans become inactive under adverse conditions to preserve energy (Wells, 2007). Reproduction is highly energy-intensive, requiring substantial investment in behaviors such as courtship and gamete production (Toledo et al., 2009), justifying the need for energy levels above 80 to reproduce in the simulation. Additionally, dispersal capacity is linked to body size and the leg-weight ratio, which influences the distance anurans can move in search of optimal conditions (Marsh and Trenham, 2001). These values ensure that the simulation accurately reflects the physiological and ecological realities of anuran species. The described model can be found on the web.[1]

On the contrary, if the area surrounding an anuran individual is optimal, it will wait on the set reproduction time and acquire energy in the meantime (Figure 4). All anuran individuals have a 50% chance to reproduce, which a new individual on the board evidences. It is also assumed that half of the population is female and must have at least 80 units of energy to generate a new individual; the new anuran individual hatches with a third of the parent's energy

[1] https://modelingcommons.org/browse/one_model/7476#model_tabs_browse_nlw.

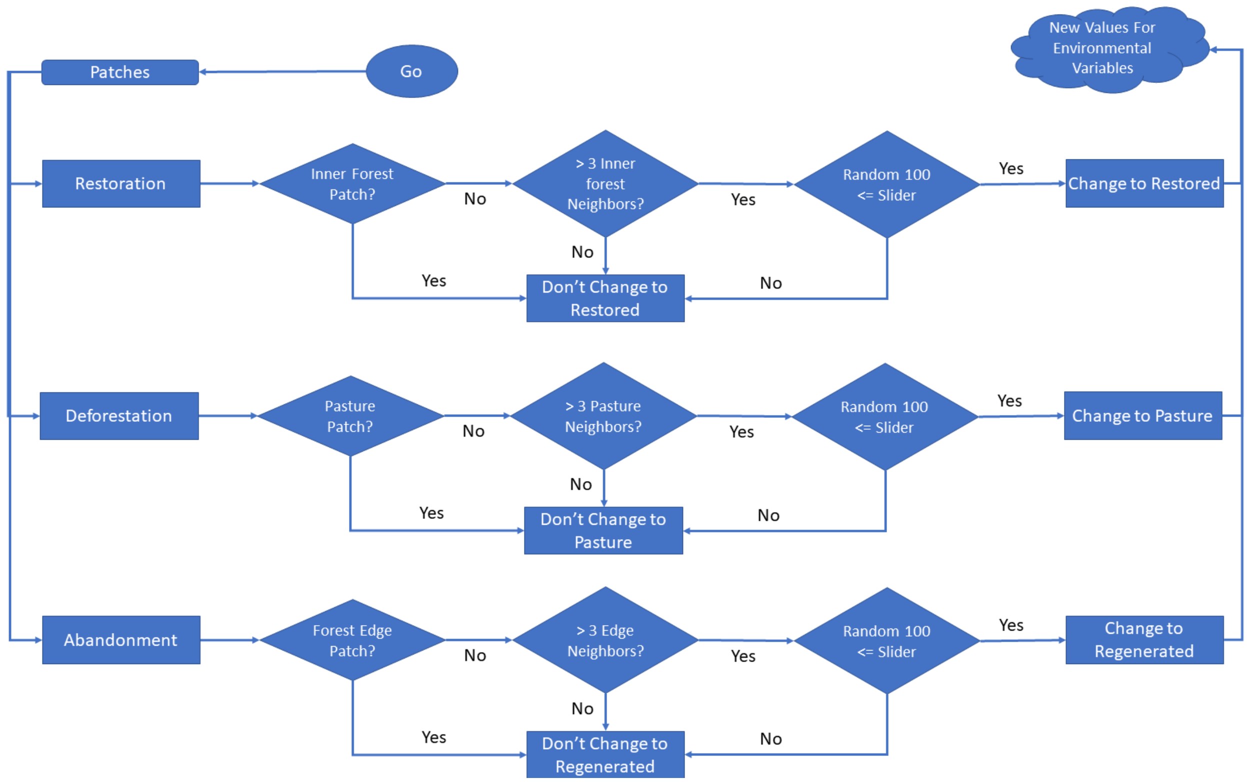

Figure 5. Flowchart of the patches change by neighbors. The change generates new variables in the environment linked with the anura decision-making, represented through the cloud in the top right.

and a random direction.

Once the anuran individuals have responded, the environment is altered, provoking a change in the proportion of habitat in the board. Then, the model randomizes the environmental conditions at the forest edge according to the range of values in the variables observed in the field (Figure 5). Depending on the user, three land use/land cover transition scenarios can be set to dominate the landscape transformation processes in each scenario, all of which have been reported to affect the amphibian populations: deforestation dominance (Agudelo-Hz et al., 2019), natural regeneration after land abandonment dominance (Herrera-Montes and Brokaw 2010; Hernández-Ordóñez et al., 2015), or ecological restoration dominance (Brodman et al., 2006; Díaz-García et al., 2017).

Application of the ABM in a classroom

A pilot study was conducted to probe changes in student responses during the three stages of evaluation: (a) before the module classes, (b) after teaching students the concepts and case studies in the 4-hour class on edge effects, and (c) after using and interacting with the agent-based model during a workshop guided by the model developer. The same person taught all the classes. During each stage, students were asked to answer the same four questions (two qualitative and two quantitative, using the Likert scale (Matas, 2018) about the intensity of the edge effect on different native forest patch sizes and shapes, and under different vegetation cover bordering the remnant native forest (Appendix 3).

The ABM tool was applied during the first semester of 2022 to undergraduate students of ecology at Pontificia Universidad Javeriana in Bogotá (Colombia), in the class of conservation ecology (7th semester). It was also taught to first-semester students of the master's degree in Conservation and Use of Biodiversity of the same university, in the class of conservation biology, for a total of 24 respondents that participated voluntarily of the evaluation during each of the class's activities. Before the ABM tool was shown and before the class on edge effects, all students received 4 hours of class on the effects of habitat loss and fragmentation on biodiversity. To familiarize the students with the tool beforehand, an explanatory video in Spanish was given[2]. This video is in Spanish and it seeks to aid in the use of the ABM tool.

[2] https://youtu.be/KOSYFKT5pZQ.

Students receive a 30-minute class on the use of the ABM tool to explain edge effects. It was expected that as students attended the class and interacted with the model, their responses (the value of the impact of edge effects) changed. Once the students had seen the agents' behavior under different configurations in the NetlLogo platform[1], they were asked for feedback on their use experience and suggestions for improvement of the graphical user interaction interface.

From the students' answers to questions 3 and 4 (Appendix 3), two multivariate response variables were obtained to evaluate changes between the three stages of evaluation in (a) the value (Likert scale from 1 to 5) of the impact of the edge effect on native forest fragments of different shape and size (in question 3), and (b) the value (Likert scale from 1 to 5) of the impact of the edge effect on native forest fragments of different shape and adjacent land use (in question 4).

Given the multidimensional nature of the student responses, which involved both qualitative and quantitative measures, we required a statistical method capable of assessing multivariate differences across multiple evaluation stages. The use of Euclidean distance matrices allowed us to compute dissimilarities between student responses across these different stages. PERMANOVA was chosen as it is a non-parametric method suitable for analyzing multivariate data without the stringent assumptions of normality or homoscedasticity. This is particularly crucial in educational studies, where data often violate these assumptions. Furthermore, PERMANOVA, when combined with type III sum of squares, allows for the partitioning of variation in the responses to specific factors—in this case, the evaluation stages—while accommodating unbalanced designs and complex, hierarchical data structures, as was present in our study (Anderson et al., 2008). Using 9,999 permutations enhances the robustness of the results, ensuring that statistical inferences are based on data-derived distributions rather than theoretical ones, thus aligning with the exploratory nature of our study.

The ability of PERMANOVA to handle both qualitative and quantitative shifts in response patterns made it an ideal tool for evaluating changes in students' perceptions of the edge effect after each interaction phase with the agent-based model. The experimental design consisted of the evaluation stage as a fixed factor (with three levels: before and after the edge effects module and after the interactive experience with the model). Given that individuals of different academic levels and genders may have varying levels of prior ecological knowledge, shaping their perceptions and attitudes towards biodiversity (Moreno-Rubiano et al., 2023; Vergara-Ríos et al., 2021), we conducted separate analyses for men and women, as well as for undergraduate and graduate students. Additionally, gender-based differences in educational environments have been shown to influence learning styles and concept appropriation (Matas, 2018). However, due to the small sample size, the degrees of freedom were insufficient to evaluate interactions between gender and academic level in a two-way PERMANOVA. Consequently, we opted to analyze men and women, as well as undergraduate and graduate students, separately. This approach allowed us to consider potential differences in learning outcomes across these demographic factors, despite the limitations imposed by the sample size. We compared the levels with statistical differences within the factors with a posterior pairwise comparison with the t-statistic based on 9999 permutations (Vergara-Ríos et al. 2021).

Results

Qualitative description of user experiences

The 14 students who had seen the conservation ecology class in the undergraduate program in Ecology were more reserved when giving feedback during the workshop compared to the ten students from the master's degree conservation biology class. After the workshop, some students wanted more details about the model, so an additional demonstration was given. On the contrary, the interaction with the students of the master's program was more dynamic, with more active participation from questions, comments, and suggestions during the presentation of the model in the classroom. Graduate students were most interested in why things were happening in the model instead of waiting for the teacher to ask them; they also asked to generate more scenarios in which they could see land cover and use transitions. Both approaches of the students exemplify the usefulness of the model, as different attitudes were evident in the questioning of the three scenarios presented (pastures created after the deforestation process, land abandonment, and ecological restoration) and the whole usage of the model as a teaching tool.

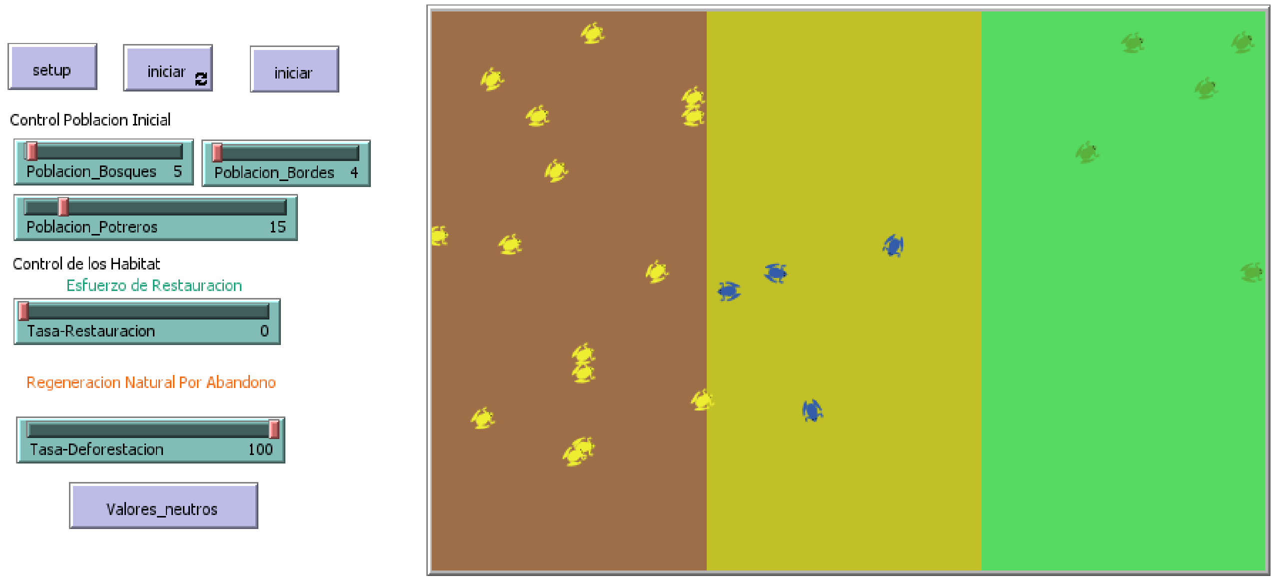

Figure 6. Model setup for deforestation scenario. The slider is at 100 for deforestation, while ecological restoration is at 0.

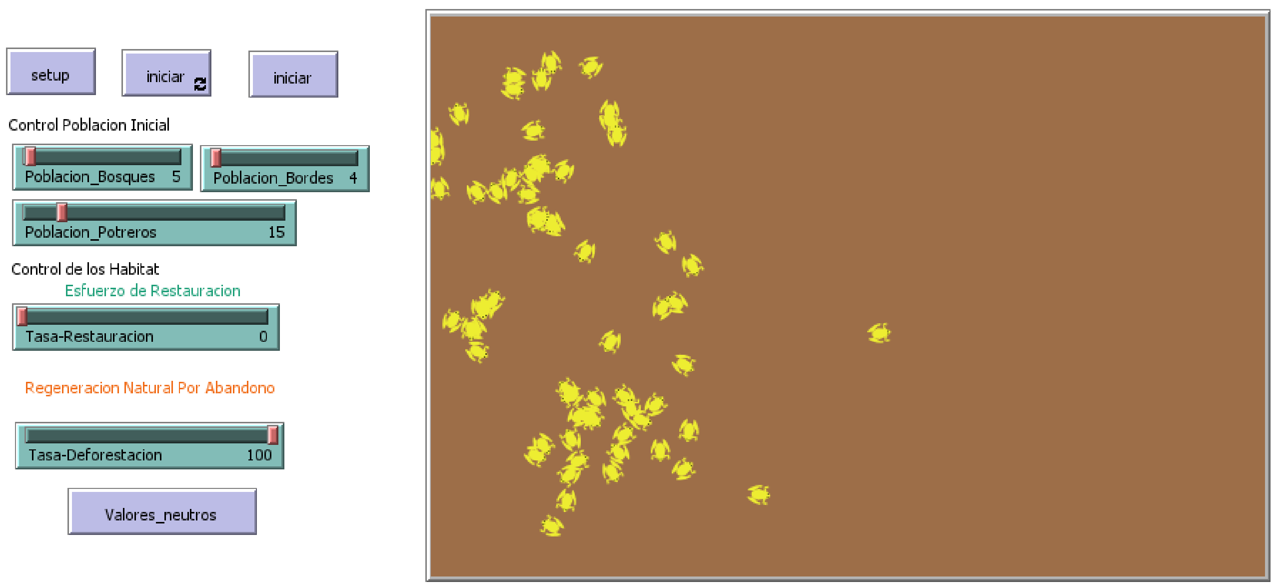

Figure 7. End of the simulation of deforestation. Pastures created after deforestation overtook the other habitats and extirpated the other two groups of native forest affine anuran species.

Model behavior as a function of landscape transformation scenarios

Deforestation scenario.—When the students favored deforestation as a dominant process in the landscape (Figure 6), they were able to see how fast the pasture overtakes the other landcover type (rainforest edge and interior), forcing the frogs that inhabited the forest edge and interior to disperse into the remaining forest, and finally visualizing the extinction of rainforest associated species. At the same time, while the population size increases for the pasture affine species. The user can visualize that the yellow species that inhabit the pasture reproduce very quickly, but no large amounts are scattered across the pixels; this happens as they are programmed to move to the best patch possible, but as they consider that the ones near them are optimal, and there is no anuran density limit for the patches, they agglomerate at the left of the screen leaving most of the pasture habitat without frogs (Figure 7).

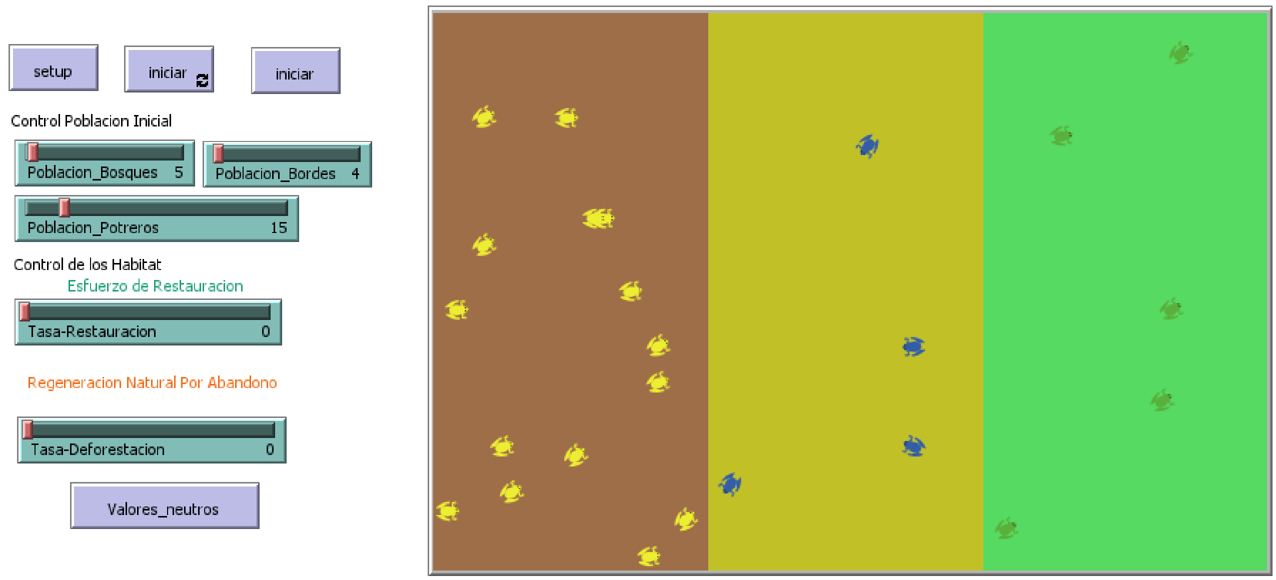

Figure 8. Model setup for land abandonment and natural regeneration. All sliders are at 0.

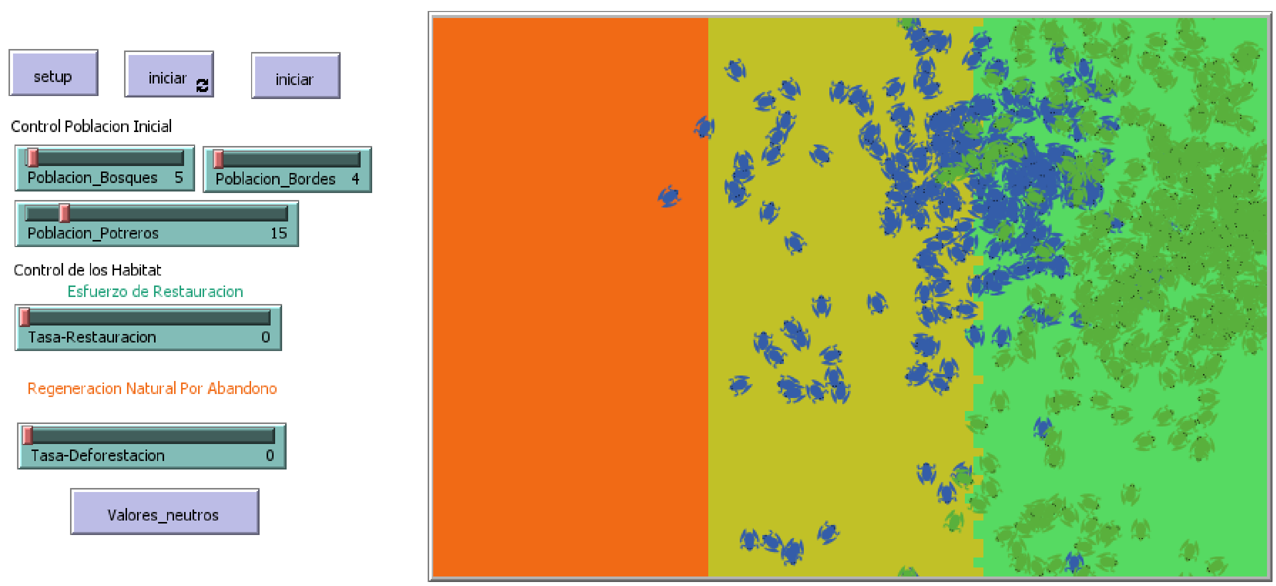

Figure 9. End of the land abandonment simulation. The pasture was overtaken by natural regeneration, in color orange, eliminating group 1 of pasture affine frogs while native forest affine anurans groups 2 and 3 grew over time. Land abandonment = orange pixels.

Land abandonment scenario.—As the class progressed, students asked what happened to the anurans when there was no deforestation and no restoration, just the abandonment of the pasture to make way for natural regeneration (Figure 8). Land abandonment as a dominant process in the landscape (Figure 6) shows how the natural regeneration (orange pixels) grows, overtaking the pasture and extirpating the group 1 of anuran species affine for pasture. In contrast, while both forest edge and interior affine species overgrow in abundance (Figure 9). They asked why the interior was growing, and the explanation was that this happens because natural regeneration serves as a buffer, giving extra protection to the interior.

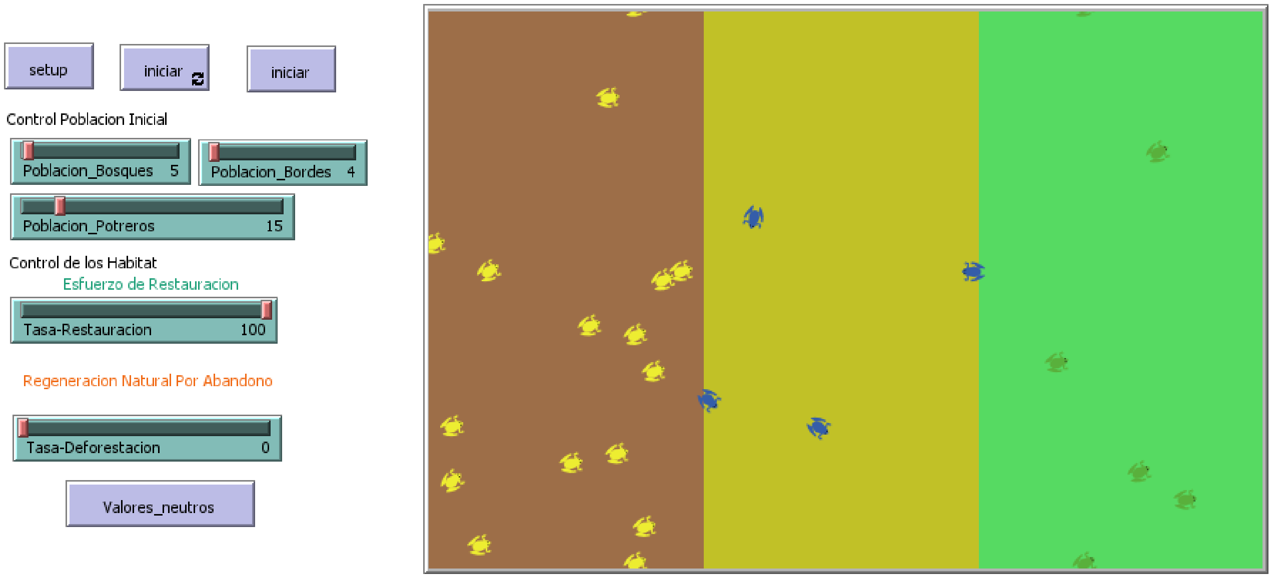

Figure 10. Model setup for restoration. The restoration slider is set to 100, and deforestation is set to 0.

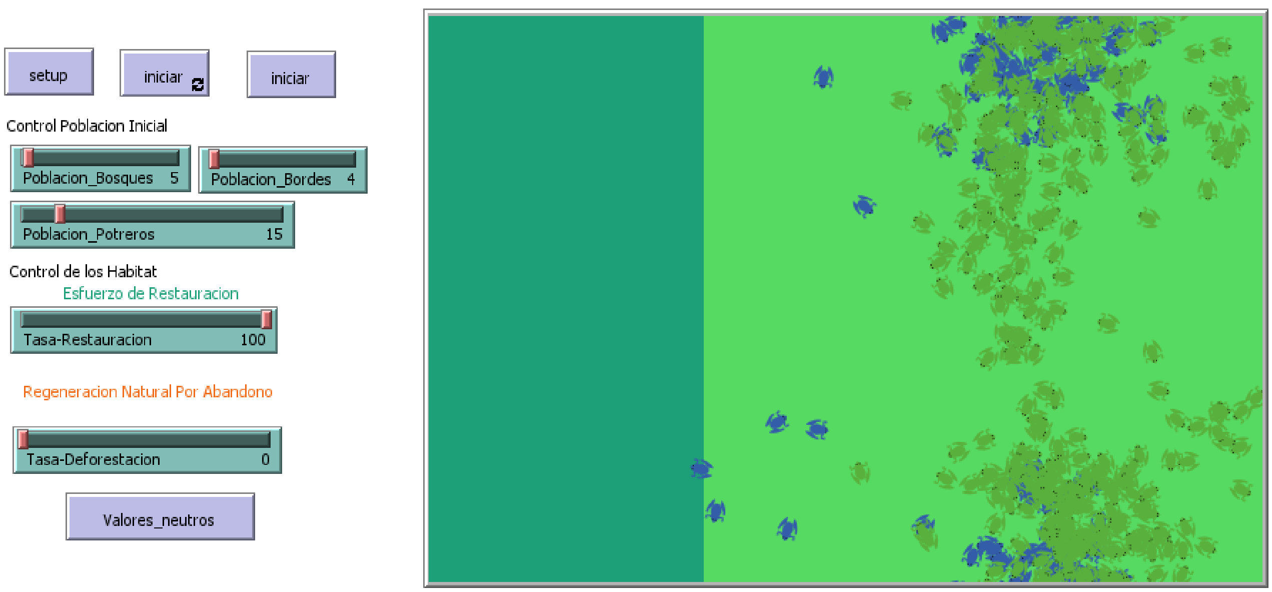

Figure 11. End of the ecological restoration simulation. The pasture was overtaken by restoration, dark blue pixels, eliminating group 1 of frogs, and the forest interior grew. Groups 2 and 3 of native forest affine anuran species grew over time. Ecological restoration = dark green pixels.

Restoration scenario.—When looking at ecological restoration as a dominant process in the landscape (Figure 10), students saw restoration (dark green pixels) emerge and forest interior borders move quickly to the left. In contrast native forest edge affine frogs and forest interior frogs usually reproduce. When restoration overtakes the whole pasture, the pasture affine frog begins to die; eventually, there are only blue and green pixels with green and blue anuran species (Figure 11).

Students' answers between stages of evaluation

For question 3 about the degree of influence of the edge effect on the abundance of a specialist native forest species on the interaction between the size of the native forest and its shape (question 3 Appendix 3), there were no statistical differences in the responses between stages of evaluation for undergraduate students (pseudo-F = 0.462; p-perm = 0.782). For graduate students, there were statistical differences between evaluation stages (pseudo-F =

2.4625; p-perm = 0.0242). Differences were present when comparing responses after the class and after interacting with the NetLogo model (t-statistic = 1.823; p-perm = 0.0121), but there were no differences between before and after the class (t-statistic = 1.428; p-perm = 0.139).

When considering all undergraduate and graduate students as a whole, it was found that the responses of women did not vary between stages of evaluation (pseudo-F = 0.88; p-perm = 0.473), but men did vary in their responses (pseudo-F = 3.32; p-perm = 0.0041), and differences were present when comparing between men responses before and after the class (t-statistic = 1.606; p-perm = 0.036) and after the class and after interacting with the NetLogo model (t-statistic = 2.153; p-perm = 0.0007).

When the interaction between these factors was tested, differences between stages of evaluation were found only for the male respondents in the graduate program (pseudo-F = 3.248; p-perm = 0.023); and differences were present when comparing between responses after the class and after interacting with the NetLogo model (t-statistic=2.281; p-perm = 0.0003).

For question 4 about the degree of influence of the edge effect on the abundance of a specialist native forest species on the interaction between the type of land use adjacent to the native forest patch and the shape of the native forest patch (question 4 Appendix 3), there were statistical differences in graduate students between stages of evaluation (pseudo-F = 2.256; p-perm = 0.045) and differences were present when comparing between responses before the class and after interacting with the NetLogo model (t-statistic = 1.938; p-perm = 0.013). However, no differences were found in the responses between evaluation stages for undergraduate students (pseudo-F = 1.101; p-perm = 0.344).

When considering all undergraduate and graduate students, it was found that the responses of women did not vary between stages of evaluation (pseudo-F = 1.798; p-perm = 0.089), as was found in the men's responses (pseudo-F = 1.695; p-perm = 0.11). When the interaction between these factors was tested, differences between stages of evaluation were found only for the responses of males in the graduate program (pseudo-F = 2.748; p-perm = 0.0234); and differences were present when comparing between responses before the class and after interacting with the NetLogo model (t-statistic = 2.27; p-perm = 0.0028).

Discussion

The model developed in this study works realistically as it considers the habitat's environmental variables and the frogs' morphological traits measured on the field (Palomino-Cuellar 2019). Because of it, when used in class, it shows how some anuran species react differently to the native forest edges after landcover transitions. It also helped the students better understand the concept of edge effect, as corroborated by the answers of a simple poll answered by 24 of his students, where 95.8% of the students stated that using the model was beneficial. Overall, using the model in class allowed the students to approach a complex subject with relative ease, enabling a more dynamic class, as students asked several questions about the model as they interacted with it. The following describes how the model was improved after feedback from the students as users.

Agent-based models to explain landscape transformation and effects on biodiversity

Considering the synthesized understanding of edge effects and their implications for biodiversity education, this study's discussions probe the intersection of ecological concepts and pedagogical objectives. Our discourse embarks on a nuanced exploration of how innovative educational technology intersects with ecological discourse. Anchored by the objectives and outcomes of the study, the ensuing discussions dissect the transformative potential of agent-based modeling in conveying complex ecological phenomena to diverse educational contexts while allowing for the integration of technology and meaningful educational applications. Through a pedagogical lens, we delve into the implications of these findings for fostering a deeper understanding of edge effects and promoting eco-literacy among students and educators alike.

Depending on the user´s needs, agent-based modeling can have varying degrees of complexity. Using a "simple" agent model, with an assumption of homogeneity, is enough when trying to show a problem in such a way that it can be used in a pedagogical environment (Brown et al., 2004); this, of course, implies that the models need to leave out information, that for the scientific community is needed to improve the rigor and robustness of information regarding the research topic (Brown and Robinson 2006). As such, agent modeling has been used to test diverse scientific hypotheses through simulations, especially regarding biodiversity. A study from Chetcuti et al., (2021) used agent-based modeling to show the impact of fragmentation regardless of habitat loss, concluding that different matrices can interact differently with the fragments, having beneficial or harmful consequences for biodiversity. However, the information provided by this article falls on the complexity side that cannot be used in class without prior conceptual training (Walls and Gabor 2019), even when the code is free and available, allowing trials and corrections from others wanting to understand the model.

In contrast, Horiuchi and Takasaki's (2012) agent modeling sought to understand how species take advantage of their group space. They did it in such a way that helped decision-makers acquire the information to understand the behavior and environment used by the Japanese macaque, beginning a dialogue to promote its conservation. With this, even though there is still room for complex models in the academy, easily understandable explanations are still needed and have been proven helpful to ensure that processes of landscape transformation and their impact on biodiversity could be considered in decision-making (Carey and Gougis 2017; Farrell and Cayelan, 2018; Read et al. 2016). In our case, the model aims to simplify a complex topic so that the students could approach it. Information regarding some environmental variables was left behind, prioritizing the ease of use.

Species functional traits and responses to edge

Grouping species according to their responses to the edge allows for more effective targeting of conservation and restoration actions within a biotic community (Pfeifer et al. 2017; Schneider-Maunoury et al., 2016). Forest-exclusive anurans are exceptionally sensitive to the edge, as richness increases with distance from it. The environmental variables that explain this effect were changes in basal area and canopy coverage (Cortés-Gómez et al. 2013). However, daily temperature and understory density were also found to have explanatory power for the changes in richness (Pearman, 1997). Alternatively, studies show that the edge effect impacts the species level, as some are unaffected while others exhibit a decrease in their abundance due to factors such as seasonality (dry or wet) and availability of sites for reproduction and predation (Gascon 1993; Tsuji-Nishikido and Menin, 2011). Likewise, Palomino-Cuellar (2019) noticed that environmental factors were the main drivers for the diversity and composition of anuran assemblages in our study region in the Caquetá department (Colombia), especially temperature, light penetration, distance to the border, relative humidity, and distance to the nearest body of water.

Additionally, it has been shown that energy consumption varies according to body size and temperature, even when the anuran is at rest (Wells, 2007), meaning that environmental changes affect the rate at which amphibians consume energy (Wells, 2007). This was not contemplated in the present model, as representing energy differently through the groups was thought to hinder the ability of the model to explain the edge effect, as it would have increased complexity.

However, the effectiveness of conservation actions depends on knowledge of the functional traits that allow species to respond to changes in their habitat in transformed landscapes (Zabala-Forero and Urbina-Cardona, 2021). Functional ecology is an approach to understanding the functions and responses of species within their environment; this acknowledges the roles within a habitat and how they react to changes in their environment regarding their functional traits (Salgado-Negret and Paz, 2016).

Functional traits of anurans, such as snout-vent length, leg length, and body weight, are crucial for understanding the response of anurans to environmental filters (Álvarez-Grzybowska et al., 2020). Traits used for the model (Table 2) align with previous literature, as size and energy are crucial for describing reactions to novel environmental conditions. The selected variables match the knowledge of how environmental variables impact amphibian ensembles, where temperature (Álvarez-Grzybowska et al. 2020; Harper et al. 2005), canopy coverage (Cortés-Gómez et al., 2013) and relative humidity (Santos-Barrera and Urbina-Cardona, 2011; Lehtinen et al., 2003), are amongst the more revised. Other variables like understory density (Pearman, 1997) and wind (Lehtinen et al., 2003) have affected the Anura but were not included in the model to remain simple.

Using the AMBs to understand edge effects better

Our results show that this model can be helpful, describing the complexity of the edge effect simply and intuitively for the students. Of all the possible variables that are affected by the edge effect on the habitat of the species (Broadbent et al., 2008) in the present research, we chose to simplify the model based on three variables: temperature, canopy cover, and relative humidity. Moreover, these variables have also been used to describe the impacts of the edge effect on other taxa, as they (amongst other variables) change in a gradient that impacts the microclimate (Harper et al., 2005; Ries et al., 2004). Using three key environmental variables and applying this model in teaching activities was helpful, as it provided a tool for students to understand a complex topic from the interaction with the model and the discussions that arose in the class. However, our results suggest that the degree of interaction with the model and its usefulness in reinforcing knowledge about edge effects vary between undergraduate and graduate students and women and men. Some of the testimonials from the students participating in the workshop show the usefulness of this tool in teaching. "Being clearer and graphical helped me to understand" (a male in the undergraduate class).

This kind of model has been used very little (Murphy et al., 2020) to mediate meaningful learning in students, as a teaching method and a way to understand learning. Still, it has been used when describing complex biological and social processes in scientific publications (Koster et al., 2016), translating complex scientific literature to keep students motivated through simple models and case studies.

A male student in the master's class mentioned, "It helped me to visualize the number of variables and the level of interactions between them." Utilizing agent-based models also enables the dialogue to "initiate a discussion between experts and stakeholders, bringing together different expertise" (Van Berkel and Verburg, 2012), allowing for better, more enriched decisions. Empirically, the statistical results have been corroborated, as some male students indicated a personal gain from using the model. At the same time, the female group didn't report acquiring new knowledge, instead, they expressed feeling more confident about what they already knew.

For example, a female student in the master's class mentioned that "I understood the concept in class, but seeing it didactically supports what was taught." A male student in the undergraduate class mentioned that "It improved, the concept became clearer and how they interact with multiple factors."

Recently, there have been some approaches to improve and expand the usage of agent-based modeling as a teaching and training tool (Romanowska et al., 2021) as the extent of field investigations and classes were reduced due to the COVID-19 pandemic (Murphy et al., 2020). Murphy (2020) breaks down the main components of an agent model and explains its benefits to students and teachers so that one can see different approaches to it. A female student in the undergraduate class mentioned, "The froggy that's on the forest can move if there is restoration. It can displace," suggesting that the model allows to better understand the concepts of edge effects, appropriate them, and generate more profound questions.

Conclusion

This study was based on the amphibian data previously collected in the field by Palomino-Cuellar (2019), which was the support that allowed the creation of an ABM that was able to represent the responses of three groups of amphibians to the edge effect. This model not only considered the functional traits that determine the movement and reproduction of the study species but also constrained the dispersal of individuals based on the values of three environmental habitat variables (temperature, canopy cover, and relative humidity) that are important not only for amphibians but in general for biodiversity. Additionally, the model had several stages, in which it was intended to maintain the core functionality of the model but to make it as easy to use as possible so that it could be used in class by students. However, the need to establish clear rules of action must first be considered, as they are the steppingstones to maintain the model's realism (to a certain extent). The workshops within the undergraduate and master's classes served as pilot studies that allowed not only to improve the model´s graphical interface, but also to explore whether there were additional changes in the understanding of the edge effects seen in class after interacting with the model.

The edge effect is a highly complex, and important topic to understand as it is intertwined with fragmentation. So, the main objective of this work was to generate a visual representation of it through modelling. The present model is versatile and flexible. It can incorporate new parameters and change scenarios as the dynamics of edge-effect classes generate new interactions for the teacher and his students. One such incorporation could be to provide a manual on how to use the model to promote independent learning. With enough usage and feedback, this model can be included in introductory University courses in ecology to aid in explaining this topic, giving more tools to both the teachers and the students, bettering the retention of the concept.

A final recommendation for the readers and users is to interact as a community with the model and the code, as it is free; they can learn more from the model by using it, adding and subtracting lines from the code, and asking the code the questions they want to answer.

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Conflict of interest

The authors have declared that no competing interests exist.

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APPENDIX 1: OVERVIEW, DESIGN, DETAILS

1.1 *Overview*

1.1.1 *Purpose*

(1) *What is the purpose of the study?*

The purpose of this model is to show, to the general public, the effect of natural forest edges on amphibian species, in such a way that they can easily grasp the core concepts through visual representation. The model must be user-friendly, meaning that buttons, sliders, and other interactive interfaces have to be easy to use and labeled. Even though this model uses specific species the model can, to a certain extent, be used to explain other species. This kind of model is necessary because the basic ecological information incorporated into the model presents a high degree of complexity and its design in such a way that someone not akin to science will not be able to integrate the different components (from species traits to habitat variables) to correctly interpret the pattern from the original data. The information mustn't be inaccessible, on the contrary, information needs to go to where it's needed the most, the next generation of students and researchers, the governors and agencies, decision-makers, farmers, between other stakeholders.

(2) *For whom is the model designed?*

This model is designed for those who are affected and/or interested in understanding the edge effect caused by deforestation but don't have a strong ecological background.

1.1.2 *Entities, state variables, and scales*

The agents are based on real amphibian species: 1) *Dendropsophus mathiassoni* for the pasture habitat, 2) *Amazophrynella minuta*, *Leptodactylus petersii* and *Pristimantis variabilis* for the border habitat and 3) *Engystomops petersi*, *P. acuminatus* and *P. conspicillatus* for the forest interior habitat. The first species is alone as it has a lot of data, giving a very good representation of the pasture habitat. The border and forest interior habitat have 3 species each, this is because alone they have a small number of reports but thanks to their similarity in reaction to the edge, we can group them in order to maximize the information per habitat. Thus, we have 3 representative groups.

Each habitat has an independent number of the same environmental variables.

The variables that change each tick: (1) Heading of the agent, and (2) Position (X and Y coordinates).

The variables that change between groups:

Idle Movement – All frogs have an idle movement, this means that they always move, different from running. This is placed to represent the type of foraging of the frogs, some are active forages meaning that they consume energy looking for food, while others are passive (sit and wait forage strategy; represented by low movement) and waiting for food (Cortés-Gómez et al. 2015).

Running Capacity – This number is set between 1 to 10. It is based on the physiological attributes of the group, such as leg length and body weight – length ratio (Cortés-Gómez et al. 2015). It determines how many pixels can the agent move in each tick.

Reproduction – Reproduction hatches a new frog, with a random heading and a third of the energy of the parent. The parent loses a substantial amount of energy, this depends on the type of reproduction (if the type of reproduction is different between species of the same group the method that implies more energy consumption is used to overestimate the consumption instead of understanding it). Reproduction has a set time for each group, and it is determined by the mechanisms employed at amplexus. The frogs can only reproduce when a set time has passed.

Energy – Energy goes from 0 to 100 and represents the percentage of available energy that the agent must perform movement o reproduction. The usage of energy is determined by 2 things, the environment in which the amphibian stands (is it optimal?) and the quantity of available energy. If there is now enough energy for reproduction, a new turtle is hatched with a third of the energy from the parent.

The frogs inhabit one of 3 habitats: pasture, forest edge, and forest interior. At setup, the turtles spawn in their optimal habitat distributed randomly. The habitat patches have three main environmental variables: temperature, canopy cover, and relative humidity. These factors change as they interacted with other habitats, constituting the edge effect. In Go, the habitats change randomly meaning that spawning patches (probably) won't have the same conditions when compared to the setup.

All variables (except idle movement) can be changed by the user of the model, including the rate at which the habitats change. The model has no explicit time or spatial scale. However, to make a more realistic approach a limit to population growth can be established this can be done by giving the pixels a spatial value. For example, if each pixel is 1 x 1 meter then we can conduct a comparison to the real field effort of Palomino. The area covered in the study from which the data was taken was 450m^2 per habitat (Palomino 2019), so our 30 pixels by 60 pixels grid equates to an area of 1600 m^2. With this, if the study found 15 *Dendropsophus mathiassoni* in 450 m^2 then, proportionally, we can estimate that in 1600 m^2 there are ~54; the model then can be stopped at 55 individuals of that species.

Some exogenous factors that exist but are not represented in the model included social and cultural processes, economics, and water flow dynamics.

Process overview and scheduling

Time is measured in discrete ticks. Before starting: Set the initial variables of the patches, the number of frogs per habitat, and their energy. All amphibians do this for each tick: The frogs look at their surrounding in a radius of 5 and check if the environment satisfies their established needs. If the environment isn't optimal, face the nearest patch with the conditions and runs towards it (run capacity). If no energy, die, disappearing the frog form the screen.

If the environment is optimal wait until the reproduction time. Acquire energy while waiting. When the time comes, reproduce. The new frog gets the same reproduction time as the parent and a third of its energy. The patches then change according to the change fact of a slider. These changes are done through neighbors and generate different temperatures, relative humidity, and canopy cover and the border moves. End of the tick

1.2 *Design Concepts*

1.2.1 *Emergence*

There are two main outputs from the model:

- Count Patches - Habitat Coverage Graph is a graph that periodically changes according to the count of patches, which changes by the value set at the beginning of the simulation
- Count frog – with this graph we can see how the populations are changing over time.

Even though the parameters on which the agents operate are fixed, both outcomes are, to a certain extent, unpredictable as there is a random generation of values that can determine the survival of an agent. Reproduction may be affected by random changes in the environment.

1.2.2 *Adaptation*

As the environment changes, the agents will look for the nearest patch that has the appropriate conditions and run towards it. The idea behind it is that the goal of the agents is just to survive, and so when they see that the environment is out of its optimal range (causing a loss in energy and ultimately death) they'll seek the best conditions as fast as possible.

1.2.3 *Objective*

The agents don't have an inherent objective. The model just wants to show the interaction of the amphibian with the with the edge that is created between a native forest and an anthropogenic production system, and they are programmed to look for the best place to survive. They can only perceive the neighbors (radius of 5 pixels) and don't recall where they have been before.

1.2.4 *Learning*

Agents do not learn.

1.2.5 *Prediction*

Agents are unable to predict future conditions

1.2.6 *Sensing*

Agents can check the environmental characteristics (temperature, humidity, and canopy cover) of the patch they're in and the neighbor patches (5-pixel radius).

1.2.7 *Interactions*

Agents do not interact with each other nor affect their actions. Patches interact with each other as there is a chance that a patch changes from one habitat to another, this is chance is determined through the interface. Patches interact with the agents.

1.2.8 *Stochasticity*

Movement direction is set by a random heading. Hatched offspring has a random float. The border takes the minimum value found on field studies for each variable and adds a random number the maximum of which would leave the variable at the average. Agents spawn at random within the boundaries of their corresponding habitat.

1.2.9 *Collectives*

Three groups were created, composed of various species that have similar responses to the natural forest edge. In the model, the pasture group of species is represented by color Yellow, forest edge species by the blue color, and forest interior species by the green color. Groups don't interact with each other, and the quantity of individuals only affects the growth rate.

1.2.10 *Observation*

In information used in the model was taken from a study of Caquetá done by Palomino (2019). Now, the interface shows at the top the setup and go button. Then, there are some sliders where the user can input the initial number of amphibians per group, their initial energy, and their movement. They can also select the change rate of the patches, selecting restoration, abandonment, and deforestation. There is also a button at the end to establish neutral values, these are the ones found in the study of Palomino and the rates of habitat change are balanced. In the world, the user can see the movement of the amphibians, their reproduction, and the changes of the patches by their color. On the right, two graphs show the changes in population and the changes in patches.

1.3 *Details*

1.3.1 *Initialization*

The model has set values for the environmental conditions when in setup and there is a button to establish the neutral values for the rate of change of the patches and the exact number of individuals found on field research. However, everything is changeable through the sliders (aside from the initial values of temperature, canopy, and humidity)

1.3.2 *Input data*

The model doesn't have external data files.

1.3.3 *Submodels*

No other models were explicitly integrated.

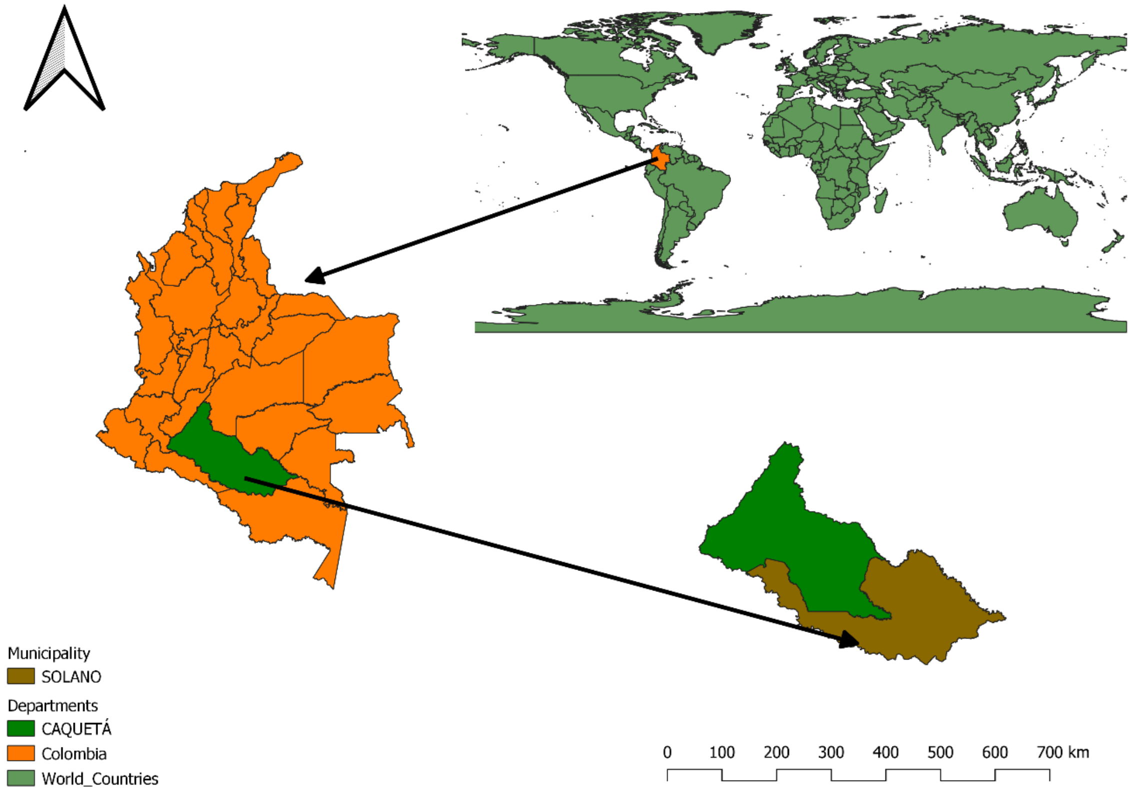

Figure 1. Map of the study area where Palomino-Cuellar (2019) collected the data. Solano, Caquetá, Colombia.

APPENDIX 2: STUDY AREA

Caquetá is a department located in the Amazon Region in southern Colombia (Figure 1). It has approximately 89.000.000 km^2, and the predominant ecosystem is the tropical rainforest. With a deforestation rate of 0.77% (Murad and Pearse, 2018), the Caquetá Department has seen a very aggressive ramp-up in deforestation due to a disorganized colonization process (Etter et al. 2006). Primarily, this colonization has introduced cattle, turning a substantial amount of area into pastures so that the cattle can be productive (Etter et al., 2008). This process has caused 12647 ha of deforestation in Caquetá between 2022 and 2023, ranking it as the most deforested department in Colombia (IDEAM, 2023), causing population declines as some species of amphibians are unable to escape or adapt to the sudden degradation of their environment (Palomino-Cuellar, 2019).

APPENDIX: LITERATURE CITED

Etter, A., C. McAlpine, S. Phinn, D. Pullar, and H. Possingham. 2006. Unplanned land clearing of Colombian rainforests: Spreading like disease? *Landscape and Urban Planning*, 77, 240–54. https://doi.org/10.1016/j.landurbplan.2005.03.002

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IDEAM. 2023. Monitoreo de la superficie de bosque y la deforestación en Colombia - 2023 (Resumen de resultados).

Murad, C. A., and J. Pearse. 2018. Landsat study of deforestation in the Amazon region of Colombia: Departments of Caquetá and Putumayo. *Remote Sensing Applications: Society and Environment,* 11, 161–71. https://doi.org/10.1016/J.RSASE.2018.07.003

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APPENDIX 3: FORMAT OF THE SURVEY

The first two questions ask about the definition of the edge effect and the aspects that can influence the impact of this effect for biodiversity.

The third question consisted of a matrix of three native forest fragment shapes (round, rectangular and irregular) vs. different native fragment sizes (big, medium or small) in which the students had to give a number between 1 and 5, were 1 is low edge effect impact and 5 high edge effect impact in a specialist species of the native forest; the students also had the chance of not putting anything if they were not confident with their answer. This matrix shows the knowledge regarding both shape and size of the patch which are key concepts when understanding the edge.

The fourth question asked students to fill out a matrix similar to the previous one but contrasting the same three native forest fragment shapes but in this case limiting with five different land uses (pasture, shade coffee plantation, cocoa plantations and secondary native forest). Students had to judge the impact on the edge effect in a specialist species of the native forest of different vegetation cover contexts bordering the remnant native forest in a scale of 1 to 5, were 1 is low edge effect impact and 5 high edge effect impact, they also had the chance of not answering if they were not confident.

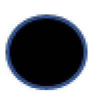
Edge Effect: Survey Phase 1   Name: ________________________________

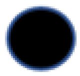
Question 1: How did the concept of edge effect changed after interacting with the model?

Question 2: List some aspects that can be affected by edge effect

Question 3: Thinking of a specialist specie of native forest: Fill the blanks on the following table, giving values between 1, when you consider that the edge effect would be weak, and 5, when you consider that the edge effect is strong. The numerical value evidences the grade of influence of the edge effect when it interacts with (a) size of the native forest and its shape; and (b) interaction between the land use adjacent with the native forest and the shape of the native forest.

1 __________________5
Weak   Strong

(a)	Sizes		
Shape	Large	Medium	Small
			
			
			

(b)		Adjacent Land Use		
Shape	Pasture	Coffee	Cacao	Secondary Forest
				
				
				

Additionally, after phase 3, once the students interact with the NetLogo model, they were asked to answer two additional questions:

Question 1: How did the concept of edge effect changed after interacting with the model?

Question 2: What new aspects did you identify, that are affected by the edge effect, after using the model?