Natural Heritage: A Teaching Game for Biodiversity Conservation

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The potential for computer games to serve as effective learning and teaching tools is now widely acknowledged. Here, we present 'Natural Heritage', an educational turn-based strategy game about biodiversity conservation. In it, the player takes on the role of an elected policy maker who has to balance ecological and economic targets while managing regional land use. The game aims to teach key principles of ecology by integrating them into its game mechanics, such as habitat heterogeneity or the species-area relationship. It also challenges players to think about the economic and political aspects of conservation. The game is open source and available online, and is intended to be used to accompany instruction in an upper secondary or undergraduate class. In this paper, we explain the goal, design, and mechanics of the game, and describe the underlying mathematical model that drives the social-ecological simulation based on the player's input.

Keywords: biodiversity conservation, landscape ecology, land use, serious game, computer game, social-ecological model

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1 Introduction

Biodiversity loss is one of the major crises of our time, threatening not just the survival of numerous species, but also the safe-guarding of nature's contributions to people (Díaz et al., 2019). Slowing this decline—and where possible, reversing it—requires an understanding of the intricate interdependencies between people and nature. In the last two decades, these have been increasingly studied using the social-ecological systems concept, which seeks to integrate environmental, economic, and political perspectives (Fischer et al., 2015). However, effecting transformative change not only requires reliable research, but also the proactive and innovative communication of scientific insights to the wider society (Bickford et al., 2012).

Computer games are a pervasive and influential medium, especially among younger people. There is a burgeoning scientific literature discussing their psychological and sociological effects (e.g. Boyle et al., 2011; de Aguilera & Mendiz, 2003). Much attention has been also payed to their educational potential (e.g. Bado, 2022; Bakan & Bakan, 2018). It is known that computer games can help with knowledge acquisition and content understanding, and games are increasingly being used and created for educational purposes (Connolly et al., 2012).

Unsurprisingly, there have been discussions of the relevance of computer games to biodiversity conservation. Sandbrook et al. (2015) identify five potential benefits of games for conservation: educating players, encouraging behaviour change, fundraising, citizen science data collection, and conservation planning (but see Fletcher, 2017, for a critical opinion). Crowley et al. (2021) report that the extensive digital worlds of some popular commercial computer games may, as a side effect, teach players about real-life species and their behaviour. Fjællingsdal and Klöckner (2019) analyse a cooperative world-building game and show that it can help player gain a better understanding of ecological interrelationships and vulnerabilities, as well as raising awareness for the necessity and possibilities of environmental action. A number of games have been created specifically for environmental and conservation teaching purposes, for example to teach children about water quality and ecosystem health in lakes (Lewerentz et al., 2021), stakeholders about conflicts of interests in national parks (Vasconcelos et al., 2009), or students about land use and sustainable development (Schulze et al., 2015). Evaluations of such games show that even though their direct impact on environmental behaviour may be limited, they can be effective learning tools (Thomas-Walters & Veríssimo, 2022).

Here, we present 'Natural Heritage', an educational turn-based strategy game about biodiversity conservation (Fig. 1). In 'Natural Heritage', the player takes on the role of an elected policy maker who has to make decisions about land use, budget allocation, and environmental regulations at a regional scale. These decisions determine the levels of biodiversity and economic productivity in the landscape. To succeed, the player has to balance ecological, economic, and political targets against a background of growing resource demands and ongoing climate change. Thus, the aim is for players to navigate socio-environmental trade-offs and crises in order to establish a resilient society.

The game was designed and created in an interdisciplinary collaborative project between the Ecosystem Modelling Group and the Games Engineering Group at the University of Würzburg, Germany. The game concept was developed by two ecology students (... and ...), and refined and implemented together with three computer science students (..., ..., and ...). The group leaders (..., ..., and ...) initiated the project and provided scientific and technical advice. This collaboration offered a valuable cross-pollination of skills and knowledge for all team members, and ensured that the resulting product is both scientifically-informed and of high technical quality.

As an educational game, 'Natural Heritage' is targeted at upper secondary and undergraduate students, and is designed to achieve two teaching goals through the concepts that players have to understand to succeed. First, it integrates key ecological concepts into its game mechanics, such as the species-area relationship and habitat heterogeneity, helping players to develop an understanding of ecological dynamics. Secondly, it challenges players to think through the societal aspects of conservation, the necessity of trade-offs between different political goals, and the short-term and long-term consequences of decisions. This makes 'Natural Heritage' a useful tool to communicate ecological theory and stimulate thought about biodiversity conservation, and enables the player to experiment with pathways to transformative change.

2 Game description

2.1 Overview

The game world of 'Natural Heritage' is implemented as a social-ecological model based on a set of equations and logical rules (Fig. 2). An ecological submodel simulates how the player's actions influence biodiversity and productivity in the game landscape. A societal submodel calculates how these in turn affects the player's budget and approval ratings in different demographic groups. The player interacts with the world by changing the usage type and intensity of landscape tiles, as well as by choosing different investment pathways and regulatory options.

The player's aim is to progressively shape the landscape in such a way as to maximise

Figure 1: 'Natural Heritage' is a strategy game about biodiversity conservation, in which the player is an elected policy maker who has to make land-use decisions to balance ecological and economic targets. This figure is a screenshot of the game, showing the game landscape and the user interface.

both biodiversity and productivity (cf. Kremen & Merenlender, 2018; Landis, 2017). The game ends either when the player fails to keep sufficient voters happy and loses an election (held every six years), or is in debt at the time of an election. Climate change and population growth make the game progressively more challenging over time. Game performance is thus measured by the number of years the player manages to remain in office.

'Natural Heritage' can be played online at https://jakob-s.itch.io/natural-heritage, and can be downloaded for Microsoft Windows and GNU/Linux from there.

2.2 Ecological submodel

The game world is based on a landscape of hexagonal tiles. Each tile is assigned a usage type (forest, field, water, or city) and a usage intensity (none, low, medium, or high). A contiguous group of tiles of the same type and intensity form a 'habitat' (Fig. 3). Each tile generates a certain biodiversity and productivity value. These are two abstract numeric values meant to represent ecosystem intactness on the one hand and economic potential on the other.

The **biodiversity value** D is high if the tile's usage intensity is low, the habitat it belongs to is large, neighbouring tiles have a low usage intensity, and there are multiple different habitat types in the vicinity (Fig. 4A, Eqn. 1). This takes into account the ecological effects of land use, the species-area relationship, edge effects, and habitat heterogeneity (cf. Tscharntke et al., 2005). The exact equation is:

$$D(f) = \overbrace{5 \times \big(3 - I(f)\big)}^{\text{Usage intensity}} + \underbrace{3H(f)^{0.2}}_{\text{Habitat area}} + \overbrace{\frac{1}{3}\left(\sum_{i \in N(f)} \big(3 - I(i) + V(i)\big) \right)}^{\text{Landscape}} + B \tag{1}$$

where $I(f)$ is the usage intensity of the tile f in the landscape L, $H(f)$ is the size of the habitat of which f is a part (i.e. the number of contiguous tiles of identical usage type and intensity), $N(f)$ are all tiles adjacent to f and $V(f)$ is the number of different usage types bordering on f. B refers to a positive or negative bonus that a tile might receive due to an event, an investment, or a law (see below for details). Numeric constants are chosen to balance the equation and produce the relative importance of factors shown in Fig. 4.

The **productivity value** P of a tile is high if its usage intensity is high, it belongs to a large habitat, the neighbouring tiles have a high biodiversity, and the overall landscape is not too intensively used (Fig. 4B, Eqn. 2). This illustrates the concepts of land use intensification, landscape simplification, ecosystem services, and environmental degradation (cf. Beckmann et al., 2019). It is defined as:

$$P(f) = \underbrace{2 \times I(f)^2}_{\text{Usage intensity}} + \overbrace{2 \ln \big(H(f)\big)}^{\text{Habitat area}} - \underbrace{\left(\frac{\sum_{i \in L} I(i)}{\max(L)} \right)^3}_{\text{Landscape}} + \overbrace{2 \ln \left(\frac{1}{6} \times \sum_{i \in N(f)} D(i) \right)}^{\text{Ecosystem services}} + B \tag{2}$$

Each tile's biodiversity and productivity values are limited to the range $1 \leq x \leq 50$.

Events are stochastic occurrences that provide a positive or negative bonus to the biodiversity and/or productivity value of certain tiles in a given year (Table 1). The first type of event is coupled to the biodiversity value of habitats: if this is either very high or very low, it may trigger an event. The second type of event is linked to climate change. These become more frequent as the game advances, with the probability of a climate event E in a given year a calculated as:

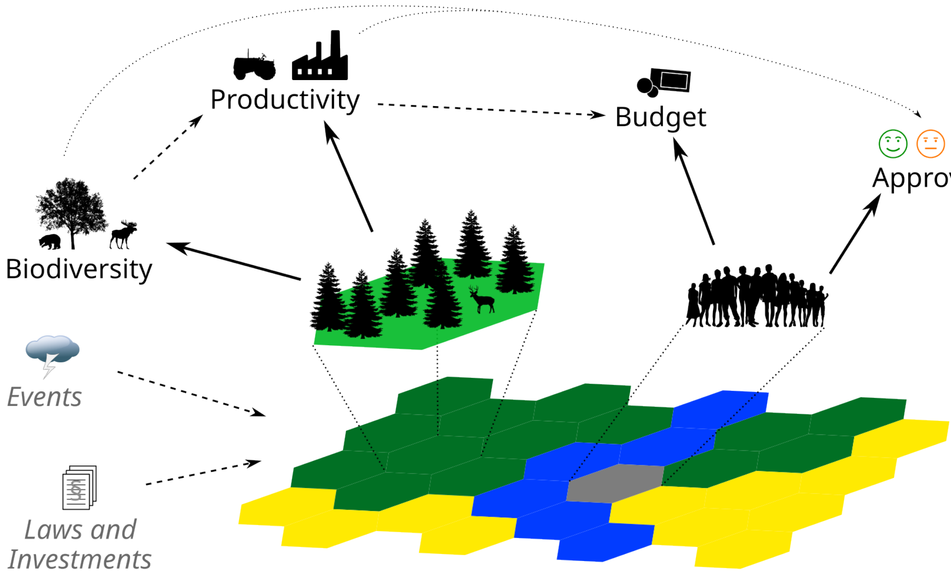

Figure 2: Components of the game's social-ecological model. The landscape consists of hexagonal tiles, each of which have an associated biodiversity and productivity value. The combined biodiversity and productivity values of the entire landscape determine the player's available budget as well as their approval ratings in the population. Stochastic events may influence certain parts of the game world, while laws and investments can be used by the player to influence game mechanics.

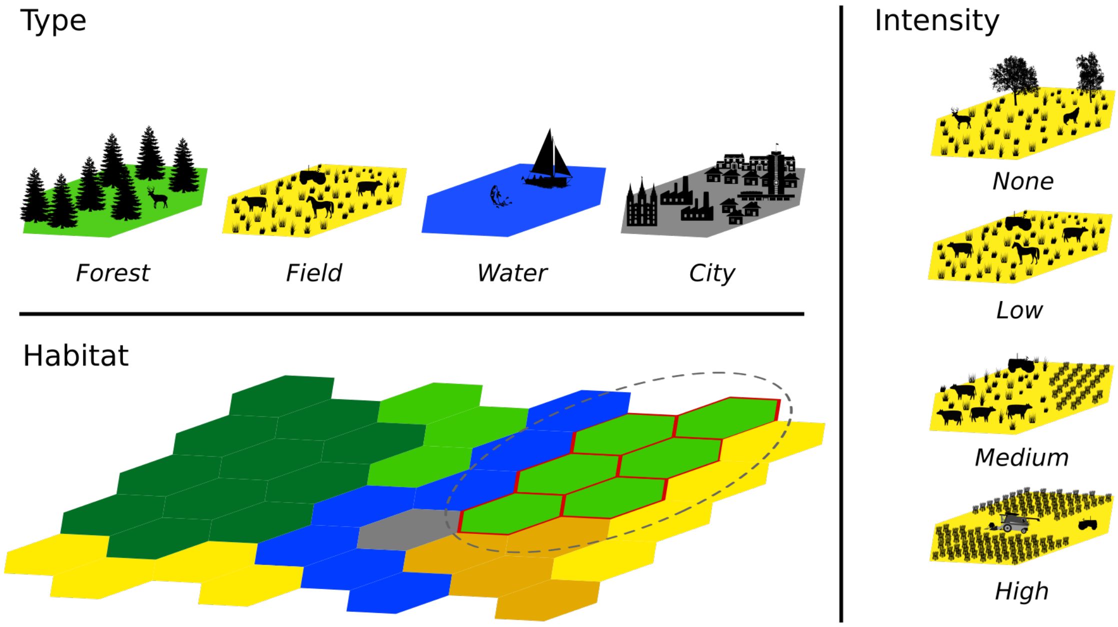

Figure 3: Important game concepts. Each landscape tile is assigned a certain usage type (forest, field, water, or city). Except for city tiles, all tiles have a usage intensity (none to high). A contiguous area of tiles of the same type and usage intensity is referred to as a habitat.

$$E(a) = \frac{1}{10} \times \ln\left(\frac{a}{3} - 1\right) \tag{3}$$

Implementing the 'climate protection' law (see below) changes the leading constant from 0.1 to 0.05.

2.3 Societal submodel

Each turn, the functionality of the game landscape is evaluated for three purposes: biodiversity, productivity, and tourism. The biodiversity and productivity landscape values are simply the sum of the respective values for all tiles. The **tourism value** was introduced to account for the preference of recreational landscape users for near-natural areas that nevertheless offer basic infrastructure (Schirpke et al., 2018). It serves to introduce the concepts of cultural ecosystem services and the co-production of nature's contributions to people (Kachler et al., 2023). It was modelled as a simple integer point value based on land use intensity: 4 points for low usage, 3 points for wilderness (no usage), 2 points for medium usage, and 1 point for high usage intensity. The tourism landscape value is calculated as the sum of tile values based on this scoring.

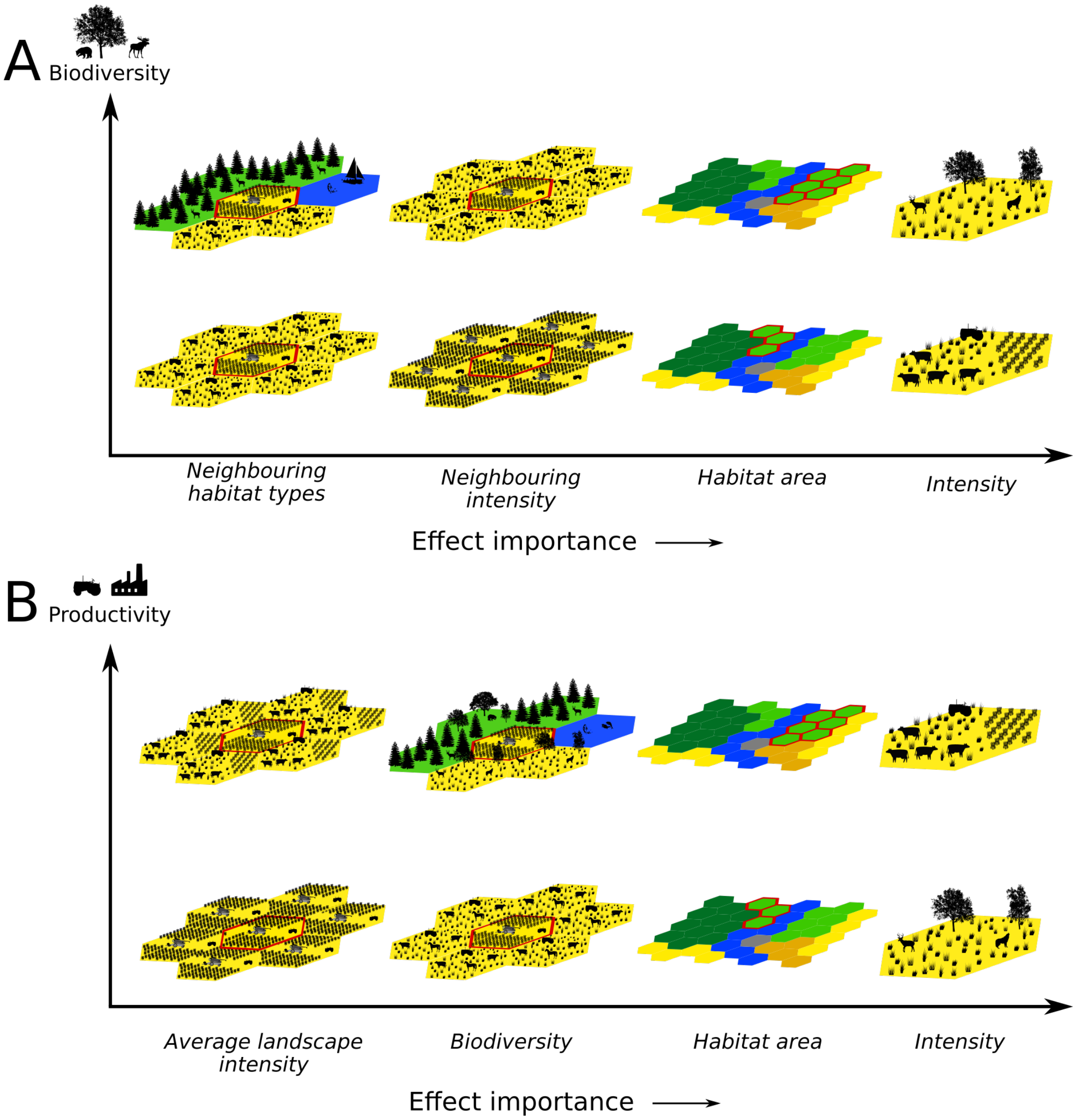

Figure 4: Graphical summary of rules governing (a) biodiversity and (b) productivity in the game world. Effect importance increases to the right (i.e. usage intensity is the most important factor for both values.)

Table 1: List of stochastic events that may occur during the game. Biodiversity events occur in habitats with especially high or low biodiversity. Climate events become more frequent over the course of the game.

Type	Event	Description
Biodiversity	Bark beetle	A forest habitat with low biodiversity suffers a productivity penalty.
	Erosion	A field habitat with low biodiversity suffers a productivity penalty.
	Eutrophication	A river habitat with low biodiversity suffers a productivity penalty.
	Rare species	A wilderness habitat (usage intensity 0) with high biodiversity is given a biodiversity and productivity bonus.
Climate	Flood	Tiles adjacent to a river habitat suffer a productivity penalty, which is higher the more intensively the river is used.
	Forest fire	A forest receives a multi-year biodiversity and productivity penalty.
	Drought	All field and river habitats with a usage intensity of at least 1 receive a productivity penalty.
	Good weather	All fields with a usage intensity of at least 1 receive a productivity bonus.

Table 2: Weighted preferences of each demographic for each landscape function.

Demographic	Biodiversity	Tourism	Productivity
Conservationists	80%	20%	0%
Tourists	30%	60%	10%
Residents	20%	40%	40%
Farmers	30%	0%	70%
Industrialists	0%	20%	80%

The game world's population is split into five equally sized **demographic groups**: conservationists, tourists, residents, farmers, and industrialists. Each of these groups have different preferences for the different landscape functions (Table 2). To calculate how appreciative each group is of the current landscape (W), the landscape values for each of the three purposes are multiplied by the group's preference for this value and summed up (Eqn. 4). This value is then used to calculate a percentage approval rating Z using a sigmoid curve function (Eqn. 5):

$$W_b(L) = \sum_z \Big(b(z) \times \sum_{f \in L} z(f) \Big) \tag{4}$$

$$Z(b) = \left(1 + e^{-0.2\left(W_b(L) - 0.5 W_b(L_m)\right)} \right)^{-1} + B \tag{5}$$

where $W_b(L)$ is the value assigned by a demographic group b to the landscape L, $b(z)$ is the preference the group has for the purpose z (Tab. 2) and $z(f)$ is the value that the tile f has for this purpose. $Z(b)$ is the approval rating of b and L_m is a hypothetical 'ideal landscape'.

In the first year of each legislative period, the player is presented with a choice of **investments** for the coming six years. One research option and one subsidy option may be chosen out of these, with differing short- and long-term consequences (Table 3). In the third and fifth year of each legislative period, the player is further presented with a **law** which can be enacted, rejected, or repealed if it was previously enacted (Table 4). All investments and laws are popular with some demographics and unpopular with others, thus giving the player bonuses and penalties to the approval ratings. These mechanics simulate governmental budget planning and legislative actions, and the trade-offs and prioritisation these necessitate.

The player's annual **profit** J is calculated by summing up the productivity of all tiles in the landscape, minus the upkeep cost of the population and any expenditures:

Table 3: List of possible investments. Each legislative period (six years), a player may choose one research and one subsidy investment, which are subtracted from their budget annually until the next elections.

Type	Target	Description
Research	Conventional agriculture	Permanently increase productivity on fields with high usage intensity.
	Organic agriculture	Permanently increase productivity and biodiversity on fields with medium usage intensity.
	Biodiversity conservation	Permanently increase biodiversity of tiles with no or low usage intensity.
Subsidy	Conventional agriculture	Temporarily increase productivity of forests and fields with medium or high usage intensity.
	Organic agriculture	Temporarily increase productivity of forests and fields with low or medium usage intensity.
	Tourism	Temporarily increase productivity of tiles with low usage intensity.

$$J(a) = \sum_{f \in L} P(f) - V(a) - K(u) - Y \tag{6}$$

where $P(f)$ is the productivity of tile f, V the upkeep costs for the current population, $K(u)$ the costs for landscaping operations (changes in tile type or usage intensity), and Y any payments for ongoing investments.

To make the game more challenging as it goes on, **cities** expand over time, thus increasing the population's upkeep costs and reducing the size of productive habitats (simulating the effects of urbanisation and urban sprawl). Additionally, the support of all demographics decreases automatically by 0.5 % per year.

2.4 User interface

The user interface is visible in Fig. 1. The player can move around the map using the WASD keys, rotating the camera with Q and E, and zooming in or out with the scroll wheel. Clicking on a tile selects it, holding 'shift' allows multiple tiles to be selected, and double-clicking selects an entire habitat.

The top bar displays the player's current budget and anticipated end-of-year income, together with a year counter and the time to the next election. The box in the top right displays the approval ratings of the five different demographics alongside their current trend (positive or negative), as well as the current biodiversity, productivity, and tourism

Table 4: List of possible laws. A random law is suggested to the player every few turns for passing or repealing.

Name	Description
Fire brigade	Invest an annual amount of money to reduce the damage caused by forest fires.
Flood protection	Invest a large one-off sum of money to reduce the damage caused by floods.
Climate protection	Invest an annual amount of money to reduce the frequency of climate-related events.
Prohibit glyphosate	Increase biodiversity and decrease productivity on fields with high usage intensity.
Allow GMO	Increase productivity on fields with medium or high usage intensity.
Rewilding	Invest a one-off sum of money to reintroduce a species to a forest wilderness habitat (no usage). Gives a biodiversity bonus to all wilderness areas.
National parks	Commit yourself to leaving at least 10 % of tiles as wildernesses (no usage). Gives a biodiversity bonus on wilderness tiles.
Expand organic agriculture	Commit yourself to setting at least 60 % of field tiles to low or medium usage.
Encourage tourism	Commit yourself to keeping at least 20 % of all tiles at low usage.

rating of the entire landscape.

The box at the top left can be used to change the usage type and intensity of the currently selected tile(s), displaying the financial cost associated with each operation. The button in the corner above it opens the in-game wiki, which provides a short description of all game concepts. The large button in the lower right ends the turn and advances the simulation by one year.

Finally, the two buttons in the lower left are used to toggle the overlays: these display the current biodiversity or productivity values of all tiles using a colour/height coding. They also enable tool-tips, which display the precise biodiversity or productivity values of a specific tile when the player hovers the cursor over it, as well as explaining what factors contribute to this value.

2.5 Tactics and player experiences

The game mechanics are designed and balanced in such a way that neither a purely profit-oriented nor a purely conservation-oriented approach will be sustainable over the long term. Players need to generate income in order to support a growing population, yet maximising short-term profits will create a social-ecological trap as accumulating environmental degradation destroys the landscape's productive potential (Brinkmann et al., 2021). To be successful, players therefore need to take a long-term perspective, incrementally optimising the landscape for both biodiversity and productivity while investing into organic agriculture research to ensure continuous but sustainable economic growth. An optimal landscape consists mostly of large but irregularly shaped habitats, which take advantage of the size and heterogeneity effects on biodiversity and productivity, managed at medium intensity. These can be interspersed with 'protected areas': smaller habitats with no usage that provide a biodiversity and ecosystem services boost to the surrounding habitats.

During development, we worked together with a group of playtesters to evaluate the game mechanics and interface. Biology students who did not know the game, but were familiar with the scientific principles behind it, found the game-play intuitive and could play for over 100 years (= turns) without a problem. On the other hand, computer science students without the background in conservation science struggled initially to make sense of the different concepts and interconnections in the game model, as the number of aspects that have to be considered give the game a rather steep learning curve. Based on their comments, we developed the in-game wiki and the tooltips to give players built-in resources to understand the game mechanics.

From this playtesting experience, we recommend that instructors who wish to use the game in class do so after students have received at least a brief introduction to the ecological and socio-economic concepts contained in it. This will allow students to deepen their understanding by operationalising their theoretical knowledge, without being overwhelmed by too many new concepts. Embedded in a well-constructed teaching unit, the game can make learning about conservation more fun and help students understand the complex challenges inherent in environmental problems (Ulrich, 1997).

While the game contents are based on typical undergraduate ecology courses, the game can be understood and enjoyed by younger audiences, given adequate guidance. When we presented the game at a science exhibition, we received much interest from teenagers and children, including a nine-year-old boy who successfully played over 30 rounds. This leads us to expect that the game can be profitably used both in a secondary school and a university setting.

3 Discussion

Our first aim with 'Natural Heritage' is to teach a number of key principles of landscape ecology. Specifically, the social-ecological world model includes land-use intensity, landscape simplification, the species-area relationship, edge effects, habitat heterogeneity, ecosystem services, and the effects of climate change. These are principles covered in many introductory ecology and conservation courses and textbooks (e.g. Begon et al., 2006; Primack, 2014). Integrating these into the game mechanics allows players to develop a deeper functional understanding for the connections between land use, landscape structure, and biodiversity (cf. Chetitah & Von Mammen, 2023).

Our second aim is to increase awareness for some of the political and social aspects of biodiversity conservation. Most importantly, players have to learn to manage for multiple goals (ecological, economic, and political), thus introducing the idea of landscape multifunctionality (Fischer et al., 2017). Furthermore, players are constantly constrained by the financial costs of their actions, an aspect that is often neglected in conservation research (Iacona et al., 2018). And as in real life, most actions will be popular with some people and unpopular with others—thus giving rise to the fundamental tension at the heart of decision-making in any democracy.

Of course, there were many trade-offs to be made during the design and implementation of the game. The socio-ecological model at the heart of the game world is in many ways very simplistic, particularly with regards to the societal submodel. As with all modelling, we had to carefully weigh the costs of any complexity we added (Sun et al., 2016; Vedder et al., 2021). This was doubly true since this is a game, not a scientific research model, and irrespective of all didactic purposes is supposed to be fun to play (Sandbrook et al., 2015).

By publishing 'Natural Heritage' and making it openly accessible, we hope that others will find it useful and enjoyable. Contributions from interested users are welcome on Github. In particular, translations into other languages would be helpful to make the game more internationally usable in teaching.

The potential of computer games to provide a stimulating and effective learning experience has been amply demonstrated over the past twenty years. With 'Natural Heritage', we present an open-source strategy game designed to teach players basic principles of ecology and to provoke thought about the societal aspects of biodiversity conservation, allowing them to experiment with pathways to transformative change.

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Availability

'Natural Heritage' can be played online at https://jakob-s.itch.io/natural-heritage, and can be downloaded for Microsoft Windows and GNU/Linux from there. The source code is available on Github (https://github.com/CCTB-Ecomods/Natural-Heritage).

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