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Article

After the Eruption: Tackling Complex Sustainability Issues Through a Role-Playing Simulation

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Abstract

Developing strategies to sustainably manage landscapes to meet environmental, social, and economic goals is an increasing concern in a world experiencing anthropogenic global change. Here we evaluate how our game *Resilience: After The Eruption*, a digital role-playing simulation game, helps us answer the question of how to design serious games to facilitate understanding of complex sustainability issues. In a simulation of the aftermath of the 1980 eruption of Mount St. Helens, players of Resilience: After The Eruption perform resource management and engage in stakeholder collaboration. Through pre- and post-gameplay surveys, we assessed user experience and whether players learn about the complexities of the natural and human phenomena that affect post-disturbance ecological recovery processes and experience the challenges of multiple-stakeholder cooperation. Players showed an overall increase in knowledge that corresponded to the desired learning objectives and generally reported a positive user experience. Our results support the idea that role-playing simulation games like Resilience: After the Eruption can be a useful tool for educating and training individuals on complex sustainability issues.

1. Introduction

1.1 Background

Developing strategies to sustainably manage landscapes to meet environmental, social, and economic goals is an increasing concern in a world experiencing anthropogenic global change [1]. Responsible decision making often involves understanding the complexities of the systems involved and cooperation among stakeholders[1] [2]. For example, an ecologist must understand how an ecosystem responds to irregular disturbance events like landslides, windstorms, and wildfires and communicate this information to resource managers, recreation managers, and resource extractors such as foresters to maximize preservation of ecosystem services[2], human lives, infrastructure, and other assets [3-4]. Communicating information about the complexities of collaborative resource management to future generations is a challenge unto itself. Complex relationships among environmental, social, and economic systems are difficult to accurately depict using conventional forms of education media such as text and infographics [5]. A promising approach for increasing understanding of complex systems from a variety of perspectives is the use of active learning facilitated by multimedia educational tools like serious games [6-8].

Serious games are games that serve a primary objective other than entertainment, such as furthering a player's knowledge of a concept, teaching them a skill, or having them experience a simulated situation [9]. Serious games have the benefit of featuring real-world content in ways that facilitate learning about complex concepts and systems in comparison to more conventional educational tools [10-11]. The interactive and experimental approach to learning permitted by serious games allows for greater understanding, particularly in fields like ecology and spatial planning, where it is important to understand the relationships between concepts and the greater whole (i.e., systems thinking) [12-13]. Presently, sustainability-focused serious games often focus on environmental, social, or economic systems separately without considering the relationships between all three [14]. Therefore, there is a need to explore how serious games can facilitate learning about issues involving the three subsections of sustainability.

We demonstrate the utility of digital serious games for educating about complex sustainability issues through *Resilience: After The Eruption* (hereafter referred to as '*Resilience*'), a game that simulates resource management and the multiple stakeholder decision-making process in an environment undergoing rapid change. The game synthesizes some of the major concepts learned after the eruption of Mount St. Helens (Washington, USA), including insights gained from over 40 years of research on recovery after a large-scale disturbance and the careful planning of resource management activities to foster recovery processes. Within the game, 1-4 players take on the role of a suite of stakeholders and interact with a simulated landscape, attempting to make management decisions that conserve the natural, social, and economic resources of the area. Our development of *Resilience* fulfils the absence of interactive educational tools that allow for the exploration of ecosystem change considering both environmental and socioeconomic dimensions.

1.2 Objectives

Our goal in developing *Resilience* is to assess if and how serious games can be used to learn about the sustainable management of several complex interconnected systems while avoiding an overly complex user experience. We seek to answer three questions to discover if our design and deployment of *Resilience* is successful: 1. Do players of *Resilience* learn about the complexities of the natural and human phenomena that affect post-disturbance ecological recovery? 2. Do players of *Resilience* experience the challenges of multiple-stakeholder cooperation? 3. Do players of *Resilience* find the game fun, engaging, educational, and easy to learn how to play? Research questions 1 and 2 concern the comprehension of the main themes

[1] We define stakeholders as all persons and groups that influence the activity or may be affected positively or negatively by changes in the provision of ecosystem services or socioeconomic conditions associated with the activity [15].
[2] Ecosystem services refer to the benefits that people derive from nature such as clean water, timber products, and recreation opportunities [1].

of the game and depend on how players meet two learning objectives: A. Players learn about the complexities of the natural and human phenomena that affect post-disturbance ecological recovery and B. Players experience the challenges of multiple-stakeholder cooperation. Research question 3 assesses how players interface with *Resilience* and is measured based on responses to questions about their experience with the game.

Here, we outline how *Resilience* expands upon previous work in the field of simulations and serious role-playing games. We then describe the scientific underpinnings and context of the game, as well as the key aspects of the development process, including design principles and elements that are important for delivering learning objectives while facilitating a positive user experience. We include an analysis of player responses to a survey designed to answer our research questions. We also analyze whether demographics and opinions on gameplay experience affect a player's ability to meet the learning objectives to address if the game is accessible across a wide audience. Finally, we discuss applications of *Resilience* and what has been learned thus far about the merits of the game through the analysis of player feedback. We show that our design of *Resilience* demonstrates the potential for serious games to engage individuals in thinking about complex sustainability issues without being overly complex to use. Finally, we discuss some potential next steps for the further development and deployment of *Resilience*.

2. Related Work

Sustainability-focused games are becoming increasingly common tools for learning and producing solutions to real-world issues [16]. Many of these games promote systems thinking focused on complex topics, often using simulations [17-18]. Simulations enable learners to explore complex systems at their own pace, test solutions to realistic problems, and gain instantaneous feedback on their choices [19]. Despite the growing number of simulation games that deliver content on environmental, economic, and social sustainability, there are few games that simulate how these three systems are interconnected, with a particular lack of games that explore social sustainability [14].

Among the growing number of sustainability-focused simulation games, several feature role-playing elements [20-21]. Role-playing increases engagement by allowing players to place themselves within the narrative of a game, focusing greater attention on the game's world and the in-game impacts of their decisions [22-23]. In games where cooperation among stakeholders is a goal, role-playing can be used to help players build collaboration skills through simulating conversations had by their roles' real-world counterparts [24-25]. *Climate Action Simulation* is one such example of a simulation-based stakeholder-role-playing game in which a digital model provides instantaneous feedback as the participants attempt to reach collective agreements on climate-based issues [26]. The game's featured data-driven model allows for interpretation of how players acting as environmental stakeholders can impact variables such as sea level rise and global temperature.

The level of abstraction from reality in a simulation can impact the efficiency of the delivery of its content [27-28]. The game *Climate Action Simulation* is framed by a digital interface that features relatively abstract depictions of real-world variables that are represented by graphs and sliders. By contrast, games that include more detailed simulations with in-depth visualizations of concepts promote greater comprehension of their content, especially among those with little or no prior knowledge of the subject areas [29-31]. However, a challenge when developing more in-depth simulations is including enough detail to orient the player without causing cognitive overload [32-33]. In comparison to physical games, digital games have the benefit of reducing cognitive load through automating game processes like scorekeeping and providing convenient access to in-game information like rules [34]. Other techniques for creating games that manage cognitive load without sacrificing depth of content include allowing players to progress at their own pace, minimizing irrelevant information, and presenting information in a conversational style [35].

The current library of serious games lacks in-depth examples focused on ecological succession: the process that a disturbed ecosystem goes through with the return of plant and animal life and re-establishment of ecosystem interactions such as nutrient cycles. Many existing interactive teaching tools that explore succession depict simplified and more outdated views of the concept that are not consistent with current scientific understanding and are targeted towards younger learners [36-37]. In the *Ecological Succession* kit, a board game-like activity for classrooms, players move along the board in a line starting from bare rock towards a “climax community” [38]. The climax community idea misrepresents the potential for nonlinear ecosystem changes reflective of the theory of alternative stable states [39], which proposes that ecosystems exist in an equilibrium state that generally resets after small disturbances but may be shifted to a new equilibrium state after a sufficiently large disturbance [40-42]. The theory of alternative stable states has proven useful in developing more robust models that inform environmental management decisions [43-44]. Therefore, there is a need for education around this concept to prepare future environmental managers.

3. Development of *Resilience: After the Eruption*

3.1 Concept

When beginning development of *Resilience*, our goal was to create an in-depth yet accessible game for learning about the aftermath of the 1980 eruption of Mount St. Helens. Specifically, we wanted to deliver concepts from over 40 years of research on management of resources and ecosystem recovery on disturbed landscapes to students grades 8 and above as well as to professionals in resource management fields [45-48]. When researching similar examples of games based on sustainable resource management, we noticed a lack of games that considered how environmental, social, and economic systems intertwined. To fill this gap, we designed *Resilience* to allow players to role-play as different stakeholders who impact and whose decisions are affected by the natural, social, and economic resources on the debris avalanche deposit at Mount St. Helens: the 60 km^2 gray, rocky landscape that was created when the top of the mountain collapsed in the 1980 eruption [49-50]. We also noticed an absence of games that featured in-depth depictions of ecological succession. To this end, we developed a spatially explicit model that simulates how the ecosystems on the debris avalanche deposit change over time.

We based the stakeholders featured in *Resilience* on four diverse professions that were engaged in the management of the debris avalanche deposit after the 1980 eruption: Ecologists, Resource Managers, Recreation Managers, and Foresters. Ecologists wanted to understand the processes and patterns of ecosystem reestablishment. Resource Managers fostered ecological benefits provided to the region such as clean water and abundant habitats, while maintaining the safety of people in and around the area by reducing risks of disturbances such as wildfires and landslides. Recreation Managers sought to provide safe, interesting, and fun opportunities for the public to learn about the eruption and ecosystem recovery as well as to enjoy outdoor experiences. Foresters managing the land for timber production focused on growth and sustainable harvesting of trees while considering forestry’s effect on the ecological recovery processes of the area [51]. Within *Resilience*, each stakeholder has different values that they are concerned with. Some values are shared between multiple stakeholders, including several values that are important to all stakeholders. We plotted stakeholder values on a four-way Venn diagram to visualize how certain variables could affect each stakeholder in *Resilience* (Figure 1).

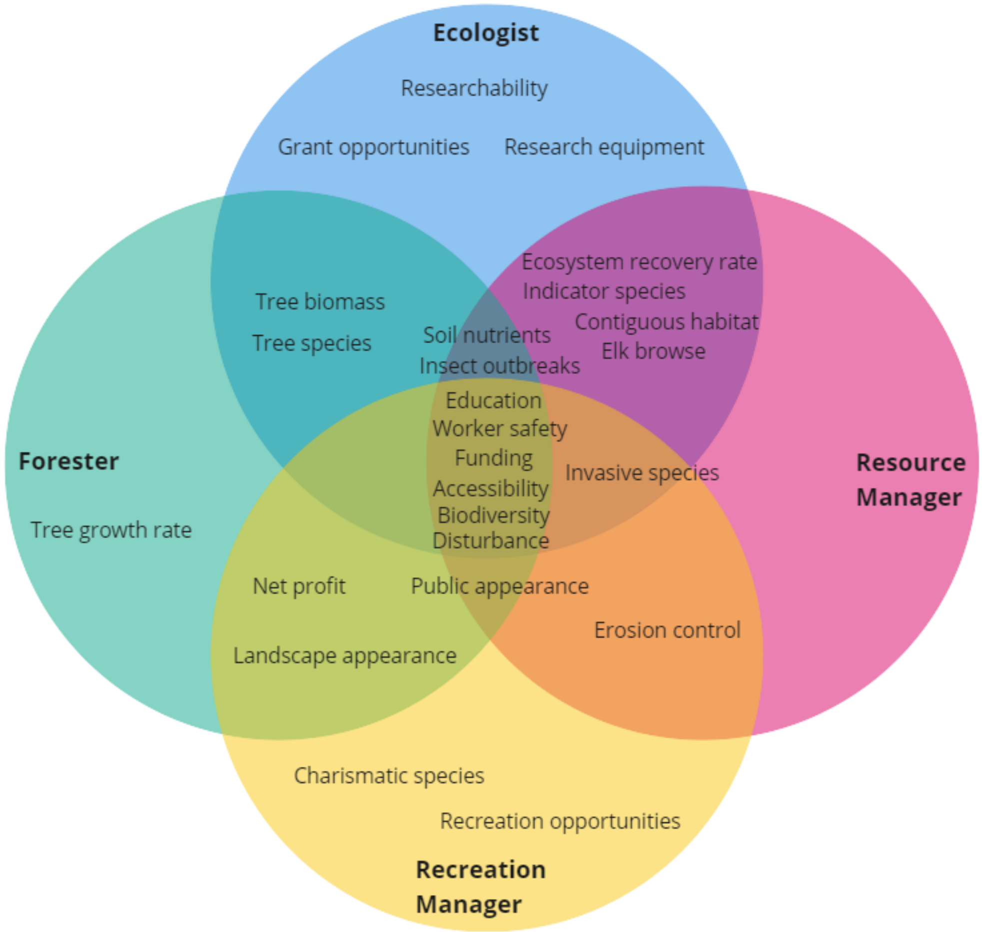

Figure 1. Venn diagram showing the overlapping concerns of stakeholders in *Resilience*.

3.2 Gameplay Overview

When beginning a new game, players view a short, narrated video outlining the game's scenario, which includes real footage from the eruption of Mount St. Helens. Then, players decide whether to play alone or with others and choose the stakeholder roles that they inhabit. When playing alone, a player takes on the role of all 4 stakeholders. In multiplayer games, players assign themselves to each of the 4 stakeholder roles. We designed *Resilience* so that single players are still able to learn about the challenges faced by multiple stakeholders with shared resources. Additionally, having a single-player mode makes the game more accessible by not requiring a group of people to be engaged or for those who prefer to play alone.

Players begin a new game in the year 1980, initially viewing a simulated debris avalanche deposit landscape composed of rocky substrate and containing a river and a few small lakes. A series of tutorial messages helps familiarize players with the user interface, controls, and goal of the game. As players zoom in and out, pan around, and click to view details of plots of land, they may notice that plant and animal life are currently scarce, and the soil is devoid of nutrients. In addition to investigating the landscape, players can also view their available actions, resources, and goals. The details displayed depend on which of the four stakeholder roles the player is currently playing as. Figure 2 shows an example of what a player will see when making decisions as the Forester including current funds (top left), actions that can be taken (middle left), the landscape simulation (middle), current year and turn order (top right), and goals (middle right).

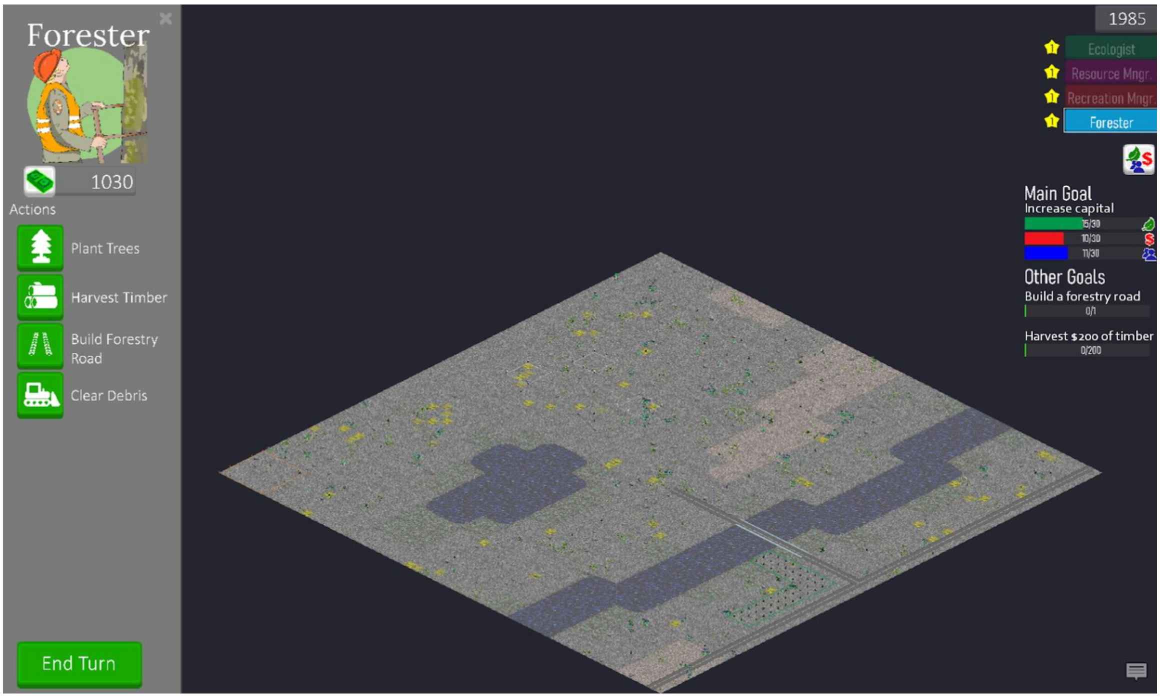

Figure 2. User interface screenshot showing available actions, resources, and goals of the Forester.

At the start of each stakeholder's turn, they will receive a salary. Then, the player that is assigned to that stakeholder's role will begin taking actions. Available actions differ among stakeholders, and the execution of each action is typically limited by one or more of three different means: money, space, and progress. If a stakeholder does not possess enough money to complete an action, they will have to wait until they receive their salary at the start of their next turn or until another stakeholder provides them with money. If there is not enough space available for an action, the stakeholder will have to manipulate the landscape in some way to either increase access or create space for that action. For example, a Recreation Manager can build roads that allows them to access new areas for building infrastructure, and a Forester can harvest trees on one of their forestry plots to make the area available for another action. Finally, several actions are not available from the start of the game and must be unlocked through in-game progress. For example, a Resource Manager does not have access to invasive species management actions until the Ecologist has published research on the invasive species. More information on stakeholder goals and the actions they can take is detailed in Table 1.

Table 1. Stakeholder role descriptions

Stakeholder	Goal	Actions
Ecologist	To study the landscape and inform environmentally responsible management by communicating their findings to the other stakeholders and the public	• Sample research plots to gain data on soil conditions, plants, and animals • Publish research after collecting enough data to provide players with information on soil conditions or a plant or animal species • Apply for grants for a chance to increase funds
Resource Manager	To monitor and protect the recovery process of the ecosystem and ensure the safety of the public	• Establish areas as “preserves” to forbid certain uses (e.g. public road development, forestry) • Remove rubble after the initial eruption and subsequent landslides • Construct a fire watchtower to prevent wildfire spread • Remove invasive species
Recreation Manager	To create opportunities for the public to engage with the landscape	• Construct a trail system to improve public enjoyment of the landscape • Construct a visitor center to greatly improve public opinion of the recreation manager and other stakeholders • Construct public roads to increase the amount of area accessible to all stakeholders
Forester	To create and maintain healthy forest systems and an ecologically and economically sustainable timber harvest	• Plant trees • Harvest mature trees to gain funds • Construct forestry roads to increase the amount of area accessible to the forester • Conduct prescribed burns to reduce the potential intensity and spread of wildfires

After all stakeholder roles have committed actions and ended their turns, time advances within the simulation. Players can determine how many years pass before they would like to take actions again. As time advances, plants establish, reproduce, and spread where conditions are suitable for the survival of the species. Over the years, animals move in and populate the area, and nutrients return to the soil as organisms die and decompose. Major disturbances may also randomly take place including wildfires, landslides, and insect outbreaks. These changes were informed by the findings of research on ecological succession that was conducted on the real-world debris avalanche deposit at Mount St. Helens [52]. After time has passed and the simulation has been updated, players resume taking actions and the process repeats. Over many years, players will notice how these changes are affecting elements in the game, like effects on trail use as shown in Figure 3.

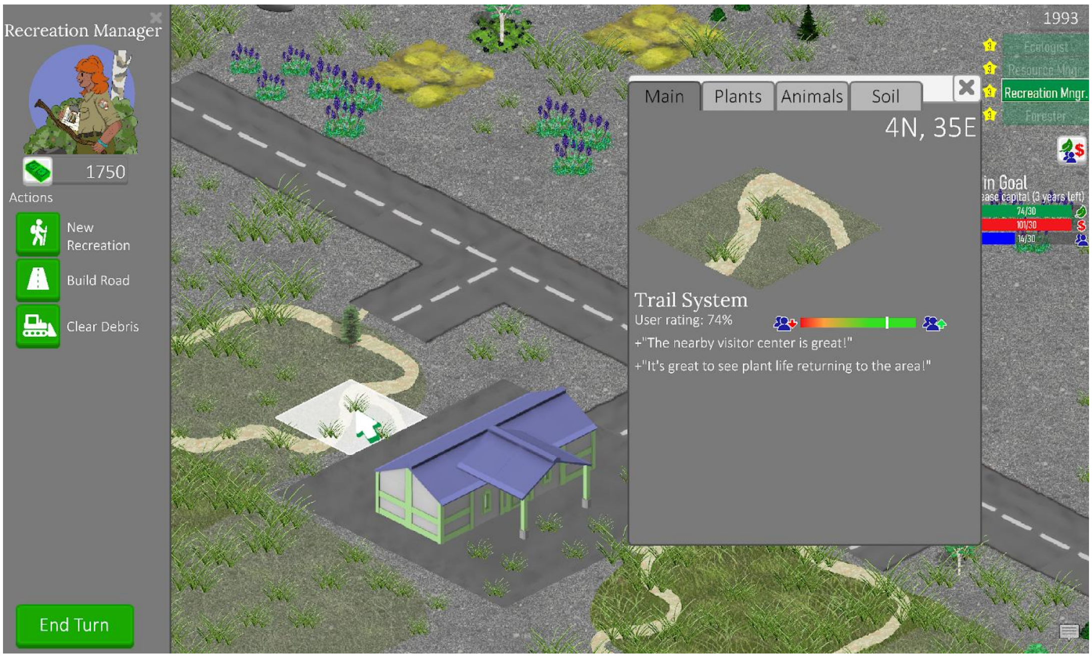

Figure 3. A screenshot showing information about a highlighted grid cell. One use of this feature is to provide the Recreation Manager with information on trail systems they have built in the form of user feedback ratings and comments. Other uses of this feature include seeing what plants, animals, and soil conditions are present in an area.

3.3 Goal of the Game

Players' progress in *Resilience* is measured through how their actions affect the natural features of the landscape, their funds and assets, and human resources. These variables are respectively represented by three types of Capital: Natural, Economic, and Social. The win condition of *Resilience* is achieved when all stakeholders hold Natural, Economic, and Social Capital above a minimum threshold at the same time. Achieving sufficient Capital in this way represents a successful equilibrium state where all stakeholders can simultaneously meet their monetary goals while serving the public and without compromising the recovery process of the landscape. More specific information on Capital types is detailed in Table 2.

Table 2. A description of the three types of Capital. "Factors for increase" and "Factors for decrease" are ways that each type of Capital can be gained or lost respectively. "Measurement basis" refers to whether the value of that type of Capital is shared among all stakeholders or unique to each stakeholder.

Capital	Factors for increase	Factors for decrease	Measurement basis
Natural	• Fostering growth of plant and animal species diversity • Fostering increase in native plant biomass • Creating more continuous wildlife habitat	• Losing plant and animal species diversity • Losing native plant biomass • Fragmenting wildlife habitat	Shared
Economic	• Increasing funds held • Investing in assets (e.g. trail systems, fire watchtowers, forestry plots)	• Decreasing funds held • Destruction of assets	Individual
Social .	• Publishing research • Designating areas as preserves • Building trails in favorable locations • Building infrastructure (e.g. visitor centers, fire watchtowers)	• Demolishing preserves • Poorly maintaining trails • Clear-cutting forests	Individual

In Figures 2 and 3, the levels of Natural, Economic, and Social Capital are represented as the three colored gauges at the middle right side of the screen. Each Capital gauge also has an associated goal that players must reach to succeed. Upon committing their actions, players see how those actions affect Capital levels. For a more long-term analysis of changes in Capital, players can access a line graph that displays how the value of each type of Capital has changed across the course of the game. After a specified number of turns, players must pass a Capital "checkpoint," which assesses if they have been successful in increasing their Capital. If Capital levels are not high enough, the game ends. Otherwise, the game continues, with higher Capital goalposts put in place. The game continues for 3 checkpoints, after which players are deemed winners. Players are then given the option to continue the game indefinitely if they wish to keep on interacting with the simulation.

In addition to the main goal, players are given short-term goals to complete. These goals are unique to each stakeholder and award a resource known as "prestige," which adds to the amount of money each stakeholder receives at the start of their turn. Short-term goals exist to give players a sense of direction towards completing the overall goal of the game.

3.4 Strategy

3.4.1 Cooperation with Nature

To progress in *Resilience*, players must learn how to work with nature. By paying attention to the ecological processes that occur throughout the game, players learn how to take successful actions. For example, a player fulfilling the Forester role must observe how certain plants increase the amount of nitrogen in the soil to make successful decisions about where to plant trees. Additionally, major natural disturbances such as droughts, landslides, wildfires, and insect infestations take place randomly every few years throughout the game and largely work against the players by setting back their progress towards reaching their goals. For example, landslides have the potential to destroy infrastructure such as roads and bridges, leading to decreases in Social and Economic Capital by limiting the public's access to certain areas and facilities. The timing of disturbances is unpredictable to encourage players to learn about the effects of disturbances and develop robust strategies to mitigate the disruption they cause. The simulation of ecological processes in combination with the actions that players take is intended to deliver the first learning objective of *Resilience*: "Players learn about the complexities of natural and human phenomena that affect post-disturbance ecological recovery processes."

3.4.2 Cooperation among Stakeholders

In addition to considering their effects on the game's environment, players must consider how their actions as one stakeholder both directly and indirectly impact the Capital of all stakeholders. Stakeholder roles may directly interact through affecting features on the shared landscape to increase Natural Capital or sending funds to each other to increase Economic Capital. When multiple individuals are playing together, a useful strategy is to converse to inform each other's decisions by sharing relevant information, bargaining, or making general comments. When an individual is playing alone, the conversation may take the form of an internal dialogue as the player strategizes to meet the needs of all 4 roles. Figure 4 shows how the game encourages players to publish research as the Ecologist, which will help other stakeholders make more environmentally responsible decisions and increase overall Natural Capital. Not every action is mutually beneficial, however. Without thoughtful action or collaboration, one stakeholder may indirectly affect the abundance of one or all types of Capital, rendering some stakeholders unable to meet their quota. For example, a Recreation Manager can build roads, which allows them to increase their Social and Economic Capital through increased visitors. This action also helps the Forester to access new areas to plant timber stands, increasing their Economic Capital. At the same time, the amount of Natural

Capital may indirectly decrease with more roads constructed on the landscape, as habitats become more fragmented and noise pollution drives away wildlife. Road building may also lead to a decrease in the quality of the habitat preserved by the Resource Manager, thus decreasing their Social Capital. Specific details on how each stakeholder can affect the three types of Capital are detailed in Table 3. The challenge of reconciling different stakeholder goals is intended to deliver the second learning objective of *Resilience*: "Players experience the challenges of multiple-stakeholder cooperation."

Figure 4. A pop-up tutorial message telling players about the effects of publishing research as the Ecologist.

Table 3. Examples of how each stakeholder may increase and decrease Natural, Economic, and Social Capital within *Resilience*. A "(+)" symbol indicates actions that increase a specific type of Capital, while a "(-)" symbol indicates actions that decrease that type of Capital.

Ecologist		
Natural Capital	**Social Capital**	**Economic Capital**
(+) Informing environmentally responsible actions through publishing research (-) Creating soil erosion through accessing plots	(+) Increasing public knowledge through publishing research (-) Failing to communicate scientific information to the public	(+) Receiving grants (-) Spending money on research equipment
Resource Manager		
Natural Capital	**Social Capital**	**Economic Capital**
(+) Removing invasive plants (-) Failing to remove rubble after a landslide	(+) Protecting human resources from disturbances (-) Failing to protect human resources from disturbances	(+) Receiving disaster relief funds (-) Spending money on removing rubble
Recreation Manager		
Natural Capital	**Social Capital**	**Economic Capital**
(+) Increasing conservation through public education (-) Decreasing habitat connectivity through building too many roads	(+) Creating opportunities for the public to engage with the landscape through trail building (-) Poorly maintaining trails	(+) Creating recreation infrastructure (e.g. trails, visitor centers) (-) Spending money to maintain infrastructure
Forester		
Natural Capital	**Social Capital**	**Economic Capital**
(+) Planting trees (-) Creating fertilizer runoff	(+) Improving landscape aesthetics through planting trees (-) Harvesting many trees in one area (i.e. clear cutting)	(+) Selling timber from harvested trees (-) Losing planted trees to a wildfire

4. Methods

We administered anonymous pre- (Appendix 1) and post-tests (Appendix 2) to assess the effectiveness of *Resilience* in delivering the learning objectives. Both tests included the same questions to measure comprehension of concepts before and after playing the game. The post-test also included an opinion and demographic-based questionnaire to gauge participant perceptions and background and to determine if there were any relationships between these variables and test scores. This questionnaire also allowed us to understand the degree to which participants were enjoying and engaging with *Resilience* and how easy or hard it was to navigate.

4.1 Study Design

We designed the pre- and post-tests to help assess the participants' grasp of the learning objectives before and after playing *Resilience* respectively. Both tests featured the same 8 short-answer questions as knowledge tests to measure if participants met the learning objectives, with the first 5 questions assessing the first learning objective (Players learn about the complexities of the natural and human phenomena that affect post-disturbance ecological recovery processes) and the next 3 questions assessing the second learning objective (Players experience the challenges of multiple-stakeholder cooperation). We designed surveys with help from professionals in education who advised keeping tests brief enough to not deter voluntary participants from completing them or becoming fatigued by the end of the tests while still allowing proper assessment of their knowledge. We developed a rubric that assigned point values to the 8 short-answer questions based on the number of criteria that a response included (Appendix 3). Our rubric was designed to score questions based on criteria that were specific enough to avoid participants being able to guess answers and avoid the possibility of practice effects. To match each pre-test with the appropriate post-test while keeping the participants' identities confidential, participants created a unique encrypted identification code.

We validated the pre- and post-tests by administering pilot tests to individuals ranging in education level from grade school to college educated. While we wrote the comprehension questions to be targeted at college-aged individuals and older, we kept the language of these questions as simple as possible. Pilot testers with as low as a 3rd-grade reading level were able to comprehend the language and provide answers in line with what we intended the questions to measure. Other pilot testers with knowledge of the subject matter being tested in comprehension questions were able to provide high-scoring answers, allowing us to validate that our rubric is an accurate way to assess knowledge of these concepts.

In addition to re-answering the comprehension questions on the post-test, we also asked participants to answer a questionnaire that included 4 opinion-based and 14 demographic and background questions. Answers to the opinion-based questions were in the form of a Likert scale rating followed by a short-answer component to allow for elaboration. The demographic questions were either in the form of multiple choice, yes/no, Likert scale, or short answer. Examples of demographic questions include asking for participants' age range, education level, experience with classes that discuss ecological succession, and experience with serious games.

4.2 Recruitment

We recruited participants from the University of Tennessee, the Tennessee Chapter of the Sierra Club, and the University of Tennessee Arboretum Society. At the University of Tennessee, we advertised the opportunity to participate in our research in the Ecology and Evolutionary Biology Department, the Geography and Sustainability Department, the School of Natural Resources, and the School of Art. We advertised the opportunity to members of the Tennessee Chapter of the Sierra Club and the University of Tennessee Arboretum Society via regular email announcements of each group. In all cases, completion of the pre- and post-tests and opinion-based questionnaire was voluntary. One professor offered extra credit to students who chose to participate in our research, but otherwise, the decision to opt in or out of our research did not affect the grades of students recruited through classes.

4.3 Study Procedure

The study occurred both synchronously (while we were present, either online or in-person) and asynchronously (on the participant's own time, without our presence). We were available for questions about technical difficulties during synchronous sessions but otherwise did not observe or interact with the participants.

To begin, we provided all potential participants with a short description of the research and what participation in the study involved followed by a link to the informed consent form and an invitation link to begin the pre-test in the online survey platform Qualtrics®. Since we retrieved data anonymously, signatures of consent could not be provided. Instead, the completion of the tests by the individual participants designated their willingness to participate in the study.

Upon completion of the pre-test, participants were provided with a link to download and play *Resilience.* Participants played the game for a minimum of 1 hour. We gave participants the option to play alone or in groups of up to 4. During synchronous sessions, we observed 5 total individuals participating in multiplayer games. We assume participants played individually in asynchronous sessions, as *Resilience* did not offer the ability to connect across networks at the time of the study.

In synchronous sessions, we provided participants with access to the post-test after an hour of playtime had passed and asked them to complete it at their leisure. In asynchronous sessions, we provided a link to the post-tests when we provided the links to the pre-test and the game.

4.4 Analysis

A single individual used the rubric to score all responses to the 8 short-answer questions on both pre- and post-tests. The scorer summed each participant's responses. The highest possible score overall was 25 points, with 18 points for the five questions measuring learning objective 1 and 7 points for the 3 questions measuring learning objective B. We used a paired sample t-test to assess the statistical differences between pre- and post-test scores overall and among individual learning objectives.

We conducted an analysis of variance (ANOVA) to determine if select reported demographics and opinions affected change from pre- to post-test scores. Our concern was whether certain factors like age or enjoyment might alter a participant's ability to learn from the game. We subtracted pre-test scores from post-test scores to determine our dependent variable of net-score change. We selected responses from surveys that we suspect may have affected the participants' ability to meet the learning objectives. The survey responses we selected acted as measurements of the following independent variables: fun had during gameplay, engagement during gameplay, ease of use, self-perception of learning, education level, familiarity with ecological succession, and familiarity with serious games. We did not include interactions between predictors, as exploratory analysis of data did not reveal any strong relationships between these variables. We did not include age range as an independent variable, as this variable is similar to highest education received.

5. Results

5.1 Knowledge Tests

We received a total of 65 responses with completed pre- and post-tests and matching identification codes. After exploring our data, we displayed the major results of our analyses graphically. We observed an increase of 21% ($p<0.001$) when comparing the sum of all pre-test (Mdn=13, SD=3.10) and post-test scores (Mdn=16, SD=2.95) (Figure 5). After partitioning scores into the learning objectives being assessed, we found an increase of 27% ($p<0.001$) when comparing the sum of pre-test (Mdn=8, SD=2.20) and post-test scores (Mdn=10, SD=2.45) associated with learning objective A (Figure 6, left) and an increase of 13% ($p<0.001$) when comparing the sum of pre-test (Mdn=6, SD=1.48) and post-test scores (Mdn=6, SD=0.98) associated with learning objective B (Figure 6, right).

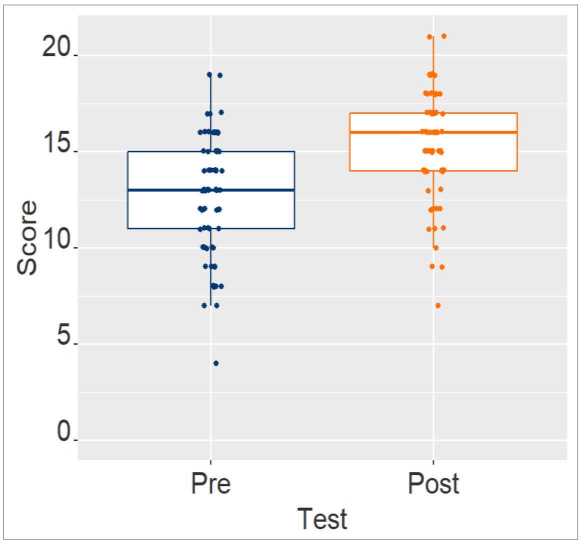

Figure 5. Comparison of total pre- and post-test scores (Out of 25 possible points, n=65, p<0.001)

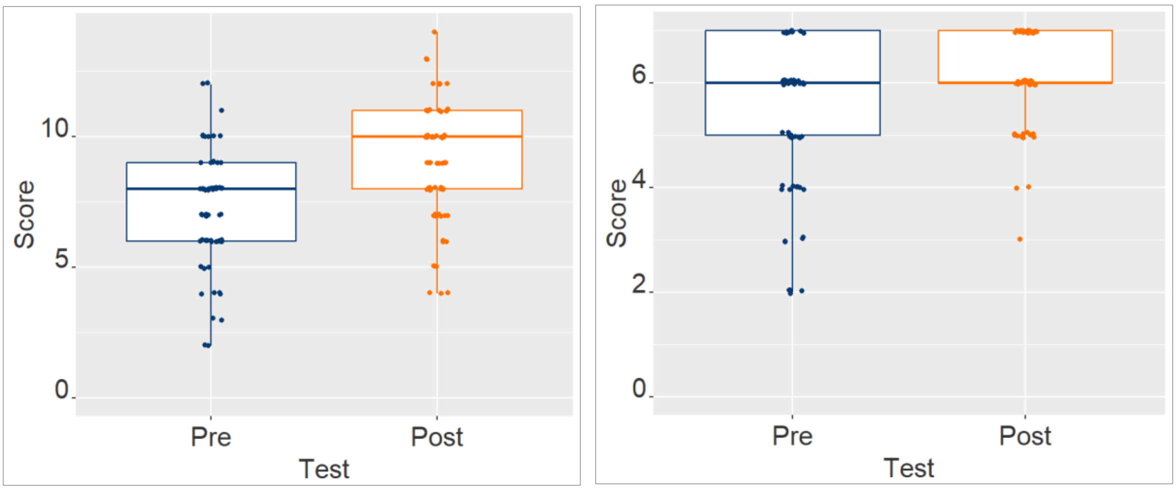

Figure 6. Comparison of pre- and post-test scores related to (left) objective A: "Players learn about the complexities of natural and human phenomena that affect post-disturbance ecological recovery processes" (Out of 18 possible points, n=65, p<0.001) and (right) objective B: "Players experience the challenges of multiple-stakeholder cooperation" (Out of 7 possible points, n=65, p<0.001).

5.2 Demographics

Responses to demographic questions revealed background information about the study sample. Of the demographic questions asked, we determined that the best representation of the overall sample derived from age, highest education received, whether they had taken a class about ecological succession, and whether they had played a serious game (Table 4). We asked participants if they had taken a biology, ecology, or environmental science class, to which all participants responded "Yes." The next question was conditional upon the previous question and asked if that class discussed ecological succession. The results of the second question in this sequence are reported below.

Table 4. Participant demographics

Demographic Category	Number of Participants	Percent of Participants
Age		
18-25	55	84.6
26-40	3	4.6
Older than 40	7	10.8
Highest education received		
High School/GED	33	50.8
Bachelor's Degree	27	41.5
Graduate Degree	5	7.7
Taken a class on ecological succession		
Yes	51	78.5
No	14	21.5
Played a serious game		
Yes	39	60
No	26	40

5.3 User Experience

We asked participants to rate their level of agreement with four different statements to measure various aspects of their gameplay experience: "Playing the game *Resilience* was a fun and entertaining experience" assessed level of fun had during gameplay (Figure 7, top left), "I feel that I could play *Resilience* for an hour without getting bored" assessed overall engagement with the game (Figure 7, top right), "*Resilience* was easy to learn how to play" assessed the game's ease of use (Figure 7, bottom left), and "I feel that I learned about ecological systems from playing *Resilience*" assessed if participants perceived they were learning about one of the game's main subjects (Figure 7, bottom right). Responses to the short-answer questions following each opinion-based question provided elaboration on these statistics.

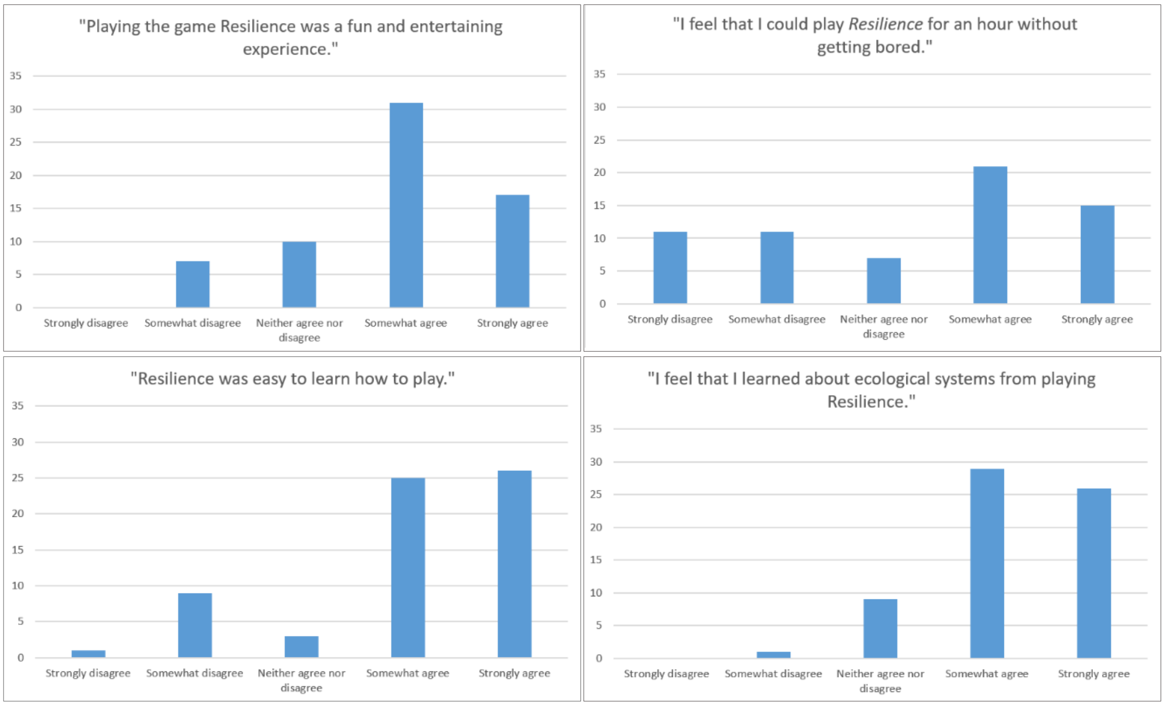

Figure 7. Participant opinions on entertainment value (top left), engagement (top right), ease of use (bottom left), and self-perception of learning (bottom right).

5.4 Effects Across Groups

The results of the ANOVA indicate that the selected demographics and opinions reported by participants do not influence their pre- to post-test score changes (Table 5) ($F(18,46)=0.95$, $p=0.53$). For each independent variable, we accept the null hypothesis that net score change is not significantly different among groups that reported different responses to the corresponding survey questions.

Table 5. Effects of participant variables on net score change.

Source of Variation	Df	Sum Sq	Mean Sq	F	p-value
Fun	3	7.38	2.46	0.3	0.83
Engagement	4	33.4	8.35	1.02	0.41
Ease of use	4	22.64	5.66	0.69	0.60
Self-perception of learning	3	45.89	15.3	1.86	0.15
Education level	2	18.17	9.08	1.11	0.34
Familiarity with ecological succession	1	6.10	6.1	0.74	0.39
Familiarity with serious games	1	6.54	6.5	0.8	0.38

6. Discussion

6.1 Implications

Our study shows that our design of *Resilience* as an in-depth role-playing simulation enables learning about complex environmental, social, and economic systems. Players of *Resilience* learned about the complexities of the natural and human phenomena that affect post-disturbance ecological recovery (a.k.a. learning objective A) as evidenced by the overall increase between pre- and post-test scores associated with this objective. We also found that players of *Resilience* experienced the challenges of multiple-stakeholder cooperation (a.k.a. learning objective B), though to a lesser degree. Score improvements associated with learning objective B were about half of the score improvements of questions associated with learning objective 1. While still significant, this lower increase in scores suggests that we need to improve the degree to which players of *Resilience* can experience and learn about stakeholder engagement or change our survey and/or scoring methods. The high pre-test scores in comparison to post-test scores associated with learning objective B suggest that the latter strategy may be an appropriate first step.

In addition to investigating if learning objectives were met, we analyzed responses to opinion-based questions to see whether players of *Resilience* found the game fun, engaging, educational, and easy to learn how to play. Participants generally agreed with the statement that playing *Resilience* was a fun and entertaining experience. There were mixed opinions on whether the game could be played for an hour without the participant getting bored. This result could be an indication that some players are not finding the game to be as engaging as others but could also imply that the question itself is not accurately capturing the true level of engagement that the participant is experiencing. Overall, participants agreed that *Resilience* was easy to play and that they felt that they learned about ecological systems by playing the game. These results generally support the idea that the gameplay experience of *Resilience* is a positive one.

Short-answer responses that allowed for elaboration on opinion-based questions provided more specific feedback on how participants felt about their gameplay experience. Since participants generally had mixed responses to the question asking whether they could play the game for 1 hour without being bored, we looked into the short-answer responses to see why some individuals may have been less engaged than others. Some responses mentioned finding the game too repetitive, slow-paced, or confusing. For example, one participant answered "I thought it got a bit repetitive and there wasn't a clear goal/ending in sight. However, it was fun to create a world and see how my decisions impacted the landscape and visitor use." These accounts helped us identify what we had done well and what might need to change in future iterations of *Resilience*.

ANOVA results provided evidence that *Resilience* is an effective learning tool across a diverse audience. All demographic and opinion-based groupings of participants showed similar pre- to post-test score improvements. While 65 individuals is a sufficient amount to infer statistics, more evenly distributed groups could provide better results. For example, only 5 participants (7.7% of the sample) reported having a graduate degree, which may not be enough individuals to determine an effect for that group. Additionally, whether survey questions are accurately measuring the intended variable may also affect the results of this analysis. Despite mixed results of engagement there was no significant difference

6.2 Future Directions

Going forward, we will use the information gained from our research to inform the development of *Resilience* before its eventual public release. If we are to release *Resilience* to fill the gap of serious games that explore multi-dimensional sustainability issues and ecological recovery, we must ensure that we are doing so in an effective way. While our study provided evidence of learning and positive user experience, it also illuminated several areas for improvement. Major changes we intend to implement include optimizing game performance and creating a more engaging gameplay experience. Due to the complex simulation including many interacting components, some participants reported game lag on their computers. A few participants noted these technical difficulties impeding their ability to have fun or engage with the game in the short-answer portion of the opinion-based responses. Due to the number of participant responses that showed lower than ideal player engagement, we could improve *Resilience* through fostering greater player involvement in the game. Engagement is a critical component of learning and correlates with student success [53-54]. One major benefit of serious games is their potential to be more engaging than traditional education media, so fostering engagement is a crucial step when creating a serious game [55]. Other potential ways to increase engagement in digital serious games include implementing clearer player feedback and allowing players to represent themselves through customizable avatars, the latter of which can specifically enhance the role-playing experience [56-57]. Changing the game's difficulty level throughout the gameplay session will also increase engagement levels by keeping the player from becoming bored by the lack of challenge or frustrated by too much challenge, thus creating a pleasantly challenging experience [8, 58]. Detecting performance issues should be a major focus when developing in-depth simulations, and engagement should be specifically prioritized during the development of any serious game.

We can make additional improvements to *Resilience* through refining our player analysis. Further analysis will involve adding survey items that measure variables presently unaccounted for, making changes to existing survey items, and conducting research on a wider audience. One factor that we predict could have affected the ability of participants to meet the learning objectives is the amount of time spent playing the game. Participants played the game for a minimum of an hour, though some participants chose to play it for longer. Based on anecdotal evidence from game testers who were not study participants, playing the game for longer than an hour allowed for the exploration of more of the game's content and therefore had the potential to lead to increased knowledge acquisition. This difference in playtimes among study participants may have impacted their responses to the post-test questions. Another factor that was not accurately accounted for is the number of players in sessions. While we observed a few cases of multiplayer games, most of the games were likely played alone. This difference in play styles could have had a significant impact on how learning objectives were met, especially regarding how players learn about stakeholder cooperation. In certain cases, learning is more effective in a collaborative environment [59-60]. There is also evidence that game-based learning experiences are enhanced when multiple players are involved [61]. In addition to accounting for additional variables, our results show that we could improve our assessment of stakeholder engagement understanding. Based on the high pre-test scores and lower percent increase from pre- to post-test scores of questions measuring learning objective B, questions may have been too easy to answer with general knowledge. Different questions that better assess the in-game experience of managing multiple stakeholders with different goals will need to be implemented in future studies. Finally, data from a larger and more diverse sample could help provide insight on how to improve the game to be more educational and user-friendly to its entire audience. We would specifically like to gain feedback from students in grades 8-12 and students over the age of 25 who are less familiar with the game's subject matter.

When reviewing the literature, we identified a lack of serious games that explore the interconnectedness of ecological, social, and economic systems, as well as an absence of games that simulate in-depth ecological recovery processes that are up to date with current scientific understanding. We plan to release *Resilience* to fill this gap and deliver relevant knowledge and experience to the game's intended audience: students in grades 8 and above and those involved in management decisions on diverse landscapes including resource managers, the recreation community, nongovernmental organizations, government agencies, and landowners. By using *Resilience* in classrooms, students can learn about and explore concepts related to ecological recovery, disturbances, and responsible resource management. In addition, we view *Resilience* as a potential tool to raise awareness of careers associated with the stakeholders within the game and increase overall recruitment to fields that involve the management of natural and human resources. *Resilience* is also intended to be used as a training tool by professionals and interest groups who may be involved with scenarios like those that appear in the game. This use could range from specific jobs that include management of resources in a recovering ecosystem or more general use like training groups on the challenges of stakeholder cooperation. Finally, we aim to release *Resilience* to the general public who seek to learn about its concepts or just to experience the game.

7. Conclusions

Our findings provide evidence that serious simulation games are suitable tools for learning about complex sustainability issues in a user-friendly manner. We found positive answers to all three of our initial questions about the game although there are some caveats: 1. Players of *Resilience* do learn about the complexities of the natural and human phenomena that affect post-disturbance ecological recovery. 2. Players of *Resilience* do experience the challenges of multiple-stakeholder cooperation. 3. Players of *Resilience* find the game fun, engaging, educational, and easy to learn how to play although we plan to make improvements to the game that would enhance the experience of playing it. We hope to improve player engagement by making the game less repetitive and tweaking the difficulty level. We also hope to increase user experience overall by improving *Resilience*'s performance as we found that different devices could not run the game's complex simulation at the same rate. Upon making these changes, *Resilience* will add to the growing library of serious games about sustainability as a unique entry that explores the interconnectedness of environmental, social, and economic systems and features an in-depth simulation of ecological recovery. Designing games like *Resilience* can help produce more cooperative and informed managers of complex systems involving multiple stakeholders, especially in sustainability fields.

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Conflicts of interest

The authors declare no conflicts of interest.

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