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To cite this article: Rowan C. Martindale, Barbara Sofia Sulbaran Reyes, Sinjini Sinha & North Cooc (2024) “Reef Survivor”: A new board game designed to teach college and university undergraduate students about reef ecology, evolution, and extinction, Journal of Geoscience Education, 72:1, 37-56, DOI: [10.1080/10899995.2023.2221818](https://doi.org/10.1080/10899995.2023.2221818)

To link to this article: <https://doi.org/10.1080/10899995.2023.2221818>



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“Reef Survivor”: A new board game designed to teach college and university undergraduate students about reef ecology, evolution, and extinction

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ABSTRACT

Educational geoscience games have been increasing in popularity because they promote learning through amusement and encourage students to engage with topical material and each other. Here we describe a new board game, “Reef Survivor”, and its use as an instructional tool in undergraduate classes. The educational objective is to teach players about ecology, evolution, and environmental perturbations, while the gameplay objective is to build a resilient reef ecosystem. Through collaborative and competitive gameplay, students learn about evolution mechanics—mutation, migration, and natural selection—as well as ecology and how reefs survive natural disasters. The game blends informed decision making and chance to encourage students to learn and model complex Earth systems and evolutionary processes. Students choose their environment and reef community, whereas chance influences mutations and disasters.

The game was incorporated in undergraduate classroom activities in 2021 and 2022 at 20 colleges and universities, mostly public institutions in the United States. Students were enthusiastic about the game, with two thirds saying they would rather play the game than have a normal lab. Notably, students said playing with a peer helped them learn better. Taken together, learning gains from 15 institutions were positive, with significant gains by the final semester of assessment. Overall, learning gains were not positive during the first deployment (online) but improved substantially when refined and played in person. A print-and-play version of the game (doi: [10.18738/T8/S3KW77](https://doi.org/10.18738/T8/S3KW77)), onboarding and follow-up assignments, and suggested extension activities are provided; modifications for time, course objective, and educational level are also discussed.

ARTICLE HISTORY

Received 18 November 2022

Revised 8 May 2023

Accepted 31 May 2023

KEYWORDS

Serious Game; ecology; paleontology; evolution; reef

Purpose and learning goals

Evolution is a fundamental but often challenging concept, and the use of interactive engagement can improve students’ understanding and acceptance of evolution (Nelson, 2008). Here, we present an educational game that allows students to experience the mechanics of evolution as well as its interactions with ecology and extinction. Educational games (also called serious games) provide students with models of complex systems (e.g., Garcia et al., 2016; Salgado-Jauregui et al., 2022), as well as opportunities to engage with peers and teachers as they strategize, test theories, and model scenarios through gameplay. We developed the board game “Reef Survivor”, herein referred to as “the game” (Figure 1), to encourage students to learn about marine ecology, biodiversity, evolution, and extinction. The intersections of these concepts over long timescales (millions of years), specifically evolutionary mechanisms such as natural selection, are modeled through various aspects of gameplay. Reef Survivor is a Eurogame of medium

complexity; Eurogames are strategy tabletop games that generally have indirect player interaction, abstract physical components, and generally require thought and planning (e.g., Settlers of Catan). Reef Survivor is approximately 1.5 to 2 hr in length (i.e., a lab period) similar to the “Taphonomy: Dead and Fossilized” game (Martindale & Weiss, 2020).

“Reef Survivor” is a competitive game with strong collaborative elements; designed as a multi-context activity (*sensu* Weissmann et al., 2019) that promotes student engagement through gaming challenges while also encouraging cooperation, collaboration, and interaction with other learners. The game allows students to model changes in a reef community over evolutionary time and makes concepts, such as natural selection, have real-time consequences for their ecosystem. Players select and build their reef to feel attachment to the game outcome and engage in high-context elements of gameplay (e.g., sharing and exchanging tokens, interacting). Game tokens represent modern and ancient reef organisms, and game boards represent environments and bathymetric profiles common in

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 Supplemental data for this article can be accessed online at <https://doi.org/10.1080/10899995.2023.2221818>.

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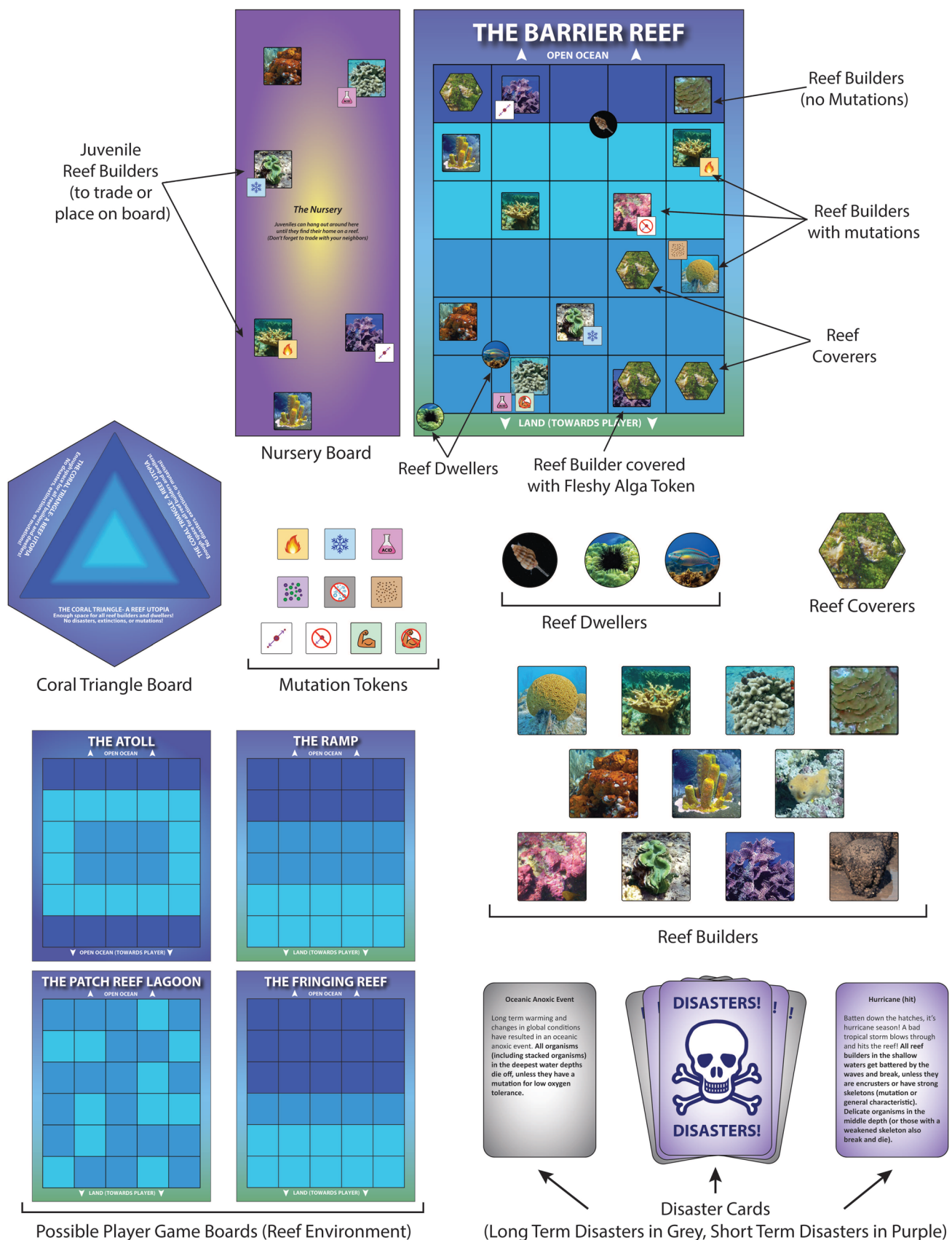


Figure 1. Schematic of the "Reef Survivor" board game and associated material, i.e., game boards (environment player boards, nursery, and coral triangle), organism tokens (reef builders, dwellers, and covers), mutation tokens, and disaster cards. Note: game pieces, boards, and cards not shown to scale.

Table 1. Student Learning Objectives (SLOs) associated with the “Reef Survivor” board game.

Topic	Student Learning Objective (SLO)		Game Mechanic that Addresses Objective
Critical Thinking & Problem Solving	SLO #1	Formulate a strategy to maintain reef function and biodiversity given the factors one might encounter during the game. Engage in complex systems thinking.	The students who complete the onboarding worksheet and plan their strategy in advance are more likely to do well when they play the game.
Evolution	SLO #2	Identify the ways in which genetic variation increases in a community (i.e., mutation and migration).	The only way to add variation to the reef community is to gain a new characteristic (mutation) or exchange juvenile organisms with other players (migration).
	SLO #3	Explain that genetic mutations are random and can be either harmful, helpful, or neutral.	Mutations are random; students select an organism to mutate and roll a dice for the mutation (e.g., heat/cold tolerant, stronger/weaker skeleton). Players may get a positive, negative, or neutral mutation; the benefit or drawback of the mutation may not be apparent until a particular environmental event.
	SLO #4	Genetic mutations are inherited by offspring from their parents.	Parents produce offspring with the same genetic mutations in the reproduction phase.
	SLO #5	Understand that organisms or communities cannot “prepare for” environmental changes or evolve before a selective pressure is exerted. Natural selection is not necessarily directional (i.e., one round it may be hot and another it may be cool), nor does mutation act for the “good of the species”.	Mutations happen before the environmental event, so the player cannot plan for what’s coming. Strategy comes down to maximizing reef diversity (e.g., trading juveniles to have both hot and acid tolerant species) and placing organisms in the best spots based on their characteristics (e.g., strong corals in environments with high energy).
	SLO #6	Identify the different organisms that live in and build reefs and explain some of their environmental preferences. Understand that benthic adults may have planktic juveniles.	Reef organisms include a variety of different species with variable characteristics and habitats; students select their starting organisms. Once selected and placed reef builders cannot move (sessile, benthic organisms), but their juveniles and the reef dwellers can move (motile planktic and benthic).
Ecology	SLO #7	Explain how local environment and bathymetric profile (i.e., antecedent bathymetry) may change the ecology of a reef community.	Students select a game board with a particular geographical layout and bathymetry; they discover that some organisms do better in deeper water and others in shallower water etc. Also, environmental events impact different game board layouts uniquely.
	SLO #8	Become familiar with ecological niches and competition. Some organisms act as reef builders, some are reef dwellers, and some damage healthy reefs.	Board has limited space, some organisms perform the same ecosystem services or occupy the same niches (e.g. builder, dweller). When students run out of space, they have to start prioritizing certain taxa and not every species can live in all environments nor recruit dwellers that eat off fleshy algae.
	SLO #9	Defend or explain why higher diversity is important for the health and long term survival of reef communities and reef ecosystems.	Usually a more diverse reef (both multiple species and a greater intra-specific variation with multiple different mutations) is the best strategy to keep the reef healthy over long timescales.
	SLO #10	Calculate the diversity of an area or community and how diversity changes through time (how do we identify extinctions).	Through choice and chance, different boards and different tables will have unique communities, just like ecosystems in the natural world. Students can calculate the diversity of the board at a given interval and track how it changes through time.
Biodiversity & Extinction	SLO #11	Understand that environmental conditions change through time and geological time is long.	The game is played over 4 million years (and can be modified to be played for longer time periods)
	SLO #12	Understand that communities can be decimated by extinction drivers (e.g., climate change) but tolerance of a particular stressor (e.g., heat) can help some taxa survive these events (differential survival leading to natural selection).	Students see several unique environmental events, which have differential impacts on their reef community depending on their composition; this leads to different communities surviving/thriving.

modern and ancient reef settings (Figure 1). These features provide a sense of realism and encourage students to connect gameplay with reef communities and environmental catastrophes in the modern world or fossil record.

As an educational tool, the game has twelve student learning objectives, or SLOs (Table 1) about evolution, ecology, biodiversity, and extinction. The paramount goal is to foster critical thinking and problem solving through the development of a winning strategy (SLO #1). Students strategize by selecting the organisms and setting for their reef (ecology, SLOs #6-9), but the possible mutations and disasters encountered are random (evolution and extinction, SLOs #2-5, & SLOs #10-12). Strategy

development is facilitated with an onboarding assignment and short introductory video, and the follow-up activity reinforces concepts, systems, and processes covered by the game. Ultimately, a learner engaged with these activities will likely have a more concrete understanding of how mutation, migration, and natural selection processes interact with environmental factors (e.g., bathymetry, climate change, and natural disasters) to shape a marine community and its evolution through time. The game guides the player through these concepts and highlights how their interactions result in long-term ecological and evolutionary changes as well as how short-term perturbations may have longer-term ramifications.

Literature context

Evolution is fundamental in both the geosciences and biosciences, yet this concept is notoriously difficult for students to understand. Students often enter college with preconceptions or naïve ideas, frequently termed misconceptions (terminology discussed in Maskiewicz & Lineback, 2013). Pedagogical strategies to improve understanding and acceptance of evolution include the use of interactive engagement, critical thinking, and metacognition about how popular preconceptions, or students' own prior understanding, explicitly differs from scientific conceptions (Nelson, 2008; Yacobucci, 2018). Some common evolutionary misconceptions detailed in Yacobucci (2018) include: organisms always get better (climbing a ladder of progress); evolution means life changed by chance; natural selection involves organisms trying to adapt; organisms intentionally select traits to evolve; natural selection gives organisms what they need; the environment causes evolution; and evolutionary change happens from one generation to the next. It is important that students confront and understand these preconceptions, so activities that model how organisms do not always "get better" during their evolutionary history, or how organisms cannot control what traits evolve, for example, can be interventions to enhance learning. "Reef Survivor" is specifically designed to help students confront these preconceptions (Table 1).

The advantages of incorporating games as education tools in formal settings, or Game-Based Learning, are well established (e.g., Abt, 1970; Egenfeldt-Nielsen et al., 2011; Li & Tsai, 2013; Pfirman et al., 2021; Randel et al., 1992; Ritzko & Robinson, 2011; Robertson, 2022). Games are active learning tools that can improve retention of material on long timescales, enhance enjoyment of material, and encourage cooperative learning (e.g., Foster, 2008; Kumar & Lightner, 2007; Mayo, 2007; Pfirman et al., 2021; Robertson, 2022; Salgado-Jauregui et al., 2022). Games also model complex systems with synergistic or antagonistic processes and interactions (de Ruiter et al., 2021; Garcia et al., 2016), which make them ideal tools for Earth Science classes and outreach (Pfirman et al., 2021). Recently, numerous educational games have been designed for geoscience topics including climate change and arctic climate mitigation (Pfirman et al., 2021), hydrologic cycling (Robertson, 2022) and hydrology with agriculture (Orduña Alegría et al., 2020), hazards and disaster risk reduction (de Ruiter et al., 2021; Mossoux et al., 2016), mineralogy (Spandler, 2016), and paleontology (Martindale & Weiss, 2020; Salgado-Jauregui et al., 2022).

As educational media, games are advantageous because they can incorporate more than just the learning objective; beneficial elements, such as collaboration, metacognition, authentic research, experiential or problem-based learning, and multi-context objectives, can be integrated into game mechanics or affiliated extension activities. For example, the game can encourage or require collaboration to solve a problem, share resources, or achieve a goal; collaborative learning has been shown to improve academic performance, learning gains, and retention, as well as having social benefits (Johnson & Johnson, 1986; Johnson et al., 1998; Johnson, Johnson, & Stanne, 2000; Johnson et al., 2014; Johnson &

Johnson, 1986; Prince, 2004). Additionally, incorporating multi-context learning into game design can benefit different demographic groups, especially those from high-context cultures (Weissmann et al., 2019). Multi-context learning blends "low-context" elements, such as linear thinking, individualism, and task orientation that are typical of university classes, with more "high-context" elements, such as storytelling, sharing, and interconnected thinking, which are more common in collaborative communities (Ibarra, 1999, 2001; Weissmann et al., 2019). While incorporating these elements is no guarantee an individual will have a strong affinity for the material, multi-context activities provide flexibility in learning style; for example, one student may remember their experience as a linear set of objectives achieved, whereas another may remember the story of their experience and their interactions with others.

Although increasing numbers of game-based activities are being developed, there is currently a paucity of serious games aimed at undergraduate geoscience and bioscience learners. Moreover, evaluating games to ensure that they are effective learning tools will increase the likelihood of their use in classrooms. This study describes and evaluates the new board game "Reef Survivor".

Study population and setting

"Reef Survivor" was used as an activity in undergraduate geoscience courses at 20 institutions over the 2020/2021 and 2021/2022 academic years. Partial or complete data were collected from 351 students (350 students from 19 U.S. institutions), with 15 institutions reporting pre and post assessment data. Schools are mostly public, 4-year institutions in the USA (demographics in Figures 2 and 3); class sizes ranged from 3 to 58 students, although individual labs were typically smaller, usually less than 16 people. Students learned about core concepts in lecture (short videos included with game material), watched an introductory video (www.youtube.com/watch?v=bw8geNpuEnQ), completed an onboarding worksheet (see Materials and Methods, supplemental data S1), and played the game in class or lab. After playing the game they completed a follow-up worksheet (supplemental data S2) and responded to an online opinion and demographic survey (see supplemental data S3).

The 338 participants that completed the survey included 138 female, 115 male, and 15 non-binary, gender queer, agender, or transgender students, Freshmen (first year), Sophomore (second year), Junior (third year), and Senior (fourth year or higher) students, and several graduate students (Figure 2). Over half were geoscience majors and about a third were other STEM majors. The population included American Indian or Alaskan Native, Hawaiian or Pacific Islander, Black, Multiracial, Middle Eastern, and Asian students, although over two thirds identified as White and one fifth identified as Hispanic/Latino/Latina/LatinX (Figure 3). A quarter of the students identified as LGBTQ+ (lesbian, gay, bisexual, transgender and queer and others). Approximately 10% identified as having a disability. The students identified their socio-economic status as mostly middle, upper-middle, or lower-middle income households. See Figures 2 and 3 for

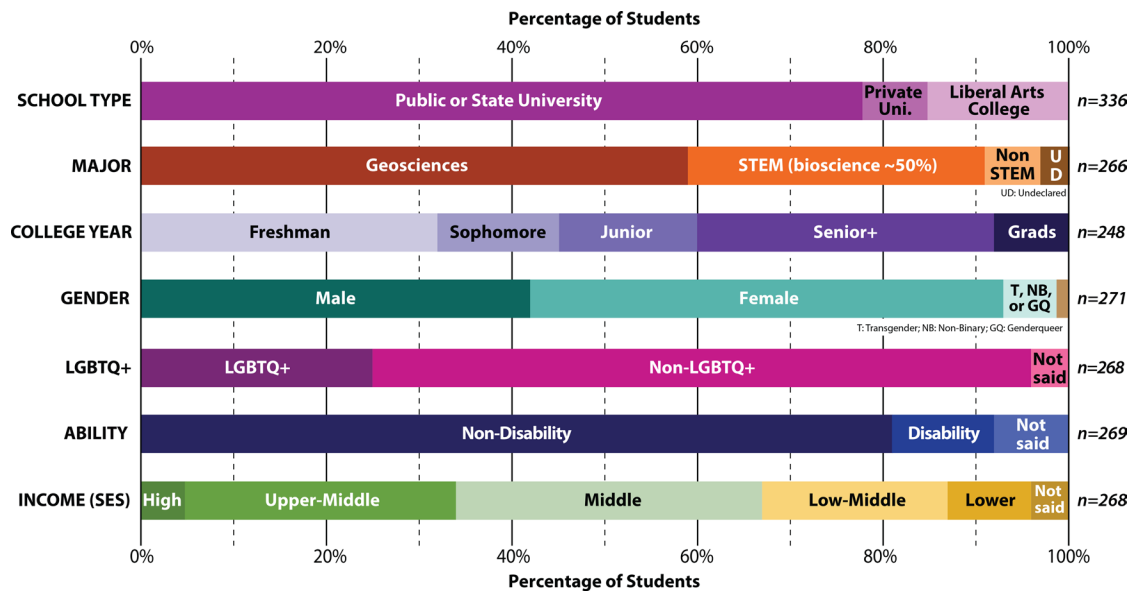


Figure 2. Demographic breakdown of the participants that responded to the demographic survey (number of participants that responded listed on the right). Note that some categories were amalgamated to preserve student anonymity and privacy without the intent to erase unique identities. School Type: 78% public 4-year university, 7% private 4-year university (Private Uni.), and 15% liberal arts college. Major: 59% geoscience major (e.g., geology, geophysics, Earth sciences), 32% STEM (Science, Technology, Engineering, or Math) major, with about half identifying specifically as bioscience majors (not all surveyed has bioscience as an option), 5% non-STEM (e.g., history, social work, art), and 3% undeclared (UD). College Year: 32% Freshmen (first year), 14% Sophomore (second year), 15% Junior (third year), 32% Senior+ (fourth year or higher), and 7% graduate students (Grads). Gender: 42% male students, 51% female students, 6% Transgender, non-binary students, and Genderqueer (T, NB, or GQ), 2% preferred not to say. Note: some individuals selected multiple categories. LGBTQ+ Status: 25% identify as LGBTQ+ (lesbian, gay, bisexual, transgender, queer, and others), 71% did not, and 4% preferred not to say or marked “other”. Ability: 81% do not have a disability, 11% have a disability, and 8% prefer not to say. Income or Social Economic Status (SES): 4% high, 29% upper-middle, 33% middle, 20% lower-middle, 9% lower, and 4% prefer not to say.

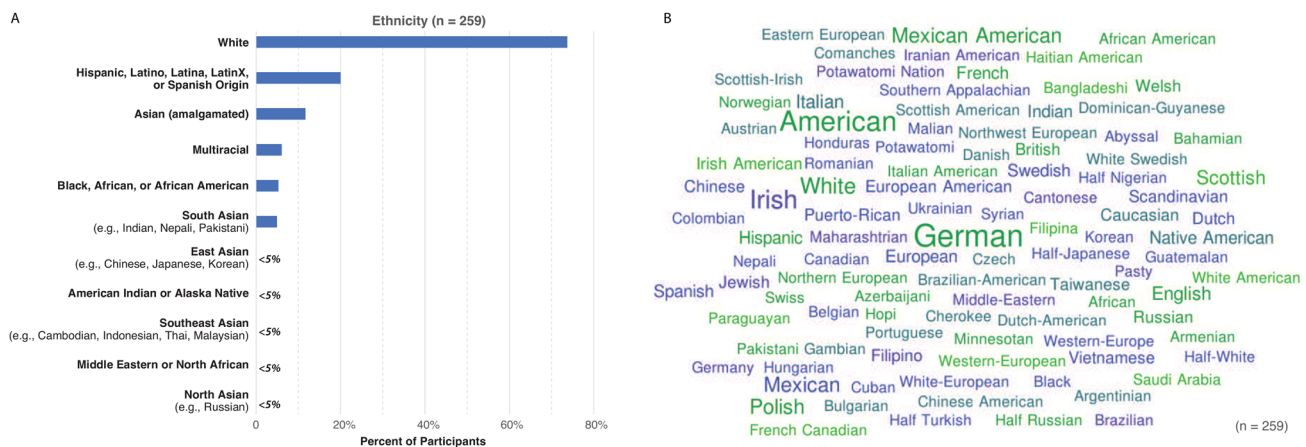


Figure 3. Race and ethnicity information from the participants that responded to the demographic survey (259 responses of 348 total participants). (A) Percentage of participants that are a given race or ethnicity (selected from a list of options); some race and ethnicity data were amalgamated to preserve student anonymity and privacy without the intent to erase unique identities. (B) The ethnic and racial identities of participants (open ended question).

a summary of population demographics; [supplemental data \(S4\)](#) includes a full demographic breakdown.

Materials and implementation

General game overview and objectives

“Reef Survivor” is a physical board game (Figure 1) that can be adapted to a virtual setting *via* Google Jamboard. It was written for four players (or teams) but can be modified for as few as one player or as many players as there

are boards and tokens available. All materials to implement and play the game (i.e., a “print and play” version) can be found in [supplemental data](#) or at doi: [10.18738/T8/S3KWT7](https://doi.org/10.18738/T8/S3KWT7).

The objective of the game is to build a diverse reef ecosystem that can survive natural disasters. Each player (or team) is a conservation expert tasked with keeping their reef healthy; they select an environment (bathymetric profile) and set of organisms to build and live on their reef. Over millions of years, environmental conditions change, and over generations species change as well through a) genetic

mutation, b) the influx of new organisms (migration), and c) environmental pressures that cause differential survival based on inherited characteristics (natural selection). Students integrate their geological and biological knowledge to strategize how to build and maintain a resilient reef. The twelve learning objectives covered and the game mechanics that reinforce them are listed in [Table 1](#).

Throughout gameplay, and associated assignments, students learn the organisms, settings, and natural disasters encountered by reefs, they apply their knowledge to the complex system (game) to maintain a community that survives environmental change. Although the game is competitive, there are strong collaborative elements that mimic real-world conservation strategies (i.e., out-planting corals from nurseries) to create a realistic and multi-context activity.

The game is designed to be used in a 1.5-to-2-hr class or lab, so students have time to develop their strategy and play multiple rounds. A pre-lab assignment and follow up worksheet are part of the activity (see Corresponding Classroom Activities); the former acquaints students with game pieces and rules so they can craft a strategy.

Gameplay (Figure 1)

Game set up (SLO #1, SLOs #6-8)

A game (or table) consists of four players; a player can be one student or a team of 2-3 students. Each player chooses a setting from five carbonate environments (e.g., patch reef, atoll, barrier reef); each environment is represented by a gameboard with 30 spaces in unique bathymetric configurations and geographic settings ([Figure 1](#), SLO #7, SLO #8). The gameboard selected is important because some organisms can only live at certain depths (SLO #6) and some disasters only impact certain depths or geographies (e.g., proximity to land). Moreover, more organisms can grow vertically in deep water than in shallow water, which encourages players to plan their community in three dimensions (SLO #7). As the game progresses, space on the board decreases, and students must consider how competition impacts their ecosystems.

Each player selects five reef building organisms (e.g., branching coral, carbonate sponge, or bivalve) to build their initial reef structure ([Figure 1](#)). As organisms have unique characteristics (e.g., depth preference, skeletal strength, reef dweller recruitment), players must select builders that suit their chosen environment (SLO #6, SLO #8). Players then place reef builder tokens on their gameboard; once placed tokens represent sessile adults (i.e., once established on a space they cannot move, SLO #6). Players are reminded that tokens often represent colonies of hundreds of individuals and since each round represents a million years, they also symbolize multiple generations, not individuals. Selecting their builders familiarizes students with reef building organisms as well as potentially unfamiliar taxa and terminology; as students go over builder characteristics, they consider habitats they can occupy (SLO #6, SLO #7).

Selecting their gameboard and organisms encourages players to feel ownership of their reef; it is their responsibility to

plan a healthy community and protect it from environmental changes. The set-up phase, which students plan in their pre-lab worksheet, allows students time to think about the game components and how they interact, in other words, systems thinking. A good strategy requires players to think critically about their reef as a whole system (SLO #1). For example, what bathymetric profiles work best with their organisms, what traits might be important close to land, or which disasters are likely to impact a board with shallow water?

While players are selecting their boards and builders (or in advance of the activity), the “Coral Triangle” is set up. The Coral Triangle board sits in the middle of the table and contains all types of reef builders and dwellers, but no fleshy algae. It never gets hit with disasters and has a steady state population (one token of each reef builder and dweller always remain in the Coral Triangle).

Once setup is complete, players begin their first of four rounds of play. Each round represents a million years of evolutionary time and is made up of four phases.

Phase 1: New friends and mutations (SLOs #1-2, SLO #3, SLO#6, SLO#8)

In the million years since reef initiation, the community has grown and evolved. If the player has “recruiting” builders, they gain reef dwellers (fish, sea urchins, and snails); dwellers eat fleshy algae off the reef (one dweller removes one reef coverer token per round) and so are key components of the community (SLO#8). Dwellers always need to be supported by two “recruiting” reef builders (i.e., corals, bivalves, and carbonate algae) but because they are motile organisms, they do not take up spaces on the board. These tokens do not mutate or reproduce, which is a simplification for gameplay (SLO #6).

In addition to dwellers, green fleshy algae (reef coverers) have also grown on the reef, so players add five tokens to their board ([Figure 1](#)). At the beginning of the game, fleshy algae are an annoyance, but as the rounds proceed, algae begin to take over the gameboard and even cover the builders (SLO #8). Covered reef builders cannot reproduce, evolve, or recruit reef dwellers nor are they worth points. In this way, students realize herbivores are critical to maintaining a healthy community (e.g., Burkepile & Hay, 2008; Graham et al., 2013; Lessios, 2016; van de Leemput et al., 2016). If algae cover a builder, they can be eaten off by a dweller and recover. This mechanic reminds students that ecosystem recovery is possible; it is important to include optimism in conservation advocacy to engage communities and show that ecosystem management is not a lost cause (Knowlton, 2021; McAfee et al., 2019).

In Phase 1, some builders also gain mutations, which adds genetic variation to the community (i.e., intraspecific variation, SLO #2, SLO#3). Each population gains two mutations; players decide which reef builder will mutate and roll a D12 die to determine which random mutation(s) occurred (e.g., stronger skeleton, acid resistance but weaker skeleton, more offspring). Students are reminded that mutations are normal and often neutral, and that offspring will inherit their parent’s mutations.

Phase 2: Spawning and migration (SLOs #1-4, SLO #6-8)

In phase 2 reef builders reproduce; since genetic mutations are inherited by offspring from their parents (SLO #2, SLO #4), each reef builder spawns an identical juvenile (the same builder with the same mutations). Although adult builders are sessile, benthic organisms, juvenile offspring are planktic (SLO #6), so juveniles are placed in the player's "nursery" while trades are negotiated and the placement on their board is decided. In rounds 2 and onwards, players with the lowest score in the last round and overall collect two juvenile offspring from the Coral Triangle. This mechanic encourages students to remain engaged even if they have bad luck; it is also an opportunity to discuss conservation efforts such as transplanting nursery-grown corals (e.g., Montoya Maya et al., 2016).

After reproduction, players can trade juveniles with their neighbors, which represents migration (SLO #2); since juveniles are planktic, they can settle in a new location (SLO #6). Students are encouraged to talk to neighboring players and collaborate for the benefit of both reefs. The opportunity to interact with others and discuss strategy provides meaningful engagement and interaction for students and allows them to correct deficiencies they realize they have on their board (e.g., having only one type of builder). In addition to self-reflection, students can share their knowledge and work collaboratively or engage in competition for a desired organism. Engagement and collaboration can increase learning and critical thinking (e.g., Gokhale, 1995; Laal & Ghodsi, 2012; Macdonald & Bykerk-Kauffman, 1995; Pinet, 1995). After trades are made, juveniles are placed on the gameboard (Figure 1); students should engage in critical thinking about bathymetry and organism characteristics, especially in later rounds when they must be strategic about their reef configuration as the board fills up (SLOs #6-8).

Phase 3: Catastrophe (SLOs #1-5, SLO #9, SLOs #11-12)

In the third phase of the round, environmental conditions change (SLO #11, SLO #12). In the disaster card deck, there are 18 short-term disasters with timescales of days to years (e.g., hurricanes or heat waves) as well as 4 long-term disasters that represent geological-scale changes (e.g., glaciation or ocean acidification events). The round of play will dictate whether the table experiences one or more disaster cards and from which deck (e.g., Round 1=one short-term event, Round 2=two short-term events). The card or cards are drawn from a shuffled deck and all reefs (except the Coral Triangle) experience them. Disasters impact the reef variably based on the organisms, their characteristics, and the gameboard (SLO #11). For example, nutrification will be devastating if there are nutrient-sensitive organisms close to land, whereas storms are worse if there is no land nearby to provide delicate organisms with protection from waves. The disaster prompts players to add or remove tokens from their gameboard and if they lose builders, they may subsequently lose dwellers (SLO #12).

The differential impact of disasters highlights the importance of having a diverse community (SLO #9) (Burkepile & Hay, 2008; Loreau et al., 2003; Nyström, 2006) and

encourages students to collaborate by trading juveniles with different characteristics or mutations in subsequent rounds. Disasters also highlight that some mutations were beneficial (e.g., having heat tolerance in a heat wave), some were detrimental (e.g., a weaker skeleton in a storm), and others were neutral (e.g., having nutrient tolerance in a heat wave); this game mechanic helps students understand that mutations are not always for the good of the species (SLO #3) and the community cannot evolve in preparation for a disaster (SLO #5). The disaster also leads to differential survival within the reef, contributing to a change in community composition over time (i.e., natural selection, SLO #12).

Phase 4: Survey the reef (SLOs #1-4, SLOs #10-12)

In the final phase of the round, players calculate a score for each player and each table (SLO #10). Players tabulate their points in a notebook, receiving one point for each builder and dweller but losing points for fleshy algae (Figure 4); they get double points for diversity (2 points for every type of organism) as well as bonus points for certain goals (e.g., high intraspecific variation or coastal protection). Although stacked organisms count toward their total, only the topmost reef builder remains on the board into the next round. The score for the whole table is also calculated and can be used to compare tables or lab groups for an "overall winning team", which encourages collaboration within the group. These data can also be used to calculate alpha, beta, and gamma diversity in follow-up activities (SLO #10).

At the end of the round, students are encouraged to reflect on their strategy; a section of their notebook asks them what they will do differently (SLO #1, Figure 4). Could they have planned better? What were they naïve about? Should they collaborate with another player to rebuild? At this point, a new round of play begins, and players repeat Phases 1 through 4 three more times (a total of four rounds, 4 million years, SLO #11). The most resilient, populous, and diverse reef through geological time (i.e., the highest cumulative total) wins the game.

Game design: Round-based gameplay

Round-based gameplay (i.e., repeating the four phases multiple times) allows students to become familiar with game mechanics so they can spend time strategizing in subsequent rounds. This structure also allows students to become more comfortable and enjoy the game as opposed to constantly learning new rules (a drawback of more linear geosciences games, e.g., Martindale & Weiss, 2020). Additionally, round-based gameplay allows the game to be lengthened or shortened to suit requirements. In a typical 2-hr lab session, students can play four rounds, but a fast group could play more, and students could play just three rounds in a shorter lab. It is not advisable to play only one or two rounds because students are still learning game mechanics and are exposed to fewer disasters. If time is limited, play a "dry run" (i.e., only one full round) so students can become familiar with the game mechanics, pieces, and strategy; students can return and play a full three rounds in the

Scoreboard- Who's Winning?

Round of Play	Player 1	Player 2	Player 3	Player 4	Cumulative Points	Total Diversity of the Table (Number of Organism Types)
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Round of Play	Player 1	Player 2	Player 3	Player 4	Cumulative Points	Total Diversity of the Table (Number of Organism Types)
Round 1						
Round 2						
Round 3						
Round 4						
Round 5						
Cumulative Points						

subsequent class. The first round always takes substantially longer (usually 30-40 min) than later rounds, when students have less need to consult the rulebook.

Onboarding worksheet

This worksheet, paired with the follow-up worksheet, also provided pre and posts assessment data.

The onboarding worksheet covers basic questions about evolution mechanics but mostly focuses on game set up. Students review organism characteristics, choose a game-board and initial set of builders, then explain their strategy. They also review the disasters and reflect on what might be most damaging for their community. Players go through a practice mutation of selected organisms and consider when the mutation might be helpful or harmful and whether it might cancel out other characteristics. Finally, they review their strategy (SLO#1); this encourages them to think critically about the interactions in their reef community and develop a plan before they play the game.

The onboarding worksheet and 10-minute introductory video (www.youtube.com/watch?v=bw8geNpuEnQ) were provided at least a week before the lab or class in which the game was played. Students were tasked to have the worksheet completed and submitted before playing the game. Since two-thirds of the students surveyed said the pre-lab worksheet was helpful (Figure 5), we suggest utilizing this scaffolding activity when implementing the game.

Follow-up worksheet and guided discussions

After the game students completed a follow-up worksheet (supplemental data S2) to codify the concepts they experienced during the game and address the learning outcomes (Tables 1 and 2). Students were instructed to record their community's diversity after each round and answer some subsequent ecological questions (i.e., abundance and evenness of the community). Students reflect on which disasters were most damaging for their reef and discuss this response with someone who played at a different table to compare their answers.

In addition, some questions cover evolutionary mechanisms for adding and removing genetic variation. These questions were designed to help students re-assess their preconception: mutations are random, and species cannot prepare for natural selection or extreme environmental events. We also ask them to sketch how mutation, migration, random processes, and natural selection can impact a community, which requires synthesizing concepts modeled by the game. Drawings can be useful knowledge assessments as they require students to sketch the components, processes, and connections within complex Earth systems (Assaraf & Orion, 2005; Dove et al., 1999). Students are also tasked with applying this knowledge in specific scenarios and explaining how conservationists might be able to protect modern reefs from disasters, what a real-world example of their reef might be, and what

criteria may confer resilience. Furthermore, students are asked to sketch their reef system to answer questions that synthesize ecological concepts (e.g., habitat preference, differential stresses in a community, change through time).

Lastly, students were asked to complete an online survey (supplemental data S3) about their enjoyment of the game and demographic information. For the assessments presented, we asked that students complete and submit their worksheet within a week of playing the game.

Advanced activities

Wrap-up discussions or metacognitive activities are important components of games as educational tools. Games are not typically common in classes or labs, so a summative activity encourages students to recall what they learned, modify preexisting conceptions of the processes modeled, and accommodate the new knowledge. If the provided follow-up worksheet is not an appropriate summative activity, the instructor may choose to have a guided discussion, or assign a different activity.

A simple, but effective, activity is to connect elements of the game to real world examples. For instance, finding localities represented by the gameboards, or researching the reef building or dwelling organisms. Students could investigate the similarities of their gameboard with local examples of modern reefs, fossil reefs, or reef components in museums or collections. Likewise, many of the disaster card scenarios have modern or geological examples. Extension activities could include readings, discussions, or projects about these how reefs are affected by hurricanes (e.g., Hubbard et al., 1991; Pascoe et al., 2021), the 1983–84 Caribbean *Diadema* sea urchin decimation (e.g., Lessios, 2016), or heatwaves on the Great Barrier Reef (e.g.,

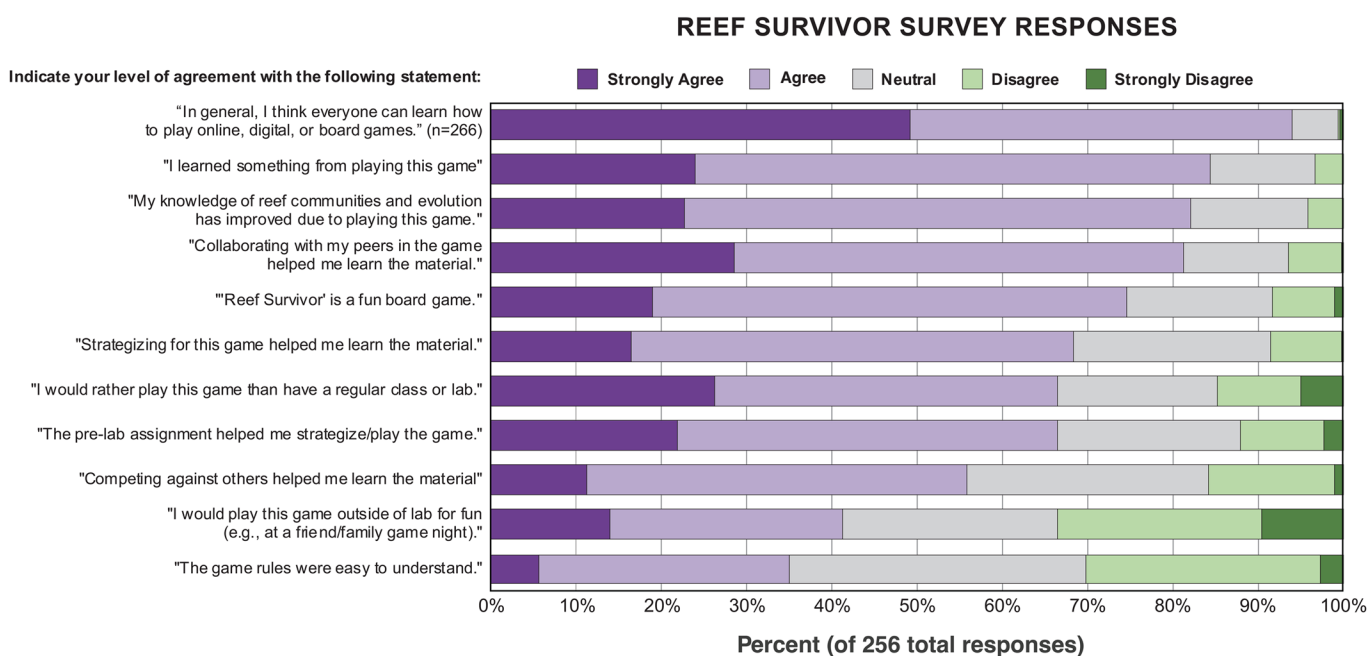


Figure 5. Stacked bar charts of participant survey data with a focus on their opinions about the "Reef Survivor" as an educational board game (256 student responses unless otherwise noted).

Table 2. Assessment questions for the “Reef Survivor” board game and their corresponding Student Learning Objectives (SLOs).

Assessment Question	SLO Assessed	How Question was Utilized
<i>(Last question of onboarding worksheet, after students walked through game setup)</i> Are you happy with your choice of game board and reef builders? If yes, why? If not, what would you change and why? Feel free to change your reef set up based on what you learned in this worksheet (you can use the strategy you have outlined here or modify your strategy).	SLO #1	Onboarding question to encourage students to familiarize themselves with the game and reflect on their strategy (results not reported here) .
What are the mechanisms that ADD variation to gene frequency?	SLO #2	Used in Pre/Post Assessment to determine learning gains about mechanisms of evolution.
Do genetic mutations occur for the good of the organism or are they random? Do they help or hurt organisms? Or can they do both?	SLO #3	Used in Pre/Post Assessment to determine learning gains about mechanisms of evolution.
A) If a mutation helps an organism survive, explain how it becomes more abundant in a community over time. B) Explain how the board game mechanics represent the tenants of Darwin's postulates.	SLO #4	Advanced assessment questions about mechanisms of evolution (results not reported here) .
Can an organism or species “prepare for” environmental changes or stresses? Explain your answer. What does this tell you about natural selection?	SLO #5	Used in Pre/Post Assessment to determine learning gains about mechanisms of evolution.
Make a simple sketch about how mutation, migration, random processes, and natural selection can impact a community. How might this lead to extinction over geological timescales? Make sure your sketch is labeled (e.g., the organism, the process description, the result of the process). Note: There are multiple correct answers!	SLOs #2-#5, SLO #12	Used in Pre/Post Assessment to determine learning gains about mechanisms of evolution and connection to longer geological processes.
Sketch a cross section of your reef bathymetry (depth of the water), include three of your reef builders. How did the water depth impact the chance of those organisms surviving (i.e., did the depth help or hinder their survival?)	SLO #6, SLO #7	Used in Pre/Post Assessment to determine learning gains about reef ecology, niches, and converting map data to bathymetry.
Sketch a reef system, identify reef builders, stresses and how those stresses may change the reef through time. Make sure your sketch is labeled (e.g., the organism, the process description, the result of the process). Note: There are multiple correct answers!	SLO #6, SLO #12	Used in Pre/Post Assessment to determine learning gains about reef ecology, niches, and environmental factors that change through geological time.
Get to know the possible game boards and reef builders! Check out the five possible game boards. Note that some have land and others do not, some are mainly shallow, and some are deeper. Choose one of the game boards to use for the lab; explain your strategy (i.e., which one did you choose and why?).	SLO #7	Onboarding question to A) introduce students to the different types of reefs (i.e., antecedent bathymetry) and B) familiarize themselves with the game and reflect on their strategy (results not reported here) .
Which community is more likely to survive environmental change, one with lots of only a few types of reef builder, or a community with many different types of reef builder?	SLO #9	Used in Pre/Post Assessment to determine learning gains about the role of diversity in surviving environmental change.
What was the composition of the community at the start of the game? At the end of the game? How did the diversity of your community change over time? How is the diversity of your game board different from the abundance of reef builders?	SLO #10	Follow-up question to introduce students to how biodiversity is measured, results could then be used in discussions of biogeography and diversity through time (results not reported here) .
What are some things a conservationist might do to help a reef ecosystem survive environmental change like we are seeing today (i.e., climate change, rising CO ₂ levels, acidification, pollution, and overfishing)?	SLO #9, SLO #12	Follow-up question to encourage students to consider applying their knowledge to reef conservation (results not reported here) .

Cheung et al., 2021; Hughes et al., 2021; Le Nohaïc et al., 2017; Pratchett et al., 2021). Many articles discuss the synergistic effects of multiple stressors (e.g., Cornwall et al., 2021; Hughes, 1994) and could make effective follow-up readings.

The game can also generate data for a biodiversity activity, such as plotting range charts or biodiversity of game tables through time (i.e., 4 million years). Students could compare biodiversity between tables or lab sessions, as one would compare geographic regions and then discuss why some regions are more significantly impacted by certain ecological or anthropogenic stresses than others. Alpha, beta, and gamma diversity could also be tracked using each gameboard as a reef, each table as a region, and the class as the globe; ecological metrics, such as diversity, abundance, evenness, and dominance could also be calculated. An introductory activity using the game as a model could build to an experimental activity using real data from modern or fossil reefs.

Games are also excellent foci for discussions of science communication (Martindale & Weiss, 2020); the game has

simplifications and is not a perfect analogy for reefs, evolution, or environmental change. Therefore, discussions could focus on identifying simplifications or expanding/changing game mechanics to represent a concept more accurately; while these modifications often make the game more complex, time consuming, or awkward to play, these discussions help students learn specific topics more deeply and think critically about the way a process works. Other discussion questions could include: what are the timescales of disasters and recovery? With what frequency do disasters occur (e.g., storms versus hurricanes); should there be more of certain cards than others to reflect this? What other consequences might there be for different bathymetries or geographies? Are coastal geographies or organisms different through geological time? How does anthropogenic disturbance influence a particular setting (e.g., dredging)? What could conservation workers do to protect a reef from environmental changes? How can the complexities of the system be equitably integrated with environmental justice issues or local culture and heritage to manage conservation?

Optional modifications to gameplay

The game was created for a 2-hr freshman “Life Through Time” lab that introduces students to geological time, paleontology, and evolution; however, it is flexible and adaptable. The easiest modifications are to play with more or fewer players, or with a different number of rounds (all SLOs met, Table 1). Below are examples of more substantial ways the game can be modified included in the “Teacher’s Version” of the rulebook (supplemental data S7).

The importance of place-based education for engaging students and fostering a sense of place is clear (Gosselin et al., 2016; Semken, 2005; Semken et al., 2017; Visaggi, 2020), and a simple modification is to focus the game on local examples. This need not be a modern coral reef, like the tokens, but the instructor could limit the builders to those represented in a local fossil or modern reef; for example, in Texas one might limit builders to the corals and rudists common in Cretaceous reefs. Local examples can encourage independent, informal learning and engagement with research projects. The bathymetric profiles could mimic those of a nearby reef, or a new layout could be designed to represent a unique setting, such as the Hawai’ian archipelago or the Australian Great Barrier Reef. If there are local names for organisms, these could be used as well, which would be especially advantageous if there is cultural significance (Apple et al., 2014), such as the Hawai’ian *Humuhumunukunua* fish (Chinn et al., 2011; Pearce & Louis, 2008). Not only does incorporating components of culture and history expand this activity, these high-context elements and connections of geology to different place meanings could be more impactful for students, especially locals or students from indigenous groups with a deep-rooted local history (Apple et al., 2014). Moreover, one could design a new set of characteristics and tokens that represent specific examples (e.g., a Cambrian reef with archeocyathids and encrusting algae). Advanced students could have a pre-lab activity that requires them to research and create a set of organism tokens and a corresponding characteristics sheet (e.g., Red Sea versus Indo-Pacific versus Caribbean reef builders); this would be highly engaging if the class then played with the new rules.

If an instructor has access to modern or fossil samples of reef builders, these specimens could be available during the game as teaching aids or part of associated activities. In advanced classes with extensive collections, students could curate a collection representative of their reef, or even search for, photograph, or collect their community at a real fossil deposit. If there are no collections, vignettes or videos of fossil and modern reef sites could be shared.

Instructors or students could modify disaster cards to highlight specific concepts. For example, a course about climate change might highlight just the climate disasters (e.g., hurricanes, heat waves, increases in degree heating months) and a course focused on human threats to ecosystems could design new cards about anthropogenic stresses, such as pollution or overfishing (Halpern et al., 2007). A pre-game activity might ask students to research disasters and design new cards to be used in the following class. If the focus of the course is on reef ecology, the game could be played

without the long-term disasters and have each round represent a shorter duration of time (e.g., a thousand years rather than a million years). More specific suggestions are included in the “Teacher notes” (supplemental data S7).

If the class favors high-context activities or the instructor wants to stress collaboration, different tables could play against each other. The four players at the table would be encouraged to work together to promote the resilience of the reefs throughout the region. This modification would decrease competition, which may decrease engagement, motivation, and performance for some students (Burguillo, 2010), but the benefits of heightened collaboration may be preferable (e.g., Basu & Middendorf, 1995; Gokhale, 1995; Laal & Ghodsi, 2012; Macdonald & Bykerk-Kauffman, 1995; Sung & Hwang, 2013).

Evaluation

Evaluation of the game was twofold; 1) students’ opinions of the game (as well as demographics) were assessed with an online survey, and 2) learning gains associated with the game were evaluated by comparing responses to pre-game and post-game assessment questions. All evaluation data were collected within a week of the students playing the game as part of the follow-up assignment. Although data was collected from 351 individuals, many students did not take the survey or failed to complete both pre and post assignments (total populations for each dataset are reported in those figures); only 185 students had complete data.

Students were asked a series of multiple-choice, short answer, and open-ended questions to address specific learning objectives (Table 2) and assess their knowledge. All pre and post questions were administered to students as low-stake assessments, typically pre-lab and post-lab assignments for simplicity (submitted on paper and scanned or submitted as a PDF); given the 15 different institutions, there were variations in delivery (e.g., assigning questions in low-stakes quizzes, <5% of their overall grade). Although onboarding (pre-lab) and follow up (post-lab) worksheets contained several identical questions (supplemental data S1, S2), allowing for direct pre/post-game assessment of learning gains, students were instructed not to copy their answers but rather apply their knowledge from gameplay to a new answer. Identical pre/post answers (i.e., copied and pasted answers) were removed from the dataset as they do not provide information about learning gains ($n=15$; not included in the 185 complete responses). Answers were all graded by the same evaluator with a rubric developed by the game designer/course instructor and teaching assistants (supplemental data S5).

An online survey (Google Form or Canvas Survey) was constructed and administered by the authors to assess students’ self-reported opinions and attitudes about the game (see S3 and S4 for survey questions and results, respectively); questions are similar to those used in Martindale and Weiss (2020). The first set of questions was the students’ opinions of the game and a self-assessment of their educational gains (13 questions on a Likert scale: Strongly Agree, Agree, Neutral, Disagree, Strongly Disagree). The second set were

open-ended questions about the students' opinions (e.g., what did you like/dislike, what would you improve?). The third set of questions was about the demographics of the population (e.g., institution, major, class level, experience with games) as well as students' opinions of games in general and a self-assessment of previous knowledge (12 multiple choice questions). The fourth set of questions addressed the students' personal demographics (multiple choice and short answer questions about race, gender, ethnicity, and socioeconomic status). The final set of questions included identifiable information for participation credit; answers were redacted before analysis.

Concerns about student survey responses are minimal; the survey was anonymous and there were no benefits to lying, which encouraged students to provide honest feedback. Previous studies confirm that self-reported surveys are consistent with other data collection techniques (Mullens, 1998; Mullens & Gayler, 1999; Porter et al., 1993). Although all teachers were instructed to play the game in the same manner, there were variations in course content, teaching delivery (e.g., online versus in person), and instructional levels, so the preparation and course objectives were not consistent. For example, the game was used in introductory and upper-level paleontology classes, biological oceanography courses, as well as conservation biology classes depending on the institution and semester.

All data were anonymized and analyzed by the authors, total learning gains (i.e., the sum of all post-lab scores minus pre-lab scores) were calculated, and results plotted in either Excel or R studio (R Core Team, 2014). Frequency data of survey answers are visualized as diverging bar charts (Figures 5 and 6). Lastly, multivariate regression models were used to

examine whether learning gains were related to different conditions or student characteristics (e.g., semester, demographics, socioeconomic status). Confidence intervals (95%) are plotted to show overall gains from gaming and for comparison with each gaming condition or student characteristic.

Results

Student opinions – Likert data and written comments

Game conditions

The summarized results (stacked bar charts) of student opinions about the game and perceived educational gains are presented in Figures 5 and 6 and summaries of selected comments are presented in Tables 3 – 6. Complete, anonymized survey responses are in supplemental data (S4); 256 students completed some or all of the survey. Most students (71%) played the game as part of a lab, 24% playing during a class (Figure 6). Gameplay times (Figure 7) ranged from about an hour (10% of respondents), to over two and a half hours (27%), although some students' comments suggested that the game had not been prepared ahead of time as instructed (thus extending time needed). Regardless, 73% of students finished in two hours (Figure 7); this number rose to 80% when virtual labs are excluded, which have their own, unique difficulties and a longer introduction video (~25 min versus 10 min). In total, 51% of students played this game in a team of two or three and 49% played solo (Figure 6).

Of the 256 students that completed the survey, 39% claimed to know a lot or quite a bit about ecology, evolution, and extinction before enrolling in the class, 41% knew a few things, and 21% knew very little or nothing about these topics. Students

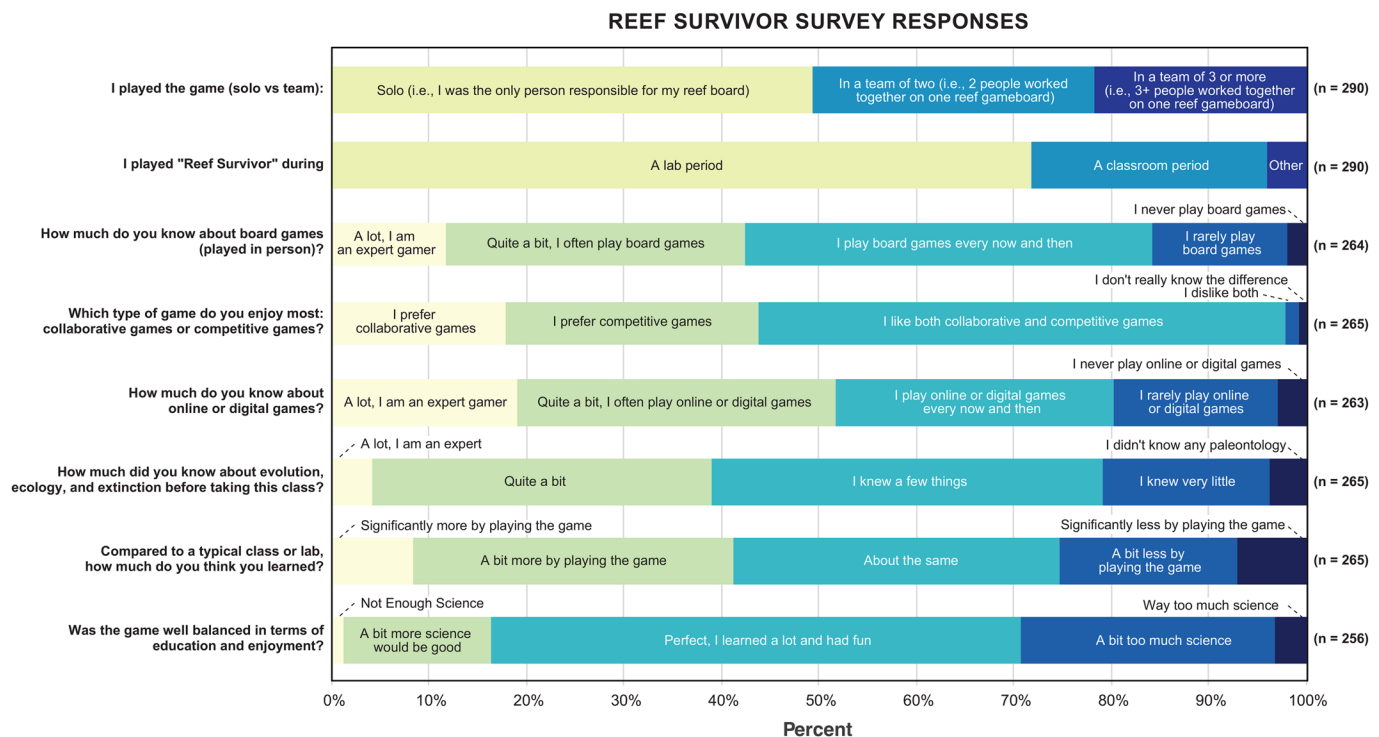


Figure 6. Stacked bar charts of participant survey data with a focus on their experience with games and how "Reef Survivor" played in their course (number of student responses noted next to each question).

Game play time (n=249)

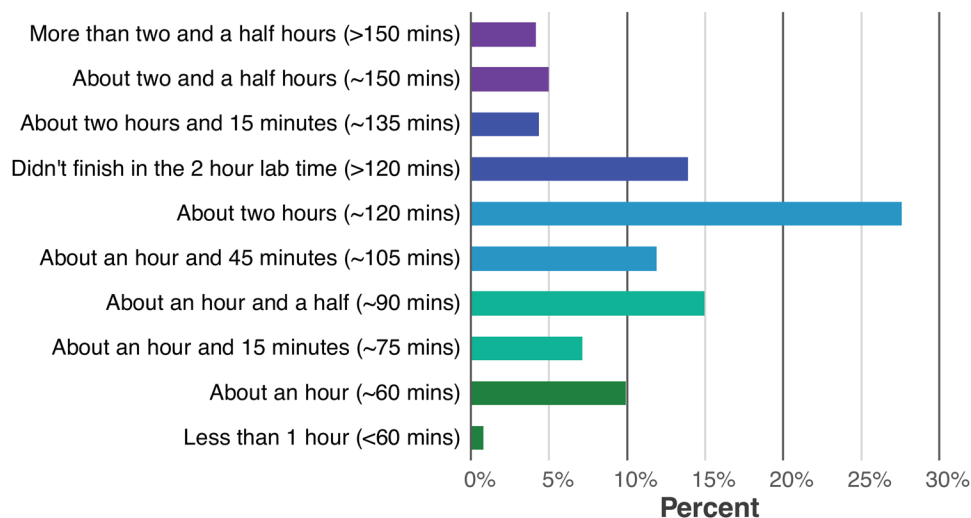


Figure 7. Time it took the surveyed participants to complete “Reef Survivor” (249 student responses).

typically played board and online games frequently (43% and 52%, respectively), or at least every now and then (42% and 29%, respectively; [Figure 6](#)). Almost all students (94%) agreed or strongly agreed that everyone could learn how to play board games ([Figure 5](#)). Half (54%) liked both competitive and collaborative games, although 26% preferred competitive games to collaborative games (18% preferred collaborative games); 3% disliked both or did not know the difference ([Figure 6](#)).

Did students enjoy and learn from the game?

Three quarters (74%) of students agreed or strongly agreed the game was fun ([Figure 5](#)); in written comments 60 students mentioned different aspects of the game being “fun” and 12 said they loved the game. There were many positive comments about the game overall ([Table 3](#)), and numerous students mentioned that they enjoyed the integration of scientific content (e.g., PSC1-9) and reflected on how much they learned (e.g., PLG1-13). Several students commented that it was helpful to see the interaction of different factors modeled by the game, and others mentioned how useful games, in general, were as learning tools (e.g., GG1-GG6, [Table 3](#)). Many comments in the student feedback were about game structure (e.g., GS1-7, [Table 4](#)) or specific components ([Table 4](#)). Comments commonly included student enjoyment of choice as well as the diversity of components (e.g., game boards, reef builders, and the ability to trade) and how the game reflected real reefs ([Table 4](#)). Lastly, 66% of students said they would rather play the game than have a regular class or lab, only 15% preferred a regular lab ([Figure 5](#)), and 41% the students would play the game for fun (34% would not).

Most students that completed the survey agreed or strongly agreed that they learned something from the game and their knowledge of reefs and evolution improved (84% and 82% of respondents, respectively; [Figure 5](#)). One-third (34%) of students thought they learned about the same amount playing the game versus having a standard lab or class, and 41% of

students said they learned a bit more or significantly more playing the game (25% said they learned more in a regular class or lab). Two thirds of students (68%) said strategizing for the game helped them learn the material and the pre-lab assignment helped them plan or play the game ([Figure 5](#)). Many students mentioned strategizing as something that they particularly enjoyed (PSC2 & PSC3, [Table 3](#); S1-4, [Table 4](#)). Most (82%) said peer collaboration helped them learn the material, with more than 20 comments specifically focusing on collaborating or collaboration (e.g., CC1-6, [Table 4](#)); however, only 56% said competing against their peers helped them learn the material (e.g., CC6-9 in [Table 4](#)). In the written comments, students often mentioned the interactions with their classmates during the game, whether that was to develop strategy, trade pieces, or compete ([Table 4](#)); in fact, several negative comments were about the lack of collaboration from their group (e.g., SI 1-7, [Table 5](#)).

Over half (54%) of students said the game was well balanced, allowing them to learn a lot and have fun, but 29% said there was too much science ([Figure 6](#)). One third (35%) of students agreed that the game rules were easy to understand but 31% disagreed ([Figure 5](#)). Several open-ended comments ([Table 5](#)) were made about the game being complicated ($n=16$) or confusing ($n=39$), with 60 comments about the rules. Nevertheless, several students perceived the complicated nature as necessary for this game type (e.g., GRI1, [Table 5](#)), and some of the issues may have arisen from incorrect deployment of the game; for example, some mentioned not receiving the pre-lab scaffolding assignment or game booklet (e.g., EG1, EG2, [Table 5](#)) and others mentioned user errors in gameplay (e.g., GRI4). Some players expressed frustration with “token management” (e.g., GP1-2, GRI2, [Table 5](#)); several institutions had convenient solutions, such as using small craft or tackle boxes, disposable condiment cups (e.g., 3 to 4 oz), or specimen trays. One student who is colorblind noted issues distinguishing tokens. Many students had issues playing online (e.g., OG 1-4, [Table 5](#)), which is largely attributed to playing on Google Jamboard. This

Table 3. Positive comments about the game and educational gains from the survey, see [supplemental material \(S4\)](#) for a complete list of student comments.

Category	ID #	Comment
Positive Comments about the Game Overall (PG)	PG1	I deeply enjoyed the concept of this board game. I am a huge fan of board games and I thought this one was really good.
	PG2	It was so much fun playing with my classmates. It's a great way to bring engagement into a classroom.
	PG3	It was a great game and I learned a good deal from it! I would love to play it again!
	PG4	It was a good balance between educational and fun, and after the first round, it was easy to follow the rules.
	PG5	The handbook explains the science behind the game very well, and I felt like I learned something.
	PG6	I like that because of the structure, each game will be different, making it not so repetitive to play again and again. Prepping for the game was fun and helpful.
	PG7	How much variety there is to the game. You could play it a million times and still have different outcomes each time
	PG8	I like being able to form my own reef and making decisions that would help my reef.
	PG9	I loved that you weren't explicitly against other people... and how it was a chill game where you could focus on yourself and still have friendly contact with other reefs (the trading aspect).
	PG10	I liked that this game had no attacks on other players, every player did their own thing. I thrive without conflict in gaming.
	PG11	[I liked] how peaceful it mostly is, it's kind of relaxing to foster a reef community.
	PG12	I liked that we had responsibility over our reef and had to do our best to keep it alive
	PG13	I liked how there were so many different pathways one could take to result in different outcomes; it really made sure to keep the game interesting and players on our feet!
Positive Comments about the Scientific Content (PSC)	PSC1	I liked that it was indicative of problems in the real world. And that you learn what keeps reefs thriving and what could endanger their health.
	PSC2	I liked how much strategy it took, and how each of the different boards and organisms had different benefits and detriments.
	PSC3	I enjoyed how strategical the game is while combining it with oceanography and being able to choose different environments to play
	PSC4	It was great seeing how the reef evolved and changed or didn't change over time.
	PSC5	I liked all the different factors you had to consider to increase your reef's chances for survival; placement, mutations, trading species, starting board, starting organisms, reef dweller selection, etc. all had to be considered based on knowledge of reef organism strengths and weaknesses.
	PSC6	The environmental dangers felt a lot more real, and I felt very protective of my reef! This might be due to the fact that the organisms are still alive.
	PSC7	I liked how the disasters affected the reefs we built up in various and unexpected ways that would either wipe out the organisms we amassed or left them in more or less the same condition. Despite our best planning, the disaster events had us with our fingers crossed hoping that we would be spared from a catastrophe which I found enjoyable and educational.
Student Reflections on Learning Gains (PLG)	PLG1	Actually going through the motions of the game really helps me understand reef processes.
	PLG2	I loved how much it taught me! The game was very educational and made me want to research more about coral reefs.
	PLG3	I liked the way it teaches you the mechanisms of ecology through acting them out yourself.
	PLG4	I liked how this game allowed us to be competitive and still learn about marine communities. We were able to create our own reefs based off of prior and new knowledge allowing for strategy to be a key factor in how successful we were. The ability to bounce ideas off of one another while playing this game allowed for us to expand our knowledge through collaboration while having fun.
	PLG5	Personally I found the game to help visualize and see properties of a reef in motion which helped cement knowledge I had already seen and learned in class. Gameplay wise my favorite part of the game was rolling for mutations and seeing the random factors that may impact our reefs.
	PLG6	I really liked the comprehensive nature of the game. All facets of a reef environment seemed to be represented somewhere, which is what allowed me to learn a lot.
	PLG7	This game was enjoyable to play due to the fact that teams weren't competing against each other and that the variability in terms of factors weren't repetitive. There were many layers to how the game played out with different rounds and a chance to win more points based on focusing on certain strategies (focusing on reef builders that supported reef dwellers). The threat of having reef builders being destroyed or negatively affected via the short and long term events as well as the fleshy algae made us less complacent in our decisions in the game.
	PLG8	the game does a good job of illustrating the complexity of how random mutations and variable environments change communities over time.
	PLG9	I liked the competition because it allowed me to reflect on where I went wrong and how to improve my reef. It made me realize what is needed to grow a strong environment and learn what adaptations/mutations help in certain situations.
	PLG10	It made me sad seeing how reefs can easily be destroyed. Alas, that is how it is in real life, too.
Comments about Games in General (GG)	GG1	I liked learning in alternative methods rather than just reading and interpreting things over and over
	GG2	The fact that it was a game was the best part- it wasn't stressful or demanding, which makes it better than normal classwork.
	GG3	I like that I can play and learn at the same time.
	GG4	Make more games. I am a huge fan and I love the sciency games.

platform is not the best vehicle for online gameplay but was deemed the most equitable option because a) students were familiar with the software and b) they need not pay additional fees or have a computer with a good graphics card.

Learning gains – comparison of pre-game and post-game assessments

The multivariate regression models of student learning gains demonstrate that most students did learn by playing the game (Figure 8). Overall, learning gains were positive, with gains increasing each semester as improvements to the game and associated material were made. The results from Spring

2021 showed statistically significant negative learning gains ($p < 0.05$) but, a) this was the first semester the game was played, and b) this was the only semester where students played online. Players clearly had issues with Google Jamboard and became frustrated, had a hard time collaborating with their teammate(s), or ran out of time (Table 5). When students played in person (Fall 2021 and Spring 2022), learning gains were positive. Increases occurred each semester as the game was refined, leading to a significant increase in learning gains between Spring 2021 to Spring 2022 (i.e., confidence intervals in Figure 8 do not overlap); in the final semester of assessment, significant learning gains ($p < 0.01$) are reported (Figure 8).

Table 4. Specific comments about components of gameplay from the survey, see [supplemental material \(S4\)](#) for a complete list of student comments.

Category	ID #	Comment
Game Structure (GS)	GS1	I like the fact that it is round based and not turn based.
	GS2	I really liked the visual interpretation of a reef... and how mutations and environmental events effect their growth through time.
	GS3	It was competitive and well-balanced in the fact that everyone could get points.
	GS4	I liked that the game had very clear rounds that repeated so that it was simple and fun to try and strategize...
	GS5	I liked the level of mechanical complexity - I think it was good for simulating the different systems at play and also was an engaging level of strategic play to chew on
	GS6	I really liked the idea of managing the coral and having choices at different stages and easily being able to adjust strategies.
	GS7	It was fun to trade and talk how each of our coral system got affected by the catastrophe. It is a mixture of dice-board game and card game, which makes it more thrilling and exciting.
Game Boards (GB)	GB1	I liked the freedom of getting to choose my own game board.
	GB2	I liked the different reef boards, it really showed just how impactful the physical environment is on the game.
	GB3	I liked that we could pick our own environment and strategize off of that.
Reef Builders (RB)	RB1	I liked being able to pick what reef builders I wanted in my reef.
	RB2	I liked that there were a variety of reef builders to choose from and that they all had unique strengths/weaknesses. It was interesting to see how each one did whenever we had a "catastrophe" hit. It also taught me a lot about the various types of corals, sponges, etc. that live in reefs.
	RB3	I enjoyed the diversity of organisms involved ... and the variety of topographic settings we could choose from...
	RB4	It was fun to see all the beautiful corals and building a coral reef
	RB5	I enjoyed learning about the different traits the different reef builders had and using those traits to strategize my game play. I also enjoyed the mutation ideas and rolling the die to see which random one was given.
	RB6	[I] LOVED the stacking mechanic.
	RB7	[I didn't like] How quickly the board became covered in fleshy algae, but I'm not sure if that's the intent of the game.
Fleshy Algae (FA)	FA1	The fleshy algae was almost impossible to manage
	FA2	
Trading Juveniles (T)	T1	The concept of trading larvae between players due to their planktonic life stage migration ability was really fun and clever.
	T2	The trading aspect really added to the quality of the game. It added a competitive edge that forces the player to consider the benefits and drawbacks to each trade and that in itself is the process through which they further their understanding of the material... I had to actually know the rules of the game (aka the material) to catch when my group didn't realize that they couldn't support 12 reef dwellers with only 8 reef builders who can accept dwellers and so on.
	T3	I ... liked that we could trade coral with each other to make our reef more diverse.
Mutations (M)	M1	What I liked most was how we could see mutations spread across offspring of other organisms.
	M2	I liked the duality of the evolution dice rolls. On one hand, you can get an evolution that can extremely benefit your organism but on the other hand, it can also kill all of that organism's population depending on the events.
Disasters (D)	D1	I liked the diversity of the disasters, and how it helped me understand how real life coral reefs can be affected by various disasters/environmental changes.
	D3	I enjoyed the harshness of each disaster and the strategizing that must incorporate these dramatic changes.
Strategizing (S)	S1	I enjoyed the strategy of trading to collect new species and mutations.
	S2	I enjoyed the strategizing and trying to anticipate a disaster in order to maintain a community
	S3	It was fun to strategize about which reef builders to choose and where to put them. And of course the catastrophes!
Collaboration and Competition (CC)	CC1	I like collaborating with my partner... that was definitely how we experienced learning about how reefs work and how stresses affect them.
	CC2	[I liked] the collaborative element. Strategizing with a friend and with other reefs to try and improve your own was very fun.
	CC3	I enjoyed strategizing with my teammates... If one of us missed something... another member would notice it.
	CC4	What I liked most about this game was being able to work with someone else as it helped me clear up misconceptions and realize that I had huge deficiencies in my strategy before starting the game.
	CC5	I really enjoyed the collaborative aspect of the game. It helped me to learn the material better. The building stages of the game were very fun. You got to choose your organisms, mutate them, and trade juveniles with others.
	CC6	I liked the fact that there was both a collaborative aspect and a competitive aspect. Strategizing with someone else rather than just on my own helped me familiarize myself with all of the material ... The competition between teams was also fun.
	CC7	I'm a competitive person so this game inspired me to pay more attention so I could win.
	CC8	Trading and competition/overall interaction with other players' reefs was fun.
	CC9	I liked the trading with other players, building deals and making bets was fun.

The regression models also demonstrate no significant differences in learning gains between demographic groups, specifically by gender, (dis)ability, race, ethnicity, or family income (Figure 8). All genders show positive learning gains, although the mean is closer to zero and there is more spread amongst genderqueer, transgender, and non-binary students than male or female students (which may be partially a result of a smaller population). Students with a disability do have negative learning gains, albeit they are very close to zero, and there is a larger range in the data than students without a disability (Figure 8); note that information about the type or severity of disability was not collected. The highest learning gains were from White and Asian students, whereas Hispanic and Black students had negative learning gains; however, the overlapping confidence intervals indicate the groups were

not statistically different (Figure 8). In some groups there was substantial variation and several groups had low numbers of individuals with complete data (i.e., less than 10 people). Interestingly, students from higher income families tended to have less positive learning gains, with the highest gains occurring with students from lower- and middle-class families (again not significantly different).

Interpretations and discussion

Strengths and weaknesses of the educational innovation

Based on qualitative and quantitative data, the board game "Reef Survivor" is an effective educational tool. Students enjoy playing the game in their labs or classes and can

Table 5. Negative comments about the game from the survey, see [supplemental material \(S4\)](#) for a complete list of student comments.

Category	ID #	Comment
Game Rules and Instructions (GRI)	GRI1	It is a little convoluted, but that's not a hard complaint. It's just that kind of game.
	GRI2	The game is a little complex for the average, non-scientist player, it might do good to simplify it a bit. Another option would be to make an online version of this game, where the computer can handle some of the complexities.
	GRI3	Sometimes the instructions felt inaccessible in the way that they were worded... as in they used what felt like academic phrasing which kind of shut off my brain as I was trying to learn a game. But the concept of the game was really enjoyable and as I was playing I enjoyed it more and more.
	GRI4	The instructions about the game were a little unclear. For example, our class didn't understand the natural disaster part of the game so each of us chose our own disaster rather than using one for the whole class.
	GRI5	The game was pretty complicated to play in the beginning so it was a huge learning curve for playing. However, the cheat sheet made it much easier ... Besides that, I enjoyed most of the game mechanics and how it was structured.
	GRI6	Some of the rules were a little hard to follow, especially at first. It took time for everybody to really get into the cycle of the game play. My partner and I already had ideas going into the game because we read the rules ahead of time, but if I were to play this with my family or other friends who are not as well versed in geology, they might have trouble figuring things out.
Game Pieces (GP)	GP1	Piece management became really complicated really quickly.. a monopoly tray or a tacklebox for the different pieces would make playing the game much easier.
	GP2	My least favorite part of the game was putting the pieces on the board, and taking them off. It was so time consuming because of how many there were.
Student Interactions (SI)	SI1	Maybe it [was] because my group did not trade organisms between nurseries very often, but I thought there could be more player/player interaction.
	SI2	[I didn't like] The inability to diversify if other players did not want to aid you.
	SI3	The game could stand to have more interaction between players other than one round of trading to make it feel more competitive and to engage the players.
	SI4	Maybe have more interaction between each player's reefs, like along with trading maybe have possibilities to sabotage or interact with their reef
	SI5	I wish it was more competitive. The game feels too solo compared to other games.
Disasters and Fleshy Algae (D)	D1	The removal of algae sometimes felt useless cause I would end up removing 5, but then just adding 5 all over again.
	D2	The disasters were pretty devastating, it became impossible to keep spaces clear of algae.
Errors in Game Implimentation (EG)	EG1	It would be easier to follow a step-by-step rule book including what to do with rounds within each phase.
	EG2	The pre-lab portion was not given/ told to us to do before the game so it was hard to fill out after playing the game.
Issues with Online games (OG)	OG1	The online version is very tedious. The need to continually copy, paste and maneuver small boxes is difficult...
	OG2	We only had time to do 2 rounds and already the stacking in our reef so was confusing and hard to navigate (this is partially jam board- I'm sure playing this in person is easier)
	OG4	I think it was just more confusing online than it would have been in person, where we can actually physically collaborate more...

identify their improved understanding of concepts surrounding evolution, ecology, and extinction (Figure 6). Most students surveyed play board games at least occasionally, suggesting that this medium is familiar to them; some even expertly commented on specific aspects of game mechanics. Although some students struggled with game rules, that is to be expected with a medium complexity Eurogame. Nevertheless, most students thought the game was fun to play (Figure 5) and over a third thought they learned more than they would have in a normal lab or class (Figure 6). These opinion data are supported by the pre/post assessments, which demonstrate clear, positive learning gains (excluding Spring 2021). When initially deployed online, the overall learning gains were not positive (Figure 8); however, the students were still positive about the activity and their improved understanding of the learning objectives. With further revision and in person gameplay, overall learning gains increased substantially, such that by the final semester, the learning gains were significant and positive. The increase in learning gains between Spring 2021 and Fall 2021/Spring 2022 is attributed to 1) the students having more time to complete the activity (shorter introduction), 2) the benefits of in-person interactions in face-to-face settings, and 3) improvements in the game as well as associated instructions and scaffolding activities. It is difficult to separate the impact of these components since the largest increase in

learning gains (Spring 2021 to Fall 2021) was coincident with changes to all three. The notable increases from Fall 2021 to Spring 2022 suggest that the move to in person was not exclusively responsible for the improvement in learning gains. Moreover, similar assessments were conducted on the board game, "Taphonomy: Dead and Fossilized" (Martindale & Weiss, 2020) and importantly, there were no significant differences between Spring 2021 (online), Fall 2021 (face-to-face), and Spring 2022 (face-to-face) semesters (Sulbaran-Reyes et al., *In Review*). Thus, online versus in person gameplay (or COVID-related burnout) is likely not the only reason the reef game learning gains increased over time.

There are no statistically significant differences between student demographic groups, although there are some trends indicating higher gains amongst majority student groups. Martindale and Weiss (2020) posited that racial and ethnic disparities in a previous educational game assessment may have resulted from socioeconomic status, which often corresponds to race (Fontenot et al., 2018). Data collected here provide evidence that socioeconomic status does not lead to a difference in learning gains; if anything, there is suggestive evidence that the highest learning gains were associated with students who grew up in a low income household and the lowest learning gains from high income households. It has been hypothesized

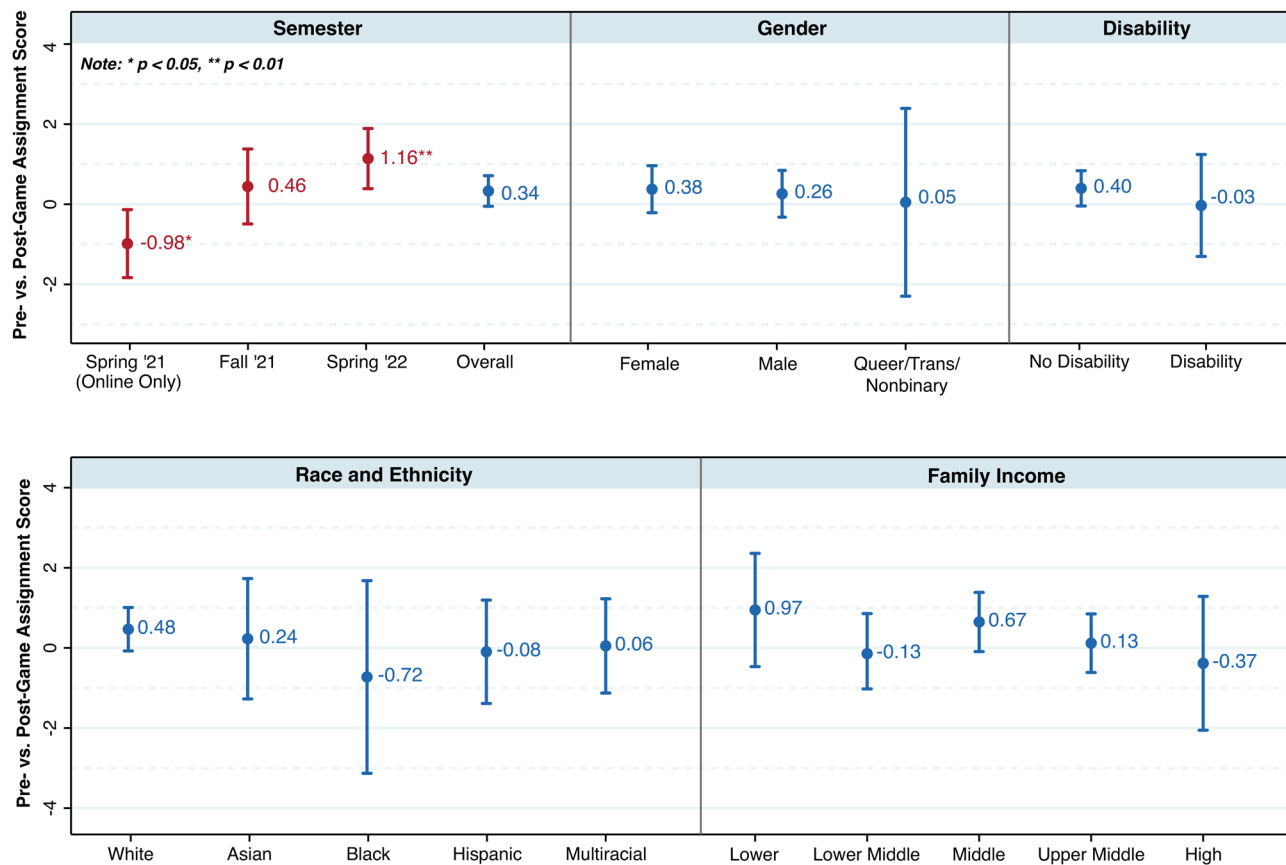


Figure 8. Multivariate regression models of participant learning gains (i.e., the sum of post-lab scores minus pre-lab scores) and their relation to the semester and demographics (185 total complete responses). Confidence intervals (95%) are plotted to show overall gains from gaming and for comparison. Blue values include all data, whereas the red values indicate data split by semester.

that high and multi-context activities may better engage students from cultural backgrounds where these elements are valued (Weissmann et al., 2019). Several high-context elements were intentionally incorporated into “Reef Survivor” (e.g., collaboration, storytelling, interconnection of the players and game boards, and application of knowledge to protect the gameboard) to make it more multi-context than the “Taphonomy: Dead and Fossilized” game; the lack of significant difference between demographic group learning gains suggests these efforts were successful, to a degree.

Lastly, it was clear from player comments and response rates that there was fatigue amongst the students (and instructors). While much of the pre-lab assignment was designed to scaffold student learning of gameplay and strategy, and thus is an important part of the activity (e.g., most students agreed the pre-lab assignment helped, Figure 6), the post-game follow-up assignment could be shortened, particularly if the instructor is focused on a subset of learning objectives (Table 1). A simplified assignment is provided in the supplemental material (S6). Another option would be to have a quick, simplified “practice round” with just a few reef builders and rounds to demonstrate game mechanics and procedures. This would allow students to become familiar with the mechanics, digest and synthesize the procedures, and plan a strategy for their next class or lab (e.g., SS1 in Table 6).

Educational activity improvements

Several students had suggestions for modifications to gameplay (Table 6). Some suggestions were incorporated throughout the assessment period; for example, students in Spring 2021 suggested a shorter introductory video, which was subsequently implemented. Other suggestions would either dramatically change gameplay dynamics (e.g., SAC1, SAC2), decrease the emphasis of a learning objective (e.g., ST3), or are not feasible given the scope of the intervention (e.g., making a video game; SS2, Table 6). In some cases, modification or accommodations should be implemented; for example, having a token management system, or playing a “warm-up game” before deploying the full activity.

Through the three semesters of evaluation, several improvements were made to game materials. Modifications include the correction of spelling and grammatical errors, instruction clarifications of common gameplay misconceptions, a simplified “cheat sheet”, mechanical adjustments to improve gameplay, and other minor edits. Reef builder and dweller tokens now include text for easier identification, which will hopefully make the game more accessible to players, especially those with minor visual impairments (i.e., color blindness). The game is still problematic for students with severe visual impairments, but if facilities are available, tokens and gameboards could be printed with braille.

Table 6. Suggested improvements for the game or associated activities, see [supplemental material \(S4\)](#) for a complete list of student comments.

Category	ID #	Comment
Suggestions for Tokens (ST)	ST1	If the long term disasters and short term disaster card could be a bit more distinctive
	ST2	Have labels on the chips ... for the corals and other organisms. It would allow us to quickly pick them out and differentiate them (esp if you have pattern recognition/colorblindness problems) instead of relying on the images alone.
	ST3	It would be helpful if the reef builder tiles had the names of the species on them... I just kept calling them "the round one" or the "pink one". Everything just blended together on my game board.
	ST4	I think adding small symbols to the tokens to notate what qualities they have would be helpful.
	ST5	A revision of the mutation system... limit the usage of small chips that are difficult to gather, move, and apply.
	ST6	Creating some kind of piece dispenser that all the pieces could be placed in easily for more efficient game play
Suggested Simplifications (SS)	SS1	It might be a little easier to understand with less moving parts... scale down on the amount of pieces [at the beginning]
	SS2	I think this game would be much easier to play if online rather than the physical version.
	SS3	I really like this game and way of learning material but I wish it was a bit shorter and less complex given the time we have to play.
Suggestions for Added Complexity (SAC)	SAC1	I think that the dwellers were not very useful, since they are only able to remove 1 piece of fleshy algae per turn and every turn 5 algae was added... the lack of special traits and characteristics for the dwellers really hurt the game. While the choosing of builders required strategy, it seemed that for the dwellers it didn't matter which one was chosen.
	SAC2	I would love to see the number of mutations for the organisms be randomized a bit instead of only two per round.
	SAC3	For an educational game, I think that the game serves its purpose in terms of teaching about mutations but I was wondering how the reef game would tie into speciation or adaptive radiation. I believe that this game shouldn't have those criteria since it would over complicate things.
	SAC4	I saw this as a game. I didn't really see any learning opportunities. ... The concepts that we covered seemed more suitable for a middle school or maybe a high school science class... I am very impressed by the layout and concepts covered in it... perhaps it is not for an upper level undergraduate class.
Suggestions for Rules and Gameplay (SRG)	SRG1	I would have understood the instructions and rules a little better if there was a video of an example play through that I could watch and listen to while going through the instructions/rules.
	SRG2	...it would be cool if for some of the short-term disasters or maybe even a long-term one, there was a die roll to see how much it would impact your reef (potentially lessening or worsening the effects of a disaster)
	SRG3	A few of the rules are somewhat unclear - examples of gameplay would be helpful.
	SRG4	Balance [the] devastating and inconvenient disasters. Losing a major portion of the coral every time isn't very fun.

Limitations

Although substantial efforts were made to assess the game with a broad community of undergraduates, student (and instructor) participation was lower than expected. Games were sent to volunteers at 20 universities, yet only 15 educators employed them and of those, not all classes returned complete datasets. Examples of issues include, a) students submitting incomplete assignments, b) instructors asking a subset of questions, and c) Learning Management Software issues (corrupted data). Of the 351 individuals data were collected from, only 185 returned complete datasets (i.e., complete pre and post assessments as well as demographic information). One teacher commented "we had maybe a third of [students] fill out any [part] of the questionnaire, even after offering bonus[es]. I've never had a semester like this, COVID exhaustion is going strong!". It is not surprising that after modifications for online learning, pandemic disruptions, and an overall sense of exhaustion both instructors and students were not always enthusiastic about additional tasks.

One of the most difficult issues to constrain is that there was minimal control over how the game was introduced and the general classroom culture. While instructors were given instructions about how to present the game and the introduction video, there were clearly several instances of instructor error. Furthermore, since the courses and experience levels differed amongst universities and semesters, students likely had different degrees of introduction to certain concepts (leading to smaller or larger learning gains). Classroom culture is especially important for comparison of learning gains by demographic groups because the numbers of participants were so small; in other words, a supportive or unsupportive classroom could sway the results for a particular demographic group.

Implications

As with other geoscience board games, students enthusiastically engaged with "Reef Survivor" as an educational game. They appreciated the variation in course content and enjoyed that the game modeled a real system, even if this made them worry about conservation issues (e.g., PSC1, PLG10 in [Table 3](#)). Board games designed to synthesize complex geological and ecological systems are excellent learning tools allowing students to integrate new knowledge while having fun and working with peers. This is an important educational take-away, beyond simply the students' learning gains; games encouraged students to talk and work together toward a common goal. We had several accounts of students forming study groups with their teams or planning long-term game strategies (e.g., revenge for their fallen organisms) if there were multiple games played in the class. Fostering collaborative scenarios and integrated knowledge of the connections amongst complex systems is especially important in fields such as ecology, oceanography, evolutionary biology, and geology, and educational games are an excellent way of achieving these goals.

Acknowledgments

We sincerely thank our colleagues Luke Pebler, Etienne Vouga, Richard Murphey, Brandon Kline, Jason Visser, Enrique Reyes, Sabrina Ewald, and the Martindale Lab group for foundational discussions about board game design, implementation, and test plays. Kathy Ellins, Anna Weiss, and Estefania Salgado Jauregui are also acknowledged for their discussions about geoscience education and assessment of learning gains associated with games. We thank our anonymous reviewers and editors for the helpful and constructive feedback, which improved this paper. We sincerely thank the faculty, instructors, and teaching assistants who took the time to incorporate this game in their classrooms; the dataset presented herein would not have been possible without their generosity and passion. Lastly, we thank all the students who test played the game so enthusiastically.

Funding

This work is supported by the National Science Foundation Division of Earth Sciences (NSF EAR) under Grant #1848393 (RCM); and the University of Texas at Austin Associate Professor Experimental (APX) Grant (RCM and NC).

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