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"Taphonomy: Dead and fossilized": A new board game designed to teach college undergraduate students about the process of fossilization

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ABSTRACT

Incorporating games in teaching can help students retain material and become innovative problem solvers through engagement and enjoyment. Here we describe a new board game, "Taphonomy: Dead and Fossilized," and its use as an active learning tool (material available at doi: 10.18738/T8/NQV2CU). The educational objective is to teach the player about taphonomy and fossilization, while the gameplay objective is to preserve and recover the best fossil collection. Through competitive gameplay, students learn how chemical, physical, and environmental factors, as well as physiology and discovery biases can influence an organism's preservation and collection potential. The game is modeled after an Early Jurassic fossil deposit for scientific accuracy and relevance. The game was incorporated in undergraduate classroom activities in 20 colleges and universities across the United States. Survey results show that students and teachers were overwhelmingly positive about the game, stating that it was fun and helped them learn or strengthen their knowledge of fossilization. When analyzed statistically, we find that students' self-reported learning outcomes and opinions vary most significantly with college year, major, ethnicity, and race. White students and geoscience or STEM majors reported the highest levels of learning and enjoyment, with minorities and non-STEM majors responding less favorably. We suggest this game is most advantageous for use in upper-level paleontology classrooms, although it is still beneficial at lower levels. It is critical to use this game as part of a larger lesson plan and tailor it to fit the needs of an individual classroom. Modifications for time and class size, as well as follow-up discussion questions, are included.

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Introduction

Purpose and learning goals

The process of fossilization is a cornerstone in the geological history of life. Taphonomy is "the study of the transition (in all its details) of animal remains [now broadened to the remains of all organisms] from the biosphere into the lithosphere" (Efremov, 1940). In other words, taphonomic processes include all modifications to an organism from its death through fossilization. These processes fundamentally alter the record of past life, resulting in biases and gaps in our knowledge of ancient organism physiology, ecology, and community structure (Briggs, 2003, 2014; Muscente et al., 2017). A particularly clear example of these biases is the record of soft tissues, such as feathers, integument, organs, and non-biomineralized organisms (i.e., those without a shell or skeleton). Delicate or non-biomineralized organisms account for a significant proportion of marine animal biodiversity (Conway Morris, 1986; Schopf, 1978; Sperling, 2013), yet are rarely preserved outside of Lagerstätten – deposits with extraordinarily detailed preservation of soft tissues and other features not typically conserved (Seilacher, 1970; Seilacher et al., 1985). The fossil record is not a complete archive of past life, but taphonomic data informs paleontologists about the information they have and the information they are missing, which is critical to geoscientific interpretations.

Taphonomic processes have received much attention by paleontologists (e.g., Allison & Briggs, 1993; Briggs, 2003, 2014; Muscente, Martindale, Schiffbauer, Creighton, & Bogan, 2019; Muscente et al., 2017; Seilacher, 1990); however, based on our experience and anecdotes from colleagues, taphonomy can be a difficult concept for new geoscientists. The timescales and biogeochemical processes involved in fossilization are often challenging for students (Ault, 1984; Kortz & Murray, 2009), particularly if they are not familiar with geological time, organism physiology, or ecology. Fossilization is complex and involves factors such

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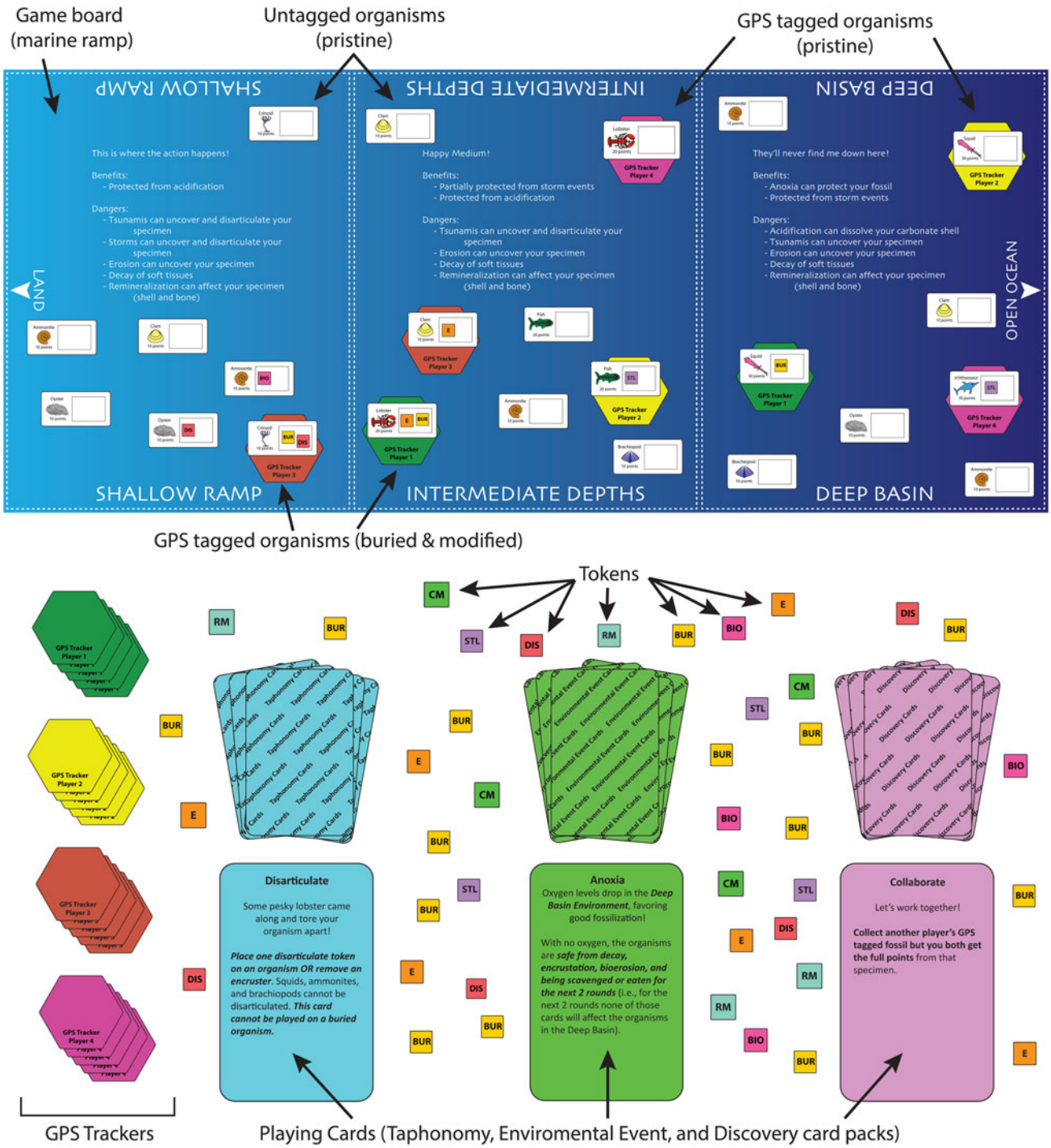

Figure 1. Schematic of the "Taphonomy: Dead and Fossilized" board game and associated material, i.e., cards, GPS trackers, tokens, game board, game pieces, and organisms.

as organism biology, local (micro)environment, global ocean chemistry, and both (re)mineralization and diagenesis more broadly (Allison & Briggs, 1993; Briggs, 2003, 2014; Muscente et al., 2017; Seilacher, 1990; Seilacher et al., 1985). We have found that many students can find these factors to be abstract and the interplay between them overwhelming and difficult to synthesize. These issues may be compounded by a paucity of good classroom specimens; not every institution has access to an extensive fossil collection with multiple examples of different organisms preserved via different taphonomic pathways.

In order to improve student understanding of fossilization we designed a board game, "Taphonomy: Dead and Fossilized," herein referred to as "the game" (Figure 1). Our aim was to create a strategic game of medium complexity (e.g., Settlers of Catan) to teach players about taphonomic processes through competitive gameplay. The game is based on the Early Jurassic Ya Ha Tinda Lagerstätte from Alberta, Canada (Martindale, Them, Gill, Marroquín, & Knoll, 2017), which connects the player to real paleontological research. The board and environmental events are representative of possible conditions in a Jurassic marine setting, and the

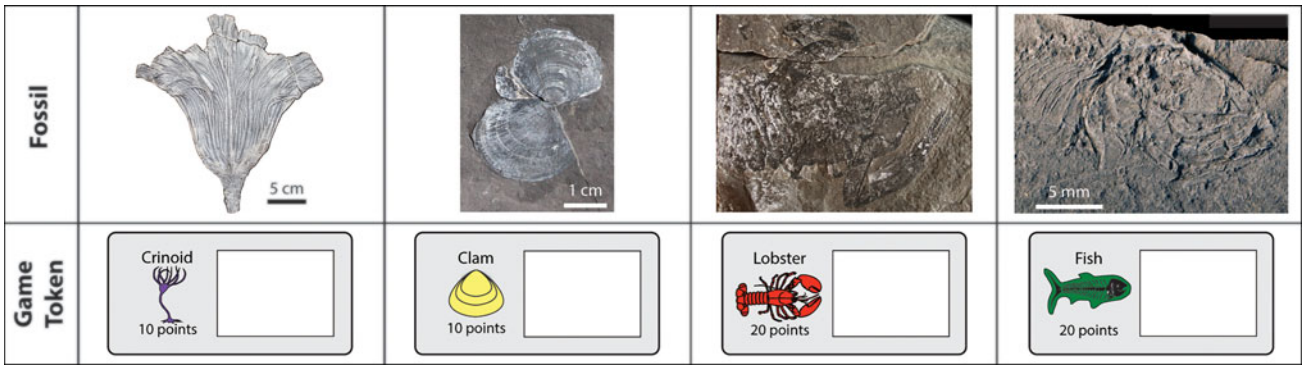

Figure 2. Photographs of Ya Ha Tinda Lagerstätte fossils with their associated game tokens.

pieces represent the Ya Ha Tinda fossils (Figure 2) (e.g., Marroquín, Martindale, & Fuchs, 2018; Martindale et al., 2017; Martindale & Aberhan, 2017; Maxwell & Martindale, 2017). Although there are some simplifications for gameplay, the game closely follows the stages of fossilization (e.g., organism death, alteration, extraction) that one might expect in a marine environment to maximize scientific accuracy (e.g., Muscente et al., 2019). The game leverages the advantages of active, hands-on learning to lead players through the process of fossilization as well as examples of stochastic factors and biases in collection. Ultimately, the player finishes the game with a more concrete understanding of fossilization processes because gameplay has guided them through each different phase of the process.

Upon successful completion of the board game without modification, the player will be able to:

- Identify physiological characteristics that make an organism more or less likely to become fossilized (Student Learning Outcome #1).
- Identify the climate, oceanographic, and geological events that occur in different marine environments and describe the effect they have on the preservation potential of fossils in that setting (Student Learning Outcome #2).
- Describe multiple taphonomic factors that would impact an organism as it fossilizes in a marine setting and determine if they would that enhance or diminish the preservation potential (Student Learning Outcome #3).
- Describe how chance and sampling biases affect fossil collections (Student Learning Outcome #4).

With the included follow up activities or a discussion, the player will also be able to synthesize how physiology, mode of death, depositional environment, environmental conditions or events (e.g., decay, storms, anoxia, acidification), burial, decay, exposure, diagenesis, and collection bias influences our understanding of ancient marine communities. Specifically, players will understand why the fossil record is not a perfect representation of ancient life (Student Learning Outcome #5).

Literature context

Students learn best when they are engaged as active participants (Perkins, 2005; Wirth, 2007), particularly diverse student populations (Griggs et al., 2009; Manduca, 2007). Innovative techniques implemented in geoscience classrooms include poetry, mnemonics, cartoons, and card games to teach mineralogy (Rule, 2003; Rule & Auge, 2005; Rule, Carnicelli, & Kane, 2004; Spandler, 2016), phone or computer "apps" (applications) that combine geological data and/or virtual field trips with kinesthetic learning (Arrowsmith, Counihan, & McGreevy, 2005; Bursztyn, Shelton, Walker, & Pederson, 2017; Bursztyn, Walker, Shelton, & Pederson, 2017; Gutierrez & Bursztyn, 2019; Stainfield, Fisher, Ford, & Solem, 2000), incorporating databases into class activities (e.g., Cohen, Lockwood, & Peters, 2018; Lockwood, Cohen, Uhen, & Ryker, 2018), or designing courses to be primarily active learning (e.g., Clapham, 2018; Olcott, 2018). No matter the innovation, increasing student engagement leads to improved comprehension of core concepts and material (Prince, 2004).

Games are effective teaching tools that enhance learning and engagement. Although historically games are rarely used as pedagogical tools in the Earth Sciences (see Reuss & Gardulski, 2001), many games are now in development (e.g., Cartier, 2018a, 2018b). Educational games or 'Serious Games' (coined by Abt, 1970) are designed to facilitate learning, make topics relevant and meaningful to students, and raise awareness of issues (Boyle, Connolly, & Hainey, 2011; Boyle et al., 2014; Foster, 2008; Mossoux et al., 2016; Nadolski et al., 2008). Advantages of serious games include their availability outside the classroom and immediacy of feedback (Ritzko & Robinson, 2006) as well as cooperative learning (Foster, 2008; Mayo, 2007). Games also enhance engagement, social interaction, and enjoyment (Foster, 2008; Kumar & Lightner, 2007; Nadolski et al., 2008; Nemerow, 1996; Ritzko & Robinson, 2006; Srogi & Baloche, 1997; Wilson et al., 2009). More broadly, using play to learn can help students retain the material, gain a deeper understanding of concepts, and become creative, innovative problem solvers (e.g., Bergen, 2009; Kolb & Kolb, 2010; Kumar & Lightner, 2007; Nemerow, 1996; Rieber, 1996; Srogi & Baloche, 1997; Wilson et al., 2009). Furthermore, including scientific content in educational games is a new or different mode of delivering information and engaging students, which encourages them to accommodate knowledge via multiple organizational structures.

Despite these advantages, familiarity with computer, video, and board games varies among demographic groups, which

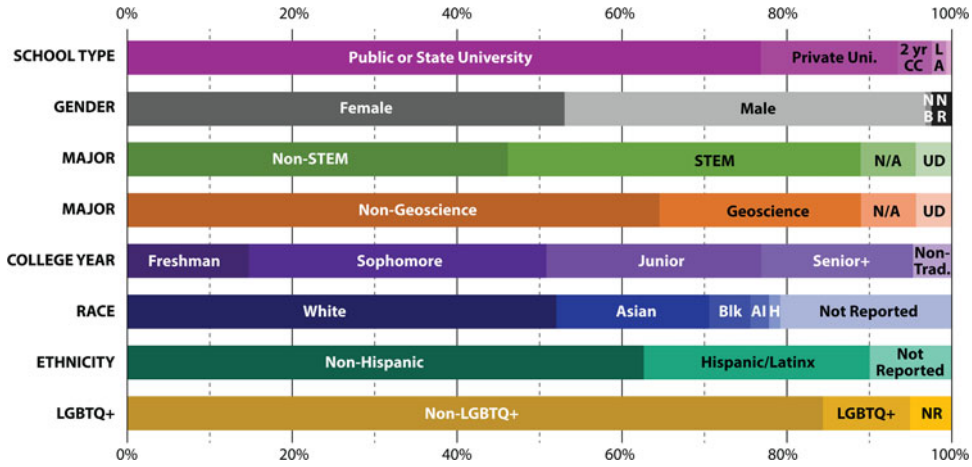

Figure 3. Summary of the test population demographics; full demographic breakdown of all 760 participants listed in the supplemental data. School Type: 76.7% Public or State Universities, 16.6% Private Universities, 4.1% two-year community colleges (2 yr CC), and 1.8% Liberal Arts colleges (LA). Gender: 53.0% female students, 43.9% male students, 0.7% non-binary students (NB), and 2.4% other/prefer not to say (NR). Major: 45.9% non-STEM majors, 42.9% STEM majors, 4.5% undeclared majors (UD), and 6.7% were not undergraduates (N/A); 24.5% were geoscience majors and 64.3% were non geoscience majors. College Year: 14.5% Freshmen (first year), 36.4% Sophomore (second year), 26.1% Junior (third year), and 18.4% Senior (fourth year or higher) students; 4.6% reported being a nontraditional student or not an undergraduate (non-Trad.). Race: 52.1% White, 18.5% Asian, 5.2% Black (Blk), 1.3% American Indian or Alaskan Native (AI), 2.1% Hawaiian or Pacific Islander (H), and 20.8% did not report their race. Ethnicity: 62.5% of students are not Hispanic, 27.5% of students are Hispanic or Latinx, and 10.0% did not report their ethnicity. LGBTQ+: 9.7% identify as LGBTQ+ (lesbian, gay, bisexual, transgender, queer and others), 85.7% did not, and 4.6% preferred not to say (NR).

may translate to different abilities to accommodate learning through gameplay. In US high schools, male students and those with a higher socioeconomic status were more likely to engage with computer and video games than female students or those from a lower socioeconomic group (Andrews, 2008). Furthermore, board game designers and illustrators are overwhelmingly white males (Pobuda, 2018) and in both video and board games, while males are substantially more likely to be represented in characters or on the box cover than white women or minorities (Pobuda, 2018; Williams, Martins, Consalvo, & Ivory, 2009). This lack of representation could lead to substantial differences in the utility of games among student populations based on the ease with which students can connect with game characters. That said, demographics are changing quickly; recent informal surveys about hobby video (Bureau of Labor Statistics, 2018; Entertainment Software Association, 2018) and board gamers (Nicole, 2016; Stonemaier Games, 2017) noted that anywhere from 8% to 33% of gamers are women, with a ratio of roughly 60/40 male/female video gamers in the last decade.

Although many studies have focused on video games and apps, in recent years, board games have regained mainstream popularity (Graham, 2016) with sales of hobby games exceeding $1.5 billion in the United States and Canada in 2017 (Griepp, 2018). Board games have advantages over video games in terms of cost, longevity, and lack of compatibility issues, making board games more accessible for low-income school districts.

Study population and setting

"Taphonomy: Dead and Fossilized" was used as an activity in undergraduate geoscience courses by 24 instructors at 20 institutions over the 2018–2019 academic year (see Figure 3 and supplemental data for institutional type). Class sizes ranged from 4 to 252 students, although most labs were between 12 and 24 students. Students played the game in class or lab and then responded to an online survey within 48 hours (see supplemental data); the first set of questions was about their opinions of the game, the second set was to assess their knowledge of the content, and the final set of questions was about demographics. Professors and teaching assistants (TAs) were asked to fill out a separate survey on the use of the game in their classrooms (see supplemental data).

The 760 participants assessed included 403 female, 334 male, and 5 non-binary students as well as Freshmen (first year), Sophomore (second year), Junior (third year), and Senior (fourth year or higher) students (Figure 3). About half were non-STEM (science, technology, engineering, and mathematics) majors and a quarter were geoscience majors. The population included American Indian or Alaskan Native, Hawaiian or Pacific Islander, Black, and Asian students, although about half identified as White. A little over a quarter of the students identified as Hispanic or Latinx, and 10% identify as LGBTQ+ (lesbian, gay, bisexual, transgender, queer and others). See Figure 3 for a summary of survey population demographics; a full demographic breakdown is included in the supplemental data.

Materials and implementation

General game overview and objectives

"Taphonomy: Dead and Fossilized" is a physical board game (Figure 1); each player is a time traveler whose mission is to create the best fossil collection. All materials to play the game can be found at doi: 10.18738/T8/UWCVKH. Players travel back in time to the Early Jurassic, when their fossils were alive, with ten Global Positioning System (GPS) trackers that allow them to claim an organism. The players compete against each other and elements of chance to create

their collection. Through the game, players must protect their specimens from taphonomic factors that reduce their specimens' potential to be preserved in the fossil record. They can also damage or degrade other specimens on the board, making that fossil worth fewer points and their collection more valuable. At the end of the game, players time travel back to the present, collect their GPS tagged specimens as well as other specimens on the board and complete their fossil collection. The winner of the game is the player with the best fossil collection, scored as the largest collection of a diverse sampling of pristine fossil organisms; there are bonuses for different collection achievements (e.g., a specialist collection or the most pristine fossils). Organisms have unique biological traits, so taxa have different preservational potentials based on their physiology. Taxa are worth different points, which are assigned based on their rarity in reality; rarity is also reflected in their abundance as game pieces (supplemental data).

As an educational exercise, the goal of the game is to help players understand taphonomy (see student learning outcomes in the Introduction). Ideally this game helps the player comprehend the factors associated with an organism's taxonomy and physiology (Student Learning Outcome #1, or SLO#1), the environmental setting (SLO#2), the physical and chemical changes during exposure, burial, and decomposition (SLO#3), as well as the biases in discovery that influence whether or not an organism is collected by a scientist (SLO#4). Ultimately, the goal is for players to be able to synthesize multiple factors that affect a specimen during fossilization (SLO#5). Professors and TAs surveyed indicated that the game took one to two hours to play, so we recommend allowing two hours for the first use in class. The game also is highly modifiable, and we provide suggestions for how to lengthen or shorten gameplay should time be a barrier to implementation. In addition, several strategies for integrating available fossil collections with the game are discussed. This helps students connect the pathways and processes they experienced through gameplay with the resulting fossil specimens in a collection or outcrop.

Gameplay

All game materials tested in this study, including a 10-minute instructional video, can be downloaded from doi:10.18738/T8/UWCVKH. An updated and improved version is available at doi: 10.18738/T8/NQV2CU; we recommend using this version.

Game set up

Each player gets ten GPS trackers to distinguish their specimens. They all begin with the same "starting organisms" – a lobster, a crinoid, a vampire squid, a brachiopod, and an ammonite – so all students start with the same possible score. The rest of the organisms are placed on the board (see set-up instructions). The board represents a shallow marine ramp setting and different sections have unique dangers to emphasize that depositional environment affects the taphonomic processes specimens might experience (e.g., storms affect shallow not deep environments; SLO#2). The game is designed for four players or teams, but it can be modified by adding or removing GPS trackers and "starting organisms." The game could also be played in small teams as one "player"; we have found teams of 2 work well (i.e., 8 students per game) but more than that can be problematic as students become disengaged or distracted. Teachers can intentionally arrange cards in the deck if they want to ensure a specific game outcome or unique outcomes for different games.

First Era - Early Jurassic, setting up fossil specimens

Each player tags their five specimens with GPS trackers and assigns them to an environment (Shallow Ramp, Intermediate Depths, or Deep Basin). As they place each specimen, players roll a die to determine mode of death; the interplay of physiology and death creates a unique starting point for each player. If an organism is lost to the fossil record, the GPS tracker is also removed from play. In this Era, players learn that mode of death and physiology (as determined by taxonomy) affects specimen preservation potential (SLO#1).

Second Era - Early Jurassic: Protect fossils from taphonomic factors

Each player starts with a hand of five cards from a shuffled deck of "taphonomy" cards as well as two "burial" tokens (Figure 1). Players restock their hand of cards and receive two "burial" tokens at the beginning of each turn. The youngest player starts; play proceeds clockwise. Each player must play three actions each turn; actions include placing a "burial" token or playing a card and can be played on any organism on the board. Any player can sacrifice all three actions during their turn to get a new hand of cards. At the end of the round an "environmental event" card is drawn from a shuffled deck; these apply to every specimen on the board but will have specific instructions about what organisms or environments are affected. The Second Era consists of two "environmental event" cards (i.e., two rounds). After two environmental events, pause play; each player keeps their cards and tokens because they will be used again in the Fourth Era.

During the Second and Fourth Eras the teacher may prescribe a specific sequence of catastrophes. To do this, shuffle the "environmental event" deck so the order is, for example, Anoxia, Storm, Decay, Remineralization. If the class has multiple boards, we recommend ensuring that groups get unique geological histories, so students see how different "regions" are affected by distinct conditions. To do this, either remove cards or shuffle the deck so that unique events come up in different groups. In the Second Era, players learn about the many fossilization factors, such as environment of deposition, physiology, diagenesis, and burial history, which make a specimen more or less likely to be preserved (SLO#1, SLO#2, and SLO#3). Gameplay incorporates both elements of chance and skill during this Era.

Third Era - Early Jurassic: Adopt additional fossils

On the board there are numerous specimens that are "untagged" (i.e., have no GPS tracker, Figure 1). Using their remaining GPS trackers, players "adopt" untagged specimens; specimens are adopted "as-is" and remain in their current environment with all of their tokens. Play shifts one player to the left and each player adopts one animal per turn until the five remaining GPS trackers are used. The adoption Era allows players to learn from past mistakes and acquire more specimens if they were unlucky in the First Era, so they are more likely to continue to be engaged throughout the game.

Fourth Era - Early Jurassic: Protect your fossils from taphonomic factors!

This Era is played exactly as the Second Era, play shifts one player to the left.

Final Era - Present day: Collect fossils

In the Final Era, players time travel to the present to collect their specimens. Each player starts with a hand of 5 cards from a shuffled deck of "discovery" cards; players restock their hand of cards at the beginning of each turn. Play shifts one player to the left; if playing with 4 people, each player has been first and last once. Each player must play three actions each turn, but a player can sacrifice all three actions on their turn to get a new hand of cards. Any two cards can be played together to collect an untagged fossil, or a GPS tagged fossil that belongs to the player (two actions). The Final Era proceeds until all tagged organisms are collected and then a final round is played.

This Era teaches players that collection biases and chance can affect what fossils are recovered, even in the best cases of fossilization (SLO#4).

Point calculation

As fossils are collected, players tally the points from their specimens on their scoring sheet. The highest scoring collection wins; rare fossils are worth more points, whereas damaged fossils are worth fewer points. Players can also get bonuses for their collections; for example, the player with the highest diversity of organisms gets 6 bonus points, whereas a specialist with five or more specimens of one fossil taxa gets 10 bonus points.

Options for a shorter game

If time is an issue, there are several ways to shorten the game. Players will miss out on the learning outcomes for that Era, but we encourage teachers to modify gameplay to fit their specific educational goals. The easiest variation is to skip the death phase (First Era); organisms are simply placed on the board as if they died without modification, which results in less emphasis on SLO#1. Similarly, in the Final Era, players could tally their points based on their tagged organisms on the gameboard and skip the fossil discovery phase (SLO#4). In both cases, players will miss some aspects of the fossilization and collection process, but this could always be discussed later or simplified in the case of a more modest learning objective.

Another possibility for faster gameplay is to omit the organism adoption phase (Third Era) and simply start each player with ten organisms in the First Era (e.g., a lobster, a crinoid, a vampire squid, an ammonite, two oysters, two clams, and two brachiopods), or only use the five tagged "starting organisms." Play the First Era with these GPS tagged fossils, then play three or four rounds of the Second Era, followed by the Final Era. This modification does not allow players to revise their strategy, but it does include all Student Learning Outcomes. If the students play multiple games, they can apply their knowledge in a subsequent game.

Corresponding classroom activities

Follow-up exercise and discussions

In addition to the "print and play" version, we have provided a student worksheet with follow-up questions aimed at a Freshman "History of Life" or "Life Through Time" class (supplemental data). This worksheet is designed to help game players accommodate and solidify their new knowledge (SLO#5). In the assessment, students often identified a pattern (e.g., "it was unfair that all the fossils in the shallow water got broken up by storms") but did not understand the process behind their observation. The worksheet is a good follow-up homework, can be used as a lab assignment, or can simply be a way to initiate class discussion. For example, a good quantitative activity is to have the students compare community compositions of "live" versus fossil assemblages. Have players take a photo of the board once they have placed all their pieces and before they begin the Final Era; alternatively, they could note how many of each kind of organism is in each section of the ramp, but this will take more time. They can use these data to calculate the changes in community composition between different games or after different events (SLO#5). Regardless of learning objective or class level, we recommend that teachers have a follow-up activity, which encourages students to utilize their new paleontological knowledge from the game.

Follow-up discussions are an excellent way to encourage student recollection of what they learned through gameplay or introduce new or more advanced learning outcomes. Topics frequently discussed, in addition to those on the worksheet, include the biases of fossil "headhunting," why different game boards experienced such different histories, the difficulties of communicating complex scientific processes to the general public, and game accuracy (i.e., what is different in the real world). Fossil "headhunting" is an issue many expert players identify; players put the most effort into preserving the specimen worth the most points. While this is not accurate for natural fossilization processes, it does affect collection biases as humans tend to target "prize specimens" (SLO#4). This issue can be discussed with real collections, such as La Brea Tar Pits, which were initially composed of large, spectacular fossil specimens (e.g.,

mammoths and sabre-tooth cats) (Miller, 1971; Shaw, 1982). Now, with better techniques, a more realistic assessment of the paleocommunity (i.e., flora, invertebrate fauna, and microfossils) is desirable and prioritized during collections.

Science communication is never perfect; often one must sacrifice detail or accuracy to convey a message. Like any serious game, our game is an imperfect representation of the real world. We suggest taking the opportunity to discuss the ways in which the fossil record is more complex than the game, especially with advanced students. Example discussion questions include: with what frequency do different environmental events or taphonomic factors (e.g., storms versus tsunamis versus acidification events) occur in the natural world and should there be more of certain cards than others to reflect this? What other negative consequences might there be for a deep depositional setting? Are there any disadvantages to an organism being encrusted? What tissues decay? How common is diagenetic alteration of fossils or soft tissue preservation in the fossil record? How might different settings (e.g., tropical versus temperate, active versus passive margin, ramp versus platform) or geological Eras affect preservation potential? Taking it one step further, one could use the game as an example of the issues that arise with science communication. For example, how do we convey a complex scientific idea in a simple, straightforward way?

Another useful exercise for an upper level undergraduate or graduate class would be to have students research the preservation potential of the taxa in the game and develop their own rules. For example, when should a specimen be removed from the record? Perhaps, dominantly soft-tissue taxa (e.g., squid or lobsters) should disappear after one soft tissue loss, whereas oysters could survive two episodes of soft tissue loss and two episodes of disarticulation. This exercise would encourage student inquiry, deepen their understanding of organism physiology (SLO#1), and create a more challenging variation of the game.

Using fossil collections

The most straightforward way to incorporate fossil specimens or collections is to have them out during gameplay. Teachers can show students real examples of game pieces, such as a fish with no soft tissue or disarticulated crinoid ossicles. Alternatively, teachers could highlight the range of examples of a particular taxon and preservational pathway to emphasize SLO#1 and SLO#3; for instance, examples of remineralized and encrusted bivalve or brachiopod specimens. In more advanced classes, one could assign specific examples and have the students find those specimens in the collection or, if local outcrops are available, search for their "game collection" in a real fossil deposit.

Evaluation

An online survey (Google Forms) was constructed by the authors to assess students' self-reported opinions and attitudes about the game (see supplemental data for survey questions and results). Students were instructed to respond to the survey within 48 hours of playing the game (see supplemental data for survey questions). The first 15 questions were about the student's opinion of the game and were scored on a Likert (1932) scale ("Strongly Agree" "Agree," "Neutral, "Disagree" and "Strongly Disagree"). An additional 12 questions were asked to assess whether students learned the concepts; answers were also structured on a Likert scale ("Yes," "Probably," "Not Likely" and "No," with "I don't know" being equivalent to Neutral). Students also had the option of including a text response about what they liked or did not like about the game as well as suggestions for improvements. The last questions of the survey collected demographic information, such as gender, institution type, previous paleontology experience, as well as information about how the game was played (e.g., number of players, professionally printed or "print and play" version). Teachers were also given a survey that had the same structure and similar questions with prompts appropriately modified (e.g., the students learned something from playing the game); see supplemental data for survey questions and results. In the text response, teachers were asked what they liked or did not like as well as suggestions they had for both gameplay and implementation in classes. Teachers were asked to take this survey after they used the game in their class, but no specific timeline was required. These results were then used to assess student and teacher enjoyment of the game as an educational activity as well as to assess whether the student learning outcomes identified in the Introduction were met.

Overall, we believe students reported their answers honestly since the survey was anonymous and there were no benefits to lying. Although the game was mostly played in the same manner, many classes were at different levels, and thus the preparation and learning objectives were not consistent. For example, the game was used in an introductory geoscience class for non-majors at one institution and an upper level paleontology class at another. The validity of self-reported survey responses is often questioned (Blank, 2002), but these methods have been substantiated; studies show that self-reported survey results are highly consistent with other data collection techniques (Mullens, 1998; Mullens & Gayler, 1999; Porter, Kirst, Osthoff, Smithson, & Schneider, 1993).

Survey data were anonymized and analyzed by the authors. Frequency tables of survey answers (supplemental data) were visualized as diverging bar charts in R (R Core Team, 2014) using the ggplot2 (Wickham, 2016), reshape2 (Wickham, 2007), RcolorBrewer (Neuwirth, 2014), dplyr (Wickham & Francois, 2015), ggthemes (Arnold, 2015), and stringr (Wickham, 2012) packages. Chi-squared tests of independence were performed using the chisq.test() function and were used to assess whether there are significant associations between opinions about the game and demographic groups (Lovelace & Brickman, 2013). If $p \leq 0.05$, standardized residuals were calculated to show which opinions were most significantly associated with particular groups. Multinomial models were constructed using the foreign (R Core Team, 2014) and nnet (Venables & Ripley, 2002) packages. These

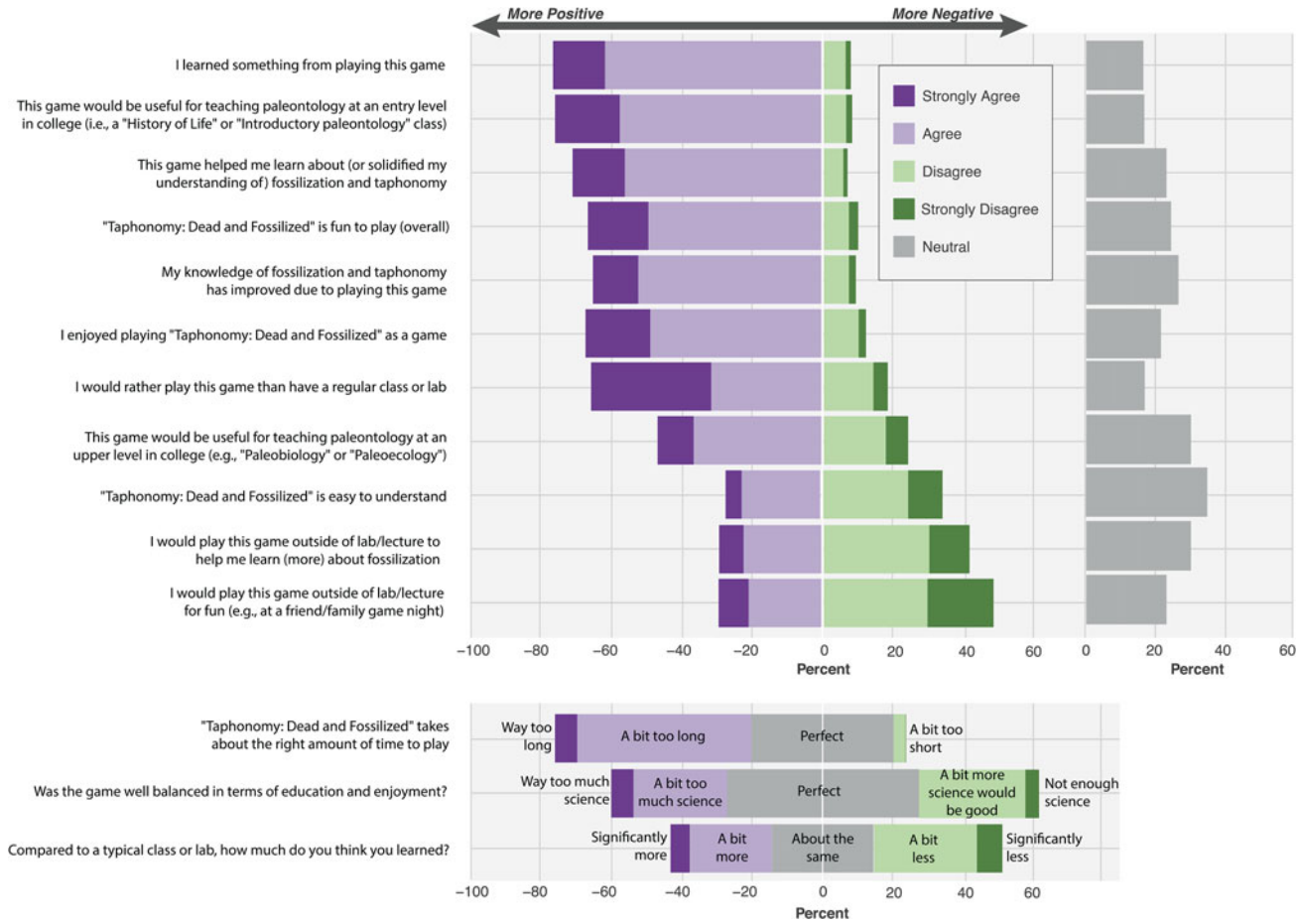

Figure 4. Diverging bar charts of student survey data with a focus on focuses on the players' opinions of "Taphonomy: Dead and Fossilized" as an educational board game.

multivariate models were used to look for correlations between demographic variables and game opinions. A z-score was calculated by dividing the coefficients from the multinomial model by their standard errors. A p-value for the multinomial model was then calculated using the pnorm() function. Long-form results of the statistical analyses can be found in supplemental data.

Results

Summarized results of student opinions about the game and perceived educational gains are presented in Figure 4, the student knowledge assessment summary is depicted in Figure 5, and teacher opinions about the game are illustrated in Figure 6 (details can be found in supplemental data). A summary of selected student comments can be found in Table 1, and selected teacher comments are in Table 2. Complete, anonymized survey data can be found in supplemental data. Several questions were broken down by student demographics to determine whether trends were apparent in particular populations; if no pattern is mentioned, there was either no difference in the data subsets, or there was not enough data to analyze (Tables 3–9; supplemental data). 66% of students agree or strongly agree that the game is fun to play overall, whereas only 10% disagree or strongly disagree. It should be noted that, for the majority of responses, classes that played the professional version did not have statistically different responses to those using the "print and play" version.

Both teachers' and students' attitudes about the game were largely positive; 96% of teachers and 66% of students agreed it was fun to play, although attitudes correlated with degree. STEM and Geoscience majors were more likely to agree or strongly agree that the game was fun, while non-STEM majors were more likely to disagree or strongly disagree (Table 3). Freshmen, Juniors, and Seniors agreed that the game was fun, whereas Sophomores were correlated with "neutral" or "disagree" statements (Table 3). Students with little to no paleontology knowledge were more likely to find the game less fun than those with more expertise. As expected, students that played board games frequently or often were more likely to enjoy it than students whom rarely played games (Table 3). Hispanic or Latinx students and nonwhite students were less likely than white students to agree that the game was fun (Table 3). Many students commented on how engaging and interesting the game was (e.g., PSC1, PSC8, PSC9 in Table 1). Both students and teachers said the game was a "nice break" from regular labs or classes; students also seemed to appreciate the different pedagogical tactic (e.g., PSC3, PSC6, in Table 1; TA3, TA7 in Table 2).

Overall, the majority of students reported that they learned something from playing the game (76% of those surveyed) and thought the game helped them learn (71%) or

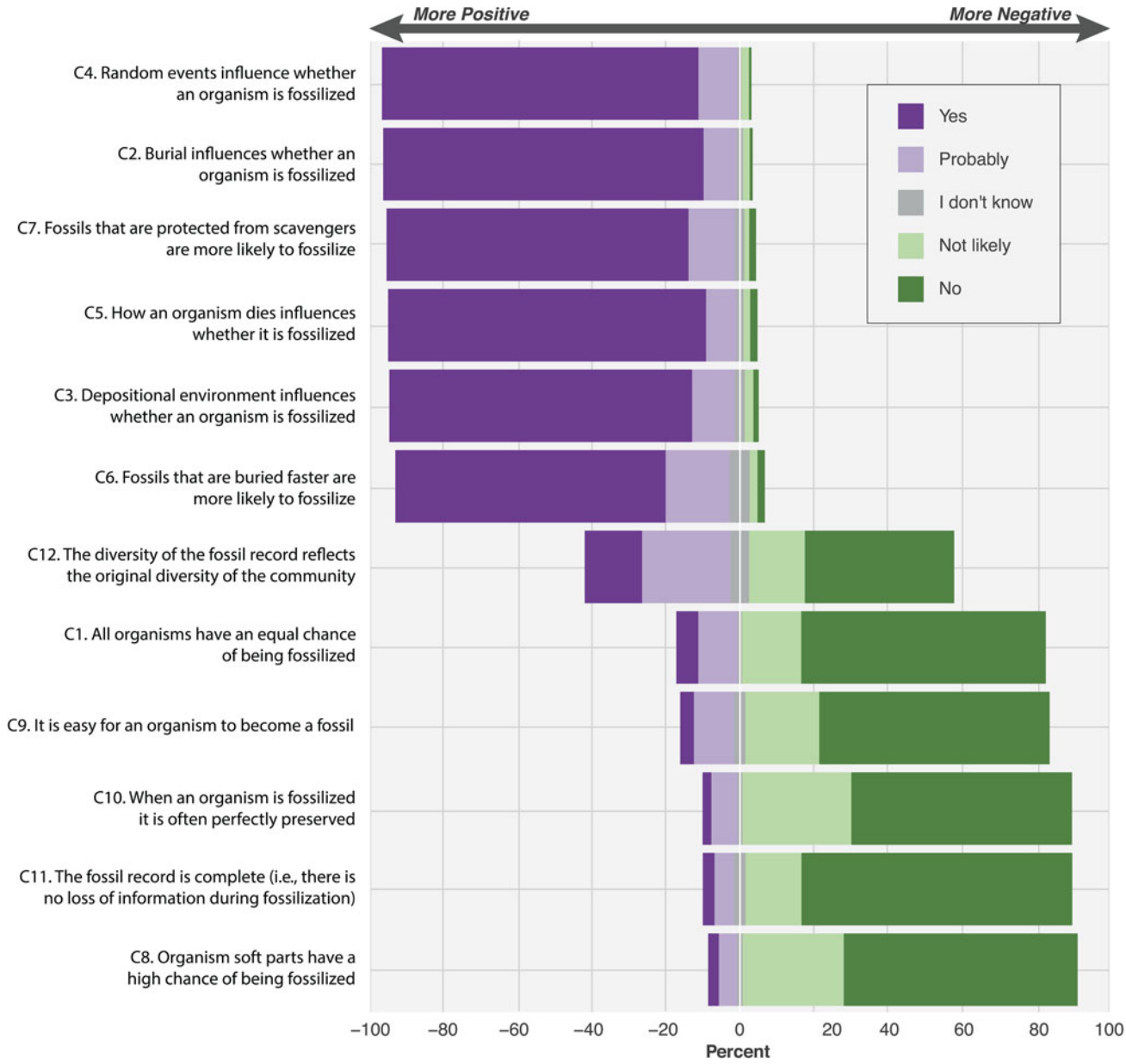

Figure 5. Diverging bar charts of student survey data with a focus on the knowledge assessments of game players following game play. Question numbers (i.e., C1-C12) correspond to the survey results in supplementary data.

improve (65%) their knowledge of taphonomy and fossilization; these assessments were overwhelmingly corroborated by teacher surveys (>90% of teachers agree; Figure 6). Most students (>80%) answered the knowledge assessment questions correctly (Figure 5), with the exception of one statement. Answers were evenly split (agree/disagree) for the statement "the diversity of the fossil record reflects the original diversity of the community," which may be a function of the disasters encountered by different groups. For example, some boards were devastated by environmental events, while others experienced minimal damage resulting in very different abundances of fossils.

Many students commented on how useful it was to see multiple taphonomic processes play out together and were surprised by how hard it was to preserve a fossil (e.g., EG2-4, EG7 in Table 1). Students also reported that they forgot they were learning because they were having fun playing the game (e.g., EG8, PSC7 in Table 1). Female students as well as Hispanic or Latinx students were less likely to agree that the game improved their knowledge of taphonomy and fossilization, while male students and non-Hispanic/Latinx were more likely to agree (Table 4). STEM and Geoscience majors were more likely to agree that their taphonomy knowledge improved by playing the game, whereas the opposite is true of non-STEM majors and Juniors (Table 4). Freshman, as well as Seniors, agreed or strongly agreed that the game improved their knowledge of taphonomy and fossilization, but curiously, Sophomore responses tended to be more neutral or negative (Table 4).

Teachers reported that students learned significantly more (17%), a bit more (22%), or about the same (52%) as a regular lab or class (Figure 6). One third of students thought they learned more playing the game than in a regular class or lab (across all levels of expertise; Table 5; EG1 in

Figure 6. Diverging bar charts of teacher survey data, including both professors and teaching assistants. Specifically, the teachers' opinions of "Taphonomy: Dead and Fossilized" as a board game and educational tool.

Table 1), with slightly fewer saying they learned about the same amount. The multinomial models suggest there is a positive interaction of race and major, with white STEM majors reportedly learning more than a typical class or lab; the models also show that Liberal Arts students reported learning less (supplemental data).

76% of students and 87% of teachers thought the game was useful for introductory classes (Figures 4 and 6). STEM and Geoscience majors typically responded more favorably than non-STEM majors; Freshmen, Juniors, and Seniors as well as occasional or frequent game players were more likely to agree that the game was useful for introductory-level paleontology classes than sophomores or non-game players (Table 6). Hispanic, Latinx, and nonwhite students were less likely to agree that the game should be played in introductory classes, whereas white and non-Hispanic/Latinx were more likely to agree (Table 6). Students felt the game was less appropriate for upper-level courses, although 47% agree or strongly agree that the game would be useful. In contrast, teachers deemed it more appropriate with 91% agreeing or strongly agreeing that that the game would be useful for upper-level courses (Figures 4 and 6). The only group with a clear distinction in the demographic analysis was Geoscience majors, who tended to respond more favorably than non-Geoscience majors (Table 7). Those with a professionally printed version of the game, as opposed to the print and play version, strongly agreed that the game would be useful for teaching paleo at an upper level at a college or university (Table 7).

Approximately 56% of students and 78% of teachers surveyed thought the game was well balanced in terms of education and enjoyment (Figures 4 and 6). Some students and teachers (27% and 22%, respectively) felt that the game could use a bit more science, whereas 18% of students felt that it had too much science (Figures 4 and 6). Not surprisingly, STEM and Geoscience majors typically requested more science or were happy with the scientific integration, while non-STEM students were more likely to think there was too much science (Table 8). There was also a differentiation by school type, with private school students more often reporting that the game had too much science, whereas public school students and students at Liberal Arts Colleges tended to request more science be integrated in the game (Table 8, supplemental data). Freshmen and Sophomores were more likely to assert that there was too much science, while Juniors and Seniors typically wanted more science integration (Table 8). This pattern held for the students that had no

Table 1. Student comments about the game and educational gains, see supplementary data for a complete list of student comments.

Category	#	Comment
Educational Gains	EG1	"It was a fun way to learn about fossils. I learned a lot more playing this game than listening in class."
	EG2	"I liked that it showed how rare it is for an organism to become a fossil."
	EG3	"It put a lot of different concepts about fossilization on the same playing field so we could see how they overlap"
	EG4	"I enjoyed that it made our group work and learn together. That it was interactive and applied concepts about fossils and fossilization recently learn[ed]."
	EG5	"It made me more vocal in class and allowed me to talk to my peers"
	EG6	" It was particularly insightful into how devastating natural/environmental events could be on the fossil record, as many organisms were lost simply due to two or three events."
	EG7	"The game was able to teach me about taphonomy [in] a way that I would be able to put my knowledge to the test! Definitely was able to memorize and engage more in this field with this game!"
	EG8	"I loved that … you forgot about [the game] being educational because you were having fun playing."
Positive Student Comments about the game (or games in general)	PSC1	"The game was engaging and interesting, the game pace was good and kept my interest very well."
	PSC2	" … it taught me so much in a short period of time."
	PSC3	"It was a nice change of pace compared to the other labs we've done"
	PSC4	"I love the aspect of learning while playing the game, and would love to have a copy for my family."
	PSC5	"Everyone enjoyed it … It did not seem like we were actually learning but we were"
	PSC6	"I liked that the purpose of the game was to educate in a classroom … without typical lecturing."
	PSC7	"It didn't feel much like an educational game, just a fun board game."
	PSC8	"The strategy of each phase in the game is different I enjoyed developing and changing for each phase."
	PSC9	"I liked the different stages the most because it reduced the amount of repetition within the game and always kept things interesting."
	PSC10	[I liked] "The collaboration when played in teams and strategy"
	PSC11	[I liked] "The "friendly" competition that the game caused by making everybody want to sabotage each other rather than accumulate points."
	PSC12	"I enjoyed how everyone had a high energy level and the game brought out excitement and a spirit of competition."
	PSC13	"Was easy to understand - was simple enough to play competitively on the first go around but also complicated and detailed enough to be challenging and make you think"
	PSC14	[I liked] "The correlation of content itself with my lab and class"
	PSC15	"I liked the use of scientific principles as game mechanics."
	PSC16	"It was not purely educational. It was competitive and a legit board game."
	PSC17	"The backstory and how the game-play took place and progressed was very creative and the science behind it is very solid and would be very good for entry-level students … "
	PSC18	"As president of our local game design club, and hobby game designer, I loved this game! … keep it up!"
	PSC19	"I found the game to be quite enjoyable and liked all of the choices I was presented with as a player- a lot of them had risks and benefits that motivated me to play strategically to win."
Suggestions and Negative Student Comments	NSC1	"The directions can be quite convoluted and difficult to understand, especially for students like me who have ADHD or similar disorders."
	NSC2	"The rules were overly complicated and the lessons were not clear"
	NSC3	"The game could be shortened and could elaborate more on what each of the taphonomic processes (encrustation, etc.) entails in a real-world context."
	NSC4	[I disliked the] "Spelling errors and grammatical errors in the instruction manual."
	NSC5	"There needs to be more diversity in terms of cards."
	NSC6	"I prefer a game with more dynamics … it was too simple"
	NSC7	"[classmates said] "I'm so confused," "I don't want to play this," and "There are too many words"
	NSC8	"Definitely requires multiple playthroughs to fully grasp the games mechanics, but past that point the ability to strategize for endgame points allows for competition and definitely makes the game worthy of replay."
	NSC9	"I think at times it would've been helpful for the game to rely more on use of [icons] rather than chunks of text, such as in card descriptions."
	NSC10	"The final era could have more variation in the cards to collect fossils."
	NSC11	"I would fix the wording on the [discovery] cards, and maybe all the cards in general, to get rid of … confusion."
	NSC12	"Could you discover a fossil if it was buried? … How many buried chips can be on one fossil? … what happens if all the fossils are buried and no players have quarry cards?"
	NSC13	"There needed to be a card that summarizes what can and cannot happen to some of the organisms. And on the green environment cards it would be helpful to put steps on them"
	NSC14	"Make it a video game or an app"
	NSC15	"limit the number of actions a person can make during the collecting phase (era). By the time it was my turn to collect most of the pieces where taken."
	NSC16	"I think it would be cool if we could see some of the fossilization process, ie. artwork printed on the back … "
	NSC17	"A flow chart that makes it very clear what should be done each round … would settle any bickering about the rules and help better streamline the experience. "
	NSC18	"soft tissue loss and other forms of decay don't seem to function intuitively. losing 100% soft tissue should still allow the bones to fossilize … and shelled creatures should have some protection from certain kinds of loss."

Table 2. Teacher (professor and teaching assistant) comments about the game, see supplementary data for a complete list of teacher comments.

Category	#	Comment
What did you like most about including the game in your class?	TA1	"Students had to talk to each other, there were fewer glazed-over faces than even in a discussion section or lab, there was some fun laughter; and I could expand upon each of the topics introduced in the game … by doing brief (<∼5-minute) explanations of more of the science, including real examples and questions to the class about how it would work."
	TA2	"The students had fun and many of them got competitive, which made them think harder about strategies to get the best collection"
	TA3	"It was very different than other labs we have done, so they enjoyed the variety."
	TA4	"Emphasizes nicely all of the factors that prevent fossil preservation."
	TA5	"The students were excited and engaged in learning while having fun playing the game"
	TA6	"It kept all of the students engaged throughout the lab period"
	TA7	"Students had fun and showed up. They were excited … and no one was absent … Students have referred [the game] in class discussions, so it helped them internalize some concepts."
	TA8	"It was fairly self-contained (I didn't have to prepare any other materials for that week)"
	TA9	"This game fostered a lot of focused discussion about strategy, differences between organisms and environments, and environmental events."
	TA10	"It's a very fun way to introduce the topic of taphonomy rather than a more traditional lecture/lab and the students got a lot out of the experience."
	TA11	"I enjoyed interacting with the students on what was closer to a peer level … "
	TA12	"It encouraged the students to communicate which doesn't always happen in the regular labs"
What did you like least about including the game in your class?	TB1	"Students weren't fully reading the cards or engaging with the science/learning part as much as I had hoped … I think that the game could benefit from a more varied set of cards to play … I wanted them to reflect and think more while playing … "
	TB2	"The instructions are very complicated and many … students became confused and frustrated"
	TB3	"Different groups finish at different times, so having a whole group discussion at the end was more difficult than usual. Some groups misinterpreted the rules so took a lot longer until I noticed what they were doing wrong and could correct it."
	TB4	"Some of the rules of game play are unclear, and in a game with so much good science … beginning students got bogged down by confusion about the rules rather than the lessons."
	TB5	"It was truly a great experience overall! My one main critique would be if there is a way to get more science into the game play for higher level undergraduate classes."
	TB6	Some students got the game right away while others did not … Also there is so much reading involved with the game. I felt that a lot of students wouldn't read most of the rules and/or cheat sheet so they modified the game without asking or verifying."
	TB7	"Not all instructions were clearly written and some were very difficult to execute correctly which did result in some conflict during game play. "
	TB8	"It was a little chaotic trying to make sure everyone was playing correctly, but I think any issues were very minor and that most students didn't have any problems."
	TB9	"I felt it required a lot of prep on my part and for the students … the game instructions are fairly complicated, especially for students who are not familiar with strategy board games, so I made them take an online quiz [rule info and taphonomy concepts] before coming to class."
	TB10	"Clarity on the instructions.. Vague/confusing a bit … "
	TB11	"I thought the content of the game was great. Engaging and educational.
	TB12	"It's great that options were provided for shorter versions, but I would recommend creating a set of instructions for a longer version that shows more of the science behind the game."
Do you have any feedback?	TC1	"Provide background reading and explanation of how the game ties into … lab material … [to] ensure the classes are getting the intended key 'take aways' of the game creator."
	TC2	"Bioerosion and casts/molds came up rarely to never for most groups."
	TC3	"More scientific details on the taphonomic processes themselves; more options in Discovery; a follow-up worksheet or set of recommended questions for upper-level students (not just intro); more clarity on which taphonomic actions affect which critters (a cheat sheet with little images of the taphonomic tokens that can impact each kind of organism) … "
	TC4	"subsequent rounds … could be more intentionally structured … so that you could have an iteration about the game that meshes with a unit about "biostratinomic factors" (focus on transport, storms, tsunamis, etc.), another that was "diagenesis" or "biogenic factors" – this would allow the game to be played quickly on multiple occasions throughout a term, with different kinds of reflections for each. That would only be useful in an upper-level course."
	TC5	"Some of the students complained that the instructions were ambiguous, but a lot of them, it turned out, hadn't really read the instructions … "
	TC6	"Clarity in the procedure for the discovery phase. Quarry cards added a lot of uncertainty in what had to be done to collect a fossil and some students thought they had to dig out fossils … "
	TC7	"For the cheat sheet it would be beneficial to have a column with pictures of the tokens that can be applied to each organism. It would also be beneficial have pictures on the cards themselves to show which tokens should be applied. The students said that there was a lot of reading involved and that it would be better to have pictures when possible. "
	TC8	"Provide very clear instruction of the 'order of operations' that players should take in responding to environmental events."
	TC9	"Write complicated actions out in steps and improve the video by adding more instruction with the game pieces."
	TC10	"I think the game is great, but there are too many rules/scenarios that can occur and it is a bit complex … Can game play be streamlined a bit? I do wonder, if this game might be more appropriate for my upper level Paleo course?"
	TC11	"My students are writing 2-paragraph reflections … The [instructions] was a lot of non-science (game) details to absorb and retain for the first game, which made it frustrating, confusing, and

(*continued*)

Table 2. Continued.

Category	#	Comment
		slow for the students … [could you] make some more visual cheat sheets … [and/or] a process-style diagram of each round of the game; or, a little bathymetric profile depicting which (real) areas are impacted by Acidification vs. Storms, etc. … Or, students could … make their own!"
	TC12	"First, thank you for creating this game! It was a great exercise for my mid-level undergraduate class and was very effective as an introduction to taphomony. … Students asked me a lot more questions during the Fifth Era/Discovery so it seems like there might be some confusing wording in that section … The more wordy Environmental Event cards are somewhat confusing - consider bulleting the actions/criteria."

Table 3. Standardized residual results for Question B1: "Taphonomy: Dead and Fossilized is fun to play (overall)." Positive values indicate positive association, negative values indicate negative association; merged cells indicate combined groups of similar responses that were analyzed together (e.g., strongly agree + agree versus disagree + strongly disagree).

	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
STEM major	3.81	3.26	−5.12	−1.77	−3.05
Non-STEM major	−3.81	−3.26	5.12	1.77	3.05
Geo major	3.22	2.55	−4.07	−2.21	−1.48
Non-Geo major	−3.22	−2.55	4.07	2.21	1.48
Freshman	1.63		−1.79	−0.03	
Sophomore	−4.46		3.67	1.81	
Junior	1.31		−1.08	−0.54	
Senior+	2.52		−1.67	−1.59	
I know nothing about paleontology	−0.8	−1.83	1.82	0.11	2.57
I know very little about paleontology	−2.24	−0.29	1.8	1.09	−0.4
I know a few things about paleontology	1.13	1.14	−1.63	−0.61	−0.89
I know quite a bit about paleontology	2.96	0.36	−2.27	−1.02	−0.38
I play games a lot	1.58		−2.18	0.63	
I play games often	3.18		−2.21	−1.89	
I play games occasionally	−0.45		0.37	0.19	
I rarely play games	−4.38		3.78	1.54	
Hispanic or Latino	−1.58	−1.92	1.33	2.09	3.1
Non- Hispanic or Latino	1.58	1.92	−1.33	−2.09	−3.1
Nonwhite	−1.52	−1.88	3.29	−0.46	1.93
White	1.52	1.88	−3.29	0.46	−1.93

Table 4. Standardized residual results for Question B6: "My knowledge of fossilization and taphonomy has improved due to playing this game." Positive values indicate positive association, negative values indicate negative association.

	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
Female	−0.87	−2.83	1.59	3.03	1.81
Male	0.87	2.83	−1.59	−3.03	−1.81
STEM major	1.93	2.31	−3.27	−0.82	−1.28
Non-STEM major	−1.93	−2.31	3.27	0.82	1.28
Geo major	1.32	2.42	−3.49	0.02	−0.99
Non-Geo major	−1.32	−2.42	3.49	−0.02	0.99
Freshman	0.89	2.09	−3.32	0.17	0.53
Sophomore	−2.64	−2.8	4.79	−0.03	1.22
Junior	−0.6	1.43	−0.84	−0.22	−0.64
Senior+	3.11	−0.08	−1.94	0.13	−1.25
I know nothing about paleontology	−1.76	−0.51	1.35	0.6	0.72
I know very little about paleontology	−1.36	−0.18	0.68	1.96	−1.93
I know a few things about paleontology	1.01	0.2	−0.61	−1.46	1.49
I know quite a bit about paleontology	2.56	0.5	−1.61	−1.57	0.01
I play games a lot	3.13	−1.86	−0.55	−0.31	1.46
I play games often	−0.11	1.71	−1.65	−0.48	0.2
I play games occasionally	−1.14	0.26	0.87	−0.77	0.44
I rarely play games	−0.75	−0.98	1.28	1.77	−1.87
Hispanic or Latino	−0.44	−3.35	2.7	1.66	−1.84
Non- Hispanic or Latino	0.44	3.35	−2.7	−1.66	1.84

paleontology background (i.e., they thought there was too much science) versus those that "knew a few things" about paleontology and typically wanted more science; interestingly, experts were more likely to think the game was well balanced (Table 8).

Both students and teachers, by and large, preferred the game to a regular lab period (66% and 70%, respectively) and commented that they enjoyed the competitive aspects of the game as well as the opportunities to collaborate at times (e.g., EG4, PSC10 in Table 1), which helped them engage

Table 5. Standardized residual results for Question A3: "Compared to a typical class or lab, how much do you think you learned?." Positive values indicate positive association, negative values indicate negative association.

	Significantly more by playing the game	A bit more by playing the game	About the same	A bit less by playing the game	Significantly less by playing the game
Freshman	−0.46	1.45	1.12	−0.96	0.08
Sophomore	−1.54	−0.8	−0.39	2.25	−0.5
Junior	0.73	1.92	−0.18	−1.93	−0.18
Senior+	2.26	−2.5	0.3	0.28	1.05
Nonwhite	0.75	2.61	−2.01	−1.58	1.04
White	−0.75	−2.61	2.01	1.58	−1.04

Table 6. Standardized residual results for Question B11: "This game would be useful for teaching paleo at an entry level at a college or university." Positive values indicate positive association, negative values indicate negative association; merged cells indicate combined groups of similar responses that were analyzed together.

	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
STEM major	4.04	0.88	−3.5	−2.19	−2.02
Non-STEM major	−4.04	−0.88	3.5	2.19	2.02
Geo major	4.4		−3.39	−2.37	
Non-Geo major	−4.4		3.39	2.37	
Freshman	1.56	0.63	−2.5	−0.06	0.15
Sophomore	−2.53	−2.55	3.71	2.81	1.45
Junior	−0.5	1.8	−1.18	−0.28	−1.49
Senior+	−2.26	0.54	−0.97	−3.09	−0.23
I play games a lot	−0.05		0.7	−0.17	
I play games often	2.03		−2.14	−0.29	
I play games occasionally	1.03		−1.22	0.03	
I rarely play games	−3.34		3.57	0.43	
Hispanic or Latino	−1.54	−1.47	1.67	2.18	1.74
Non- Hispanic or Latino	1.54	1.47	−1.67	−2.18	−1.74
Nonwhite	−3.34		3.63	0.36	
White	3.34		−3.63	−0.36	

Table 7. Standardized residual results for Question B12: "This game would be useful for teaching paleo at an upper level at a college or university." Positive values indicate positive association, negative values indicate negative association.

	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
Geo major	3.25	1.14	−3.39	−1.55	−2.06
Non-Geo major	−3.25	−1.14	3.39	1.55	2.06
Paper game	−3.61	0.72	0.3	0.89	1.06
Professionally printed game	3.61	−0.72	−0.3	−0.89	−1.06

Table 8. Standardized residual results for Question A2: "Was the game well balanced in terms of education and enjoyment?." Positive values indicate positive association, negative values indicate negative association.

	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
STEM major	0.27	3.08	0.14	−3.27	−2.44
Non-STEM major	−0.27	−3.08	−0.14	3.27	2.44
Geo major	1.36	2.75	0.02	−4.69	−1.25
Non-Geo major	−1.36	−2.75	−0.02	4.69	1.25
Private university	0.24	−2.73	−0.43	2.68	1.02
Public university	−0.24	2.73	0.43	−2.68	−1.02
Freshman	0.08	0.44	1.12	−0.97	−0.46
Sophomore	−0.02	−3.26	1.37	3.35	−0.54
Junior	−0.73	2.34	−2.35	−0.74	0.19
Senior+	0.78	0.97	−0.03	−2.4	0.86
I know nothing about paleontology	−1.51	−2.48	3.08	2.77	2.37
I know very little about paleontology	−0.36	0.82	−2.06	0.66	−0.61
I know a few things about paleontology	0.74	1.49	0.07	−2.26	−1.58
I know quite a bit about paleontology	0.93	−1.69	0.36	0.05	1.59

with the material (Figures 4 and 6). Students were split on whether the game was easy to understand (27% agreed or strongly agreed it was easy, whereas 38% disagreed or strongly disagreed). In the written comments, students and teachers articulated that the game was complicated, and instructions were not intuitive, unclear, or had too much text (NSC1-18 in Table 1 and TB2-TB12 in Table 2). Nevertheless, a number of players highlighted that the complexity was expected for the first playthrough of an involved board game and several students even lauded the complexity, stating that it challenged them and kept the class from being boring (e.g., PSC9, PSC13, NSC6, NSC8 in Table 1). STEM and Geoscience majors typically found the game easier to understand than non-STEM majors. Seniors were

Table 9. Standardized residual results for Question B3: ""Taphonomy: Dead and Fossilized" is easy to understand." Positive values indicate positive association, negative values indicate negative association; merged cells indicate combined groups of similar responses that were analyzed together.

	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
STEM major	−0.08	2.94	1.05	−1.05	−3.95
Non-STEM major	0.08	−2.94	−1.05	1.05	3.95
Geo major	−0.63	2.55	0.69	−0.9	−3.13
Non-Geo major	0.63	−2.55	−0.69	0.9	3.13
Freshman	0.33		0.45	−0.74	
Sophomore	−3.71		0.72	2.67	
Junior	0.33		−1.28	0.95	
Senior+	3.89		0.14	−3.68	
Hispanic or Latino	−0.84	−0.6	−1.15	0.33	2.99
Non- Hispanic or Latino	0.84	0.6	1.15	−0.33	−2.99
Nonwhite	−2.26		−0.23	2.36	
White	2.26		0.23	−2.36	

more likely to find the game easier to learn than Juniors or Sophomores (Table 9). In addition, Hispanic or Latinx students and nonwhite students were more likely to disagree that the game was easy to understand, whereas white students were more likely to agree (Table 9). Only about 30% of students and 65% of teachers would play the game outside of lab, although 78% of teachers would encourage students to play outside of class (Figures 4 and 6). Students and teachers found the game a bit too long, but we requested that teachers not shorten the game for this assessment; hopefully, that can be modified in the future with our suggestions for shortening the activity.

Interpretations and discussion

Strengths and weaknesses of the educational innovation

Based on our survey data, we regard "Taphonomy: Dead and Fossilized" as a success. Our goal was to create a strategic paleontology board game of medium complexity that was a fun and educational alternative to a fossilization or taphonomy lab; we wanted the game to help students learn about taphonomy, and this objective was clearly met (Figures 4 and 5). Both students and teachers were enthusiastic about the game (Figures 4 and 6, Tables 1 and 2), finding it enjoyable and educational. Comments were often excited and optimistic, even if the respondent had gameplay critiques (Tables 1 and 2). Many students were impressed with the integration and balance of entertainment and scientific content, with several students appreciating that the game was tied to a fossil deposit (e.g., EG8, PSC7, PSC14, PSC15, PSC17 in Table 1). Students articulated that they found it useful to synthesize multiple concepts from their lectures into one fossilization scenario. There were also multiple comments that they forgot they were learning because they were simply having fun playing the game (Table 1).

Over three quarters of students reported that they learned or solidified their knowledge of taphonomy and fossilization by playing the game (Figure 4). This result is corroborated by the teacher surveys (Figure 6) and is in line with previous studies incorporating active learning or games in classes (e.g., Freeman et al., 2014; McConnell, Steer, & Owens, 2003; Nehm & Reilly, 2007). The student responses to the knowledge assessments questions indicate that the student learning outcomes were met, since the majority of knowledge assessments questions were answered correctly (all but C12 were answered with >80% correct; Figure 5). More specifically, responses to knowledge questions C1, C8, and C10 (Figure 5) demonstrate that students understood that physiological characteristics play a role in fossilization potential (SLO#1). Similarly, responses to C3 and C4 (as well as C1 and C7 to some degree; Figure 5) reveal that students recognize that diverse environments confer different preservation potentials for fossilization due to their unique climate, oceanography, and geological history (SLO#2). Several players were surprised by how hard it was to preserve a fossil or how quickly an environmental event could change the board (e.g., EG6 in Table 1). Nevertheless, most students subsequently reflected that this was an accurate representation of fossilization. Student responses to C2, C5, C7-C9 show that they have learned about a multitude of taphonomic factors (SLO#3), and their responses to C11 demonstrates recognition of sampling bias to a degree (note that there was no question explicitly addressing sampling bias, SLO#4). Student answers to C11 and C12 (Figure 5) and all knowledge questions more generally, suggest that after playing the game and conducting the follow up activities they were able to synthesize how multiple taphonomic factors and collection biases might influence a collection or the fossil record in general (SLO#5). It should be noted that for SLO#5, a follow up discussion or activity is critical for integrating concepts and driving home the lessons learned during the game. One nice example of this is the confusion with knowledge question C12 (i.e., the diversity of the fossil record reflects the original diversity of the community; Figure 5). Students likely formulated their response based on the disasters or taphonomic processes they encountered in the iteration of the game they played; therefore, teachers need to encourage data sharing across multiple game boards, playing several games, or including a follow-up activity, such as a Jigsaw (Aronson & Patnoe, 2011), to highlight the variation in preservation by locality.

Although the learning gains are overall positive, there are notable demographic trends. A consistent trend was that under-represented minority students were less likely to agree the game improved their knowledge, whereas STEM and Geoscience majors, which often lack under-represented

minority students, were more positive. We suggest that this disparity is due, at least in part, to the students' familiarity with board games. Andrews (2008) posited that male students and those with a higher socioeconomic status are more engaged with educational computer and video games; there is also clearly a predominance of white men in game development as well as characters in games or on box covers (Pobuda, 2018). Our gameplay results rarely identified a significant difference between male and female students (Tables 3–9), which may be a function of the increasing number of women who play board games (Nicole, 2016; Stonemaier Games, 2017). Nevertheless, there was still a significant divide between white students and racial or ethnic minority students. This may still be a function of the underrepresentation of these groups in the board game community (Nicole, 2016), but it could also be tied to socioeconomic status and experience with games growing up. Over 98% of hobby board gamers surveyed by the Daily Worker Placement said that they played board games as a child (Nicole, 2016), and since players experienced with board games found the taphonomy game to be more enjoyable and educational (Tables 3, 4, and 6), it stands to reason that some of our data may be explained by the whether or not students grew up with games. The prevalence of household gameplay and family game nights may correlate to socioeconomic status, both in terms of availability of family time (i.e., the number of jobs held, number of parents working or frequently in the home) as well as availability of funds to purchase games. Unfortunately, in the United States underrepresented minorities are more likely to live in poverty than white families; in 2017 the poverty rate for non-Hispanic white Americans (8.7%) was less than half the rate for Black or Hispanic Americans (21.2% and 18.3% respectively; Fontenot, Semega, & Kollar, 2018). Thus, we encourage teachers to consider the demographics of their student population before incorporating this game; if the student group enjoys board games in general, they are much more likely to engage with and learn from the taphonomy game.

Students enjoyed the variety of strategies one could adopt in gameplay, such as defensive, aggressive, collaborative, or vindictive (e.g., EG4, PSC10-12, PSC19 in Table 1). A few mentioned that the game encouraged them to work or learn together and become more involved and vocal in lab (EG4-7 in Table 1) and increasing student engagement and active participation at any level has been shown to be beneficial for learning and comprehension (Perkins, 2005; Prince, 2004; Wirth, 2007). If a teacher wanted to implement more collaborative learning, a class or group could "play against the game," which would result in more collaborative and less competitive interactions. Essentially, instead of playing against one another, players would be a team of researchers and their goal is simply to bring in the best collection as a group; this would force students to work together and help each other strategically. In general, incorporating games in science classes can enhance social interaction, engagement, and student enjoyment (Foster, 2008; Kumar & Lightner, 2007; Nadolski et al., 2008; Nemerow, 1996; Ritzko & Robinson, 2006; Srogi & Baloche, 1997; Wilson et al., 2009), which was clearly demonstrated in the case of the Taphonomy game (e.g., Figures 4 and 6, Tables 1 and 2). Nevertheless, some teachers and players mentioned that not everyone was engaged in gameplay or that the detailed instructions were difficult for students with learning disabilities (e.g., NSC1, NSC 7 in Table 1); in these scenarios, we hope that the icons in the updated cheat sheets and the instructional movie with closed captioning helps make the game more accessible. Despite our hope that this game, as a uniquely structured active learning activity, might speak to under-represented minority students or non-majors, it was the traditional geoscience students that reported liking it the most.

The survey results also highlight the possibility of the game, both the professionally printed and "print and play" versions, being a replacement for a traditional lab or lecture. Over a third of students and teachers felt that students learned more by playing the game than in a regular class or lab. Moreover, half the teachers and a third of students asserted that they learned as much as a regular lab (Figures 4 and 6). Although serious games are often praised for their availability outside of the classroom (Ritzko & Robinson, 2006), only a third of students would play the game outside of class. Two thirds of teachers, however, would use the game as an extracurricular activity, so it could still be useful, especially with a keen group of students. Both students and teachers commented that the game was a good change of pace from regular labs and classes (Tables 1 and 2); moreover, several teaching assistants mentioned that it boosted morale, making their class "the fun lab." Furthermore, students identified and appreciated the game's unique pedagogical tactic, which confirms studies that show a variety of teaching techniques are beneficial to student learning (Griggs et al., 2009; Manduca, 2007). A nice example of this is that, despite learning about taphonomic biases in lectures, several players were surprised by the difficulty of fossil preservation and the improbability of an environment conducive to fossilization (e.g., EG2, EG6 in Table 1). Upon reflection, however, most students subsequently determined that this was an accurate representation of the fossil record. Some students remarked that they were unclear of the educational "takeaways" (e.g., NSC2 in Table 1) and several teachers requested more background material (e.g., Vignettes) or follow-up material (e.g., TC1 and TC2 in Table 2). This highlights the importance of the follow-up exercises after gameplay; educators should ensure their class has understood the learning outcomes for their specific course. Over three quarters of students and teachers felt that the game would be appropriate for an introductory lab with half of students and almost all teachers being enthusiastic about playing the game in an upper-level geoscience class (Figures 5 and 6). Both board game and paleontology experts as well as STEM and Geoscience majors were more likely to enjoy the game and respond positively to survey questions (Tables 1–4 and 6–9), so we suggest that the game may be most effective in specialist classes.

We encourage modification of the game to suit a particular classroom; if a paleontology class is composed of enthusiastic, Junior/Senior geoscience majors, they will want a

more science-heavy game and so instructors should incorporate more complex concepts or challenge students to expand on the game. In contrast, if a class is dominantly Freshman/Sophomore non-majors, it may be better to simplify the game and focus on fewer scientific concepts.

Educational activity improvements

Both students and teachers said the game was long and complex (Tables 1 and 2), but we do provide instructions for abridging the game in "Gameplay" and suggest simplifying the game to match the desired educational objectives. This is especially important with a non-majors or a class that is not familiar with board games, where the complex mechanics of gameplay may be "cognitive overload." In these cases, students with less board game experience spend all their mental energy learning the rules of the game, not the science or strategy inherent in it (e.g., NSC7 in Table 1; TB2, TB4 in Table 2). One solution for this, would be to scaffold the game learning with a pre-lab quiz, activity, or discussion about the rules or mechanics of gameplay (e.g., TB9 in Table 2). Game designers are encouraged to focus on making their instructions clear and simple. In particular, focus on instructional diagrams, icons, and videos rather than text; our modified version of the game (doi: 10.18738/T8/NQV2CU) has clarified language issues and includes more visual aids. To combat game complexity, we agree with several of the surveyed teachers that having a "practice round" to learn the instructions would help students focus on the science and strategy in subsequent games. This would be especially useful if playing multiple iterations of the game with a class (e.g., focusing on different aspects of fossilization). It should be noted that although there were many negative comments about the complexity of the game (NSC1, NSC3, NSC7, NSC8 in Table 1), several players noted that the rule complexity was typical for an involved board game and some even lauded the complexity and challenge (e.g., EG6, PSC8, PSC 9, & PSC 13 in Table 1); one student even said the game was too simple (NSC6 in Table 1).

Another issue in our assessment was that students and instructors did not always read instructions, leading to confusion and a poor synthesis of scientific concepts and game dynamics. An example of this was students not understanding why "environmental [event] cards seemed to heavily favor deep water environments [unfairly]." We encourage game designers and teachers to focus on having clear instructions and enforcing the pre-game readings and/or viewings by having a "pre-lab quiz," practice game, or similar activity to help students learn the game rules. Survey respondents also requested more diversity of card and organism types as well as more variety in the flavor text (i.e., text that adds interest but does not affect game mechanics). The modified game iteration improves on this issue, as will future iterations, specifically by integrating text about undergraduate populations, museum volunteers, or local populations (e.g., "Your local fossil hunting group wants to help you collect fossils, so you take them to your field site").

We also emphasize that this exercise is not a replacement for a good instructor. The game works best when students are well prepared. Thus, we suggest including a preparatory lecture and/or reading to scaffold learning, as well as follow-up activities to synthesize the new information and identify critical learning outcomes. In particular, it is clear that students from different playgroups need to discuss how their gameplay resulted in a different fossil collection than their neighbor's board. One excellent suggestion for an upper-level paleontology class was to play the game multiple times with structural differences. For example, the first game could be an iteration that highlights biostratinomic factors (i.e., focus on the effect of transport, storms, tsunamis, etc.), whereas the second game could focus on diagenetic or biogenic factors (TC4 in Table 2). Students could play these different game iterations, potentially with a final synthesis game, and reflect on the significance of different taphonomic factors.

Following the student review of the game and educational activity, several improvements were made to the board game materials. This updated version is available from doi: 10.18738/T8/NQV2CU. Modifications to the game include, the correction of spelling and grammatical errors (NSC4 in Table 1), instruction clarifications of common gameplay misconceptions (e.g., NSC2, NSC11-13 in Table 1; TC8, TC9 in Table 2), a "pre-lab" exercise to help students learn the game rules, a simplified "cheat sheet" with more icons and less text (e.g., NSC9 in Table 1; TC3, TC7 in Table 2), more flavor text in the discovery cards (e.g., NSC5, NSC10 in Table 1; TB1, TC2, TC3 in Table 2), and other minor edits. With the simplification of the instructions and more interesting flavor text, the game will now, hopefully, be more accessible to those less experienced or interested in boardgames. We have also included some resources for connecting with local paleontologists or fossil collecting communities in the Teacher's Notes, which may help personalize the experience and help students feel connected to the local geology and scientists.

Limitations

The main limitation of serious games is the tradeoff between the scientific accuracy and playability; in order to make the game easy to understand and fun to play, one must sacrifice or simplify aspects of the science or have an overly complicated game. While this is a limitation, game design or utilization should be approached with the target audience in mind. For example, elevated difficulty but higher scientific accuracy is better for an upper-level paleontology college class. In our survey, Geoscience majors and students with paleontology expertise wanted the game to have more scientific content, often commenting that some game mechanics were not accurate. Simplification of certain aspects of the game is encouraged if the target demographic is lower-level college classes (e.g., non-majors) or non-experts; in our surveys, non-STEM majors and under-represented minority students were more likely to find the game more difficult to understand and too scientific. Moreover, these groups often articulated that they struggled

with understanding game complexities, so streamlined gameplay and fewer or more focused learning objectives would be better in these cases to avoid cognitive overload. We encourage designers and users to appreciate the limits of the game medium and simplify or challenge where appropriate for their audience and learning goals.

We should also highlight several biases in our game evaluation. Firstly, games were tested in classes where the instructors were eager to modify their content and use the game. Thus, we presume they presented the game in a positive manner (i.e., a fun, new innovation) so both they and their classes were more likely to react positively. The game may not have been as effective if it had been presented as a normal lab or by a group that was not enthusiastic. Another issue is that we sacrificed controlled testing conditions to gain statistically meaningful participant numbers; the game was administered by different teachers in unique courses and universities. Ideally, the same game administrator would have presented the game in every classroom. In some cases, written survey comments made it clear proper instructions had not been provided or that the protocol we requested teachers use (supplemental data) was not followed. For instance, students were told to quarry fossils out before collection, which is incorrect, and in some cases, students had to set up the game, which resulted in the game being played with unshuffled card decks. Additionally, not all of the students prepared for the lab as instructed, which likely led to difficulties in understanding and learning from gameplay. For example, one student wrote that we should "create a video on YouTube explaining all the rules"; the student was, in fact, supposed to watch the instructional video (https://youtu.be/FnJae8uMN9Y) before coming to lab.

Furthermore, the surveyed population (mostly) played the complete game in the same manner. Many of these classes were at different levels, for example some were introductory classes for non-majors whereas others were upper-level paleontology classes; therefore, the scientific preparation and learning goals were not consistent across test groups. While this did not provide the most precise assessment, our aim was to test the efficacy of this game across a broad survey of classes and populations, so our results have less precision but can be broadly applied. There is also a paucity of paleontologically relevant Geoscience Concept Inventory (GCI) questions; we only found one question. We did have colleagues review the survey questions; however, they were not formally validated. Ideally, formalized pre and post-tests would have been administered to assess learning gains or the class with the educational innovation would be compared with a control group. Given the paucity of paleontological GCI questions as well as the large scale of implementation and class types, control groups and pre/post-tests were not feasible in this analysis.

Implications

In summary, students and teachers were eager and enthusiastic to integrate "Taphonomy: Dead and Fossilized" in their classrooms. Our design goal was to make a strategic game that reflected the complex taphonomic pathways of fossilization. We also wanted to tie the game closely with a real deposit – the Ya Ha Tinda Lagerstätte (Martindale et al., 2017) – which the students appreciated, so we conclude the game and associated educational material have accomplished these objectives. The authors encourage other educators to "gamify" their material as there was an overwhelmingly positive reaction to this creative innovation.

It is clear that both students and educators are hungry for interactive classroom activities such as the Taphonomy game, if nothing else, for the variety they bring to a teaching lab (Tables 1 and 2). Furthermore, students reported learning about as much from the game as a regular lab, often with more enjoyment, engagement, and peer interaction. Students were surprised that it felt like a "legit[imate]" game, and appreciated the quality, creativity, visual esthetic, and attention to detail (Table 1). Several even requested personal copies of the game. Thus, we urge serious game designers to integrate artwork and creativity with scientific concepts. We also urge game designers to include rigorous and extensive playtesting of material, such as testing the games at geoscience or educational workshops or conferences. Even after dozens of trial runs, there were still some simple errors or clarification issues. With educational games it is critical to have clear and thorough instructions, "how to play" videos, or icon-rich "cheat sheets"; many students do not read the rules and objectives ahead of time and a simple, intuitive gameplay strategy will help them understand the material. Lastly, but most importantly, any educational game must be flexible because every educator has a unique course, student body, and educational needs. The best games are adaptable, and we hope educators will modify our game to meet their needs.

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