Shroomroot: An Action-Based Digital Game to Enhance Postsecondary Teaching and Learning about Mycorrhizae

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ABSTRACT

The majority of terrestrial plants associate with fungi in symbiotic resource-exchange relationships called mycorrhizae. Because of the importance of these mycorrhizal systems to ecosystem functioning, it is crucial that future resource managers and scientists have a solid understanding of mycorrhizal ecology. Limited interest of postsecondary students in plants and fungi compared with animals, combined with difficulties visualizing below-ground processes, present challenges for learning mycorrhizal concepts. To address this, we created the digital, plant-ecology-centric, action-based game Shroomroot for use in a second year, postsecondary Introduction to Soil Science course. We then assessed effects of Shroomroot on students' knowledge acquisition and engagement with the topic of mycorrhizal ecology using a pre- and post-test evaluation. Students' knowledge of mycorrhizal ecology increased significantly after playing Shroomroot, and tended to increase more for items related to Shroomroot gameplay than in rewards-based game content. Student engagement with mycorrhizal content tended to increase after gameplay. These results suggest positive potential for action-based, plant-ecology-oriented digital games in a postsecondary science curriculum. Furthermore, greater understanding of mycorrhizae has the potential to improve our multifaceted relationships with the ecosystems upon which we depend.

Key Words: *ecology; mycorrhizae; soil biology; symbionts; undergraduates; digital-game-based learning; action games.*

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○ Introduction

The functioning of forest ecosystems depends on the below-ground activity of plant roots and their environment, which includes fungi, microbes, nutrients, water, and many other factors. Mycorrhizae are symbiotic relationships between fungi and plant roots formed by an estimated 90 percent of plants in terrestrial ecosystems (Fortin et al., 2009), in which the fungus helps the plant acquire resources from the soil such as nitrogen (N), phosphorus (P), and water, and the plant provides the fungus products of photosynthesis that contain carbon (C).

The fungi in these symbioses can be connected to multiple plants at the same time, allowing resource exchange to occur indirectly between neighboring plants, in a system known as a mycorrhizal network. Mycorrhizae and mycorrhizal networks are important in ecosystems worldwide, affecting nutrient cycling, soil aggregation, forest stand dynamics, and many other ecosystem processes (reviewed in Simard et al., 2015; van der Heijden et al., 2015). Mycorrhizal ecology is complex, occurs below ground, and is close to impossible to observe in action. This makes it a challenging subject to learn, especially in introductory university forestry and soil science courses, in which the topic of basic mycorrhizal ecology is often covered (Collins, 2008).

Digital games offer one approach to teaching and learning about complex and difficult-to-see concepts such as mycorrhizal ecology. In postsecondary contexts, digital games have most frequently been linked to positive outcomes in student knowledge acquisition, but also to engagement, behavioral change, and problem-solving (Boyle et al., 2016). There are examples of positive outcomes from ecology-based games for both animal-focused systems (Sarab et al., 2009; Schaller et al., 2009) and plant-focused systems (Hwang et al., 2013; Su & Cheng, 2014). To our knowledge, however, there are no studied examples of below-ground-ecology-focused digital games in which the player assumes the role of a plant in the first- or third-person, controlling plant growth in a physically explicit way. In this study, we aimed to test how this kind of game affected student knowledge aquisition about and engagement with mycorrhizal ecology.

We created and evaluated Shroomroot, an action-based personal computer and mobile game focused on mycorrhizal content for postsecondary curriculum in an introductory soil science course. The first objective of this study was to

build Shroomroot, balancing design constraints based on scientific accuracy as well as principles of motivation and knowledge acquisition derived from personal gaming experience and pedagogical theory. The second objective was to assess the effects of Shroomroot on student knowledge acquisition and engagement with the topic of mycorrhizal ecology.

○ Creation of Shroomroot

General Narrative of Shroomroot

Shroomroot is an action-based game built for an introductory undergraduate science course. In Shroomroot, which is comprised of 12 levels (Table 1), players direct the growth of a Douglas fir root through a podzolic soil (i.e., a typical soil type of western North America where Douglas fir is a native species), collecting resources (e.g., H_2O, N, P) from the soil (Figure 1).

As the player progresses through levels, the plant root drains its resources and has to acquire new resources quickly to prevent starvation. Halfway through the game, the player can interact with fungi and form mycorrhizal associations and mycorrhizal networks,

thereby expanding the resource-gathering dynamic to include organic nutrients and a wider collection radius (mycorrhizae increase the surface area over which plants can gather resources). After completion of Level 12, the game presents a graphic of a small Douglas-fir tree in a forest along with statistics about the player's success in the game (e.g., how many mycorrhizal links they formed).

Alongside the root-growing gameplay, players unlock Rewards for various achievements within the game. There is a specific Rewards screen in the game, and clicking on an unlocked reward opens a window that contains a picture and a short description. Rewards are given for achievements such as the number and type of resources collected, length of root growth, and the number and types of mycorrhizal relationships. For example, after the player forms at least 5 mycorrhizal links with seedling roots, the "5 seedling links" reward is unlocked, with a picture and description of the source-sink pattern of resource transfer through mycorrhizal networks (Figure 2).

Design

Shroomroot was designed by authors J. Amerongen Maddison and C. Adderley, based on personal experience playing and building

Table 1. Shroomroot gameplay by level and associated concepts. In all levels the player is controlling the growth of the Douglas fir root to achieve the listed Gameplay Goals. Each level offers practice of "associated new concepts" as well as concepts from previous levels (e.g., players must consider the importance of seeking out the most limiting resource from Level 4 onward).

Level	Gameplay Goals	Associated New Concept(s)
1	Avoid obstacles (e.g. rocks, sticks); collect water (W).	Plants need W; roots grow toward water as needed.
2	Avoid obstacles; collect W and nitrogen (N).	Plants need N, have to balance time spent seeking N and W; N affects collection radius.
3	Avoid obstacles; collect W and phosphorus (P).	Plants need P, have to balance time spent seeking P and W; P affects energy (speed).
4	Avoid obstacles; collect W, P, and N.	Importance of seeking out most limiting resource; cannot access organic P or N.
5	Avoid obstacles; collect W, P, and N.	Continued importance of seeking out most limiting resource; cannot access organic P or N.
6	Avoid obstacles; collect W, P, or organic P (OP), and N or organic N (ON); can choose to be mycorrhizal.	Being mycorrhizal allows access of organic P and N.
7	Avoid obstacles; collect W, P or OP, and N or ON; can be mycorrhizal.	Being mycorrhizal makes access of W in between rocks easier.
8	Avoid obstacles; collect W, P or OP, and N or ON; can be mycorrhizal, if mycorrhizal can link to mature roots.	Being mycorrhizal when growing near a mature root allows formation of a mycorrhizal network and resource gain.
9	Avoid obstacles; collect W, P or OP, and N or ON; can be mycorrhizal, if mycorrhizal can link to seedling roots.	Being mycorrhizal when growing near a seedling root allows formation of a mycorrhizal network and resource gain OR LOSS if seedling has less of a given resource than player.
10	Avoid obstacles; collect W, P or OP, and N or ON; can be mycorrhizal, can link to seedling and/or mature roots.	Sometimes it is better for a plant to be mycorrhizal, other times it is not.
11	See Level 10 gameplay goal description.	Continued practice of all concepts.
12	See Level 10 gameplay goal description.	Continued practice of all concepts.
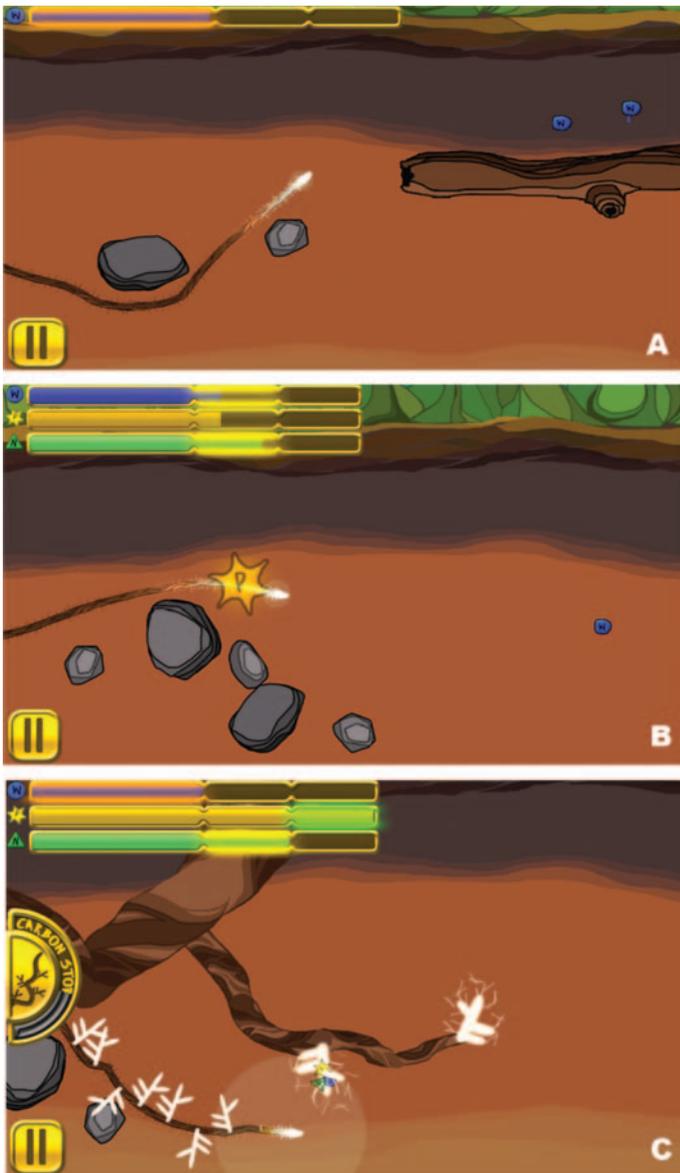
Figure 1. Screenshots of Shroomroot showing progression through levels. **(A)** Level 1: Player controls the root to collect water. **(B)** Level 4: Player must collect water, nitrogen, and phosphorus. **(C)** Level 8: Player can be mycorrhizal and link with other plants.

Figure 2. Shroomroot screenshot showing the 5 seedling links reward and explanation of the source-sink dynamic of resource transfer via mycorrhizal networks.

digital games, pedagogical theory, and consultation from relevant course instructors and graduate students in the field of mycorrhizal and soil ecology. Shroomroot was designed with these goals: (1) to meet mycorrhizal-oriented learning objectives for the target audience, second-year undergraduate students majoring in Forestry, Land and Food Systems or Science at the University of British Columbia; (2) to be engaging and functional as a digital game; and (3) to be scientifically accurate within the target content. For a full description of target concepts and a more detailed description of the design process, see Amerongen Maddison (2016).

Development

Shroomroot was developed using the 3D Unity game engine (a game-building software) by Christopher Adderley (programming, user interface, game design) and Alex Catamo (sound) of Area Denial Games (Vancouver, BC), and Julia Amerongen Maddison (graphic design, in-level gameplay, game design). Construction of the game took approximately 750 person-hours. Shroomroot is playable through Firefox or Safari web browsers with the free download of the Unity Web plug-in at http://shroomroot.com/game.html.

Shroomroot Intervention in the Introduction to Soil Science Course

The Introduction to Soil Science course is a second-year course offered over a 13-week academic term by the Faculty of Land and Food Systems at the University of British Columbia (UBC), Vancouver, Canada. This course provides students with a broad overview of basic soil principles, including physical, chemical, and biological properties of soils, soil formation, classification, use, and conservation. Basic concepts of mycorrhizal ecology, such as the exchange of nutrients for C compounds, are covered as part of one lecture on soil biology.

Midway through the winter term in the 2014–15 academic year, Shroomroot was played in Introduction to Soil Science during one 50-minute lecture session. In that term, the course had 232 students across two concurrent sections (119 in one section and 113 in the other). Shroomroot was used to deliver the initial lesson on mycorrhiza and was played in both sections on the same day. Students played Shroomroot two days after a lecture session providing an overview of soil biology that did not address mycorrhiza. Throughout this article, we will use "intervention" as a general term encapsulating the integration of Shroomroot into the course.

Delivery of Assessments and Gameplay

Students in the course were informed about the study a week before initial pre-test assessments were performed. It was made clear that participation in assessments was voluntary, anonymous, non-marked, and would not impact their class standing. One lecture

period (i.e., 2 days) before the intervention with Shroomroot, students were invited to fill out the pre-test online on their own time (the closed-book nature of the pre-test was via honor system), via Fluid Surveys (Ottawa, ON, Canada). On the day of the intervention, students who had not completed the online survey were also given the opportunity to fill out an identical paper version of the pre-test.

When students were contacted about taking the pre-test, they were also given instructions to download the Shroomroot game files, and asked to bring their laptops to class at the next lecture period. Access to the game required an online component that was deactivated previous to in-class game-play (and could be re-activated remotely) to restrict student game-play to the desired time period. Once in class, students sat in groups of 2 or 3 around each laptop, taking turns to play the game.

In both lecture sections, a designated helper was available to assist the students with any technological issues related to the game, but little to no organized content-related discussions were had between the students and the helper or instructors. Short text-based tutorials included within Shroomroot game-play led the students through the mechanics and goals of game-play and in some cases also presented content while explaining game-play. For example, small text boxes appear at appropriate times to explain how to become a mycorrhizal root. These same text boxes also introduce the concept that mycorrhizal fungi can help plants access organic nutrients, which is relevant to both game-play and ecological content. After about 35 minutes of game-play, students were directed to take the post-test either on paper or online. All participating students completed the post-test within class on the day of game-play.

Assessments

In discussing the pre- and post-tests, individual units of each assessment will be referred to as "items" to encapsulate short-answer questions, multiple choice questions, and Likert-style statements with rating scales. Pre- and post-tests were linked by non-identifying usernames that the students wrote on the assessments themselves. Only pre- and post-tests with unambiguously matching usernames were considered "matched" and used in the final analyses. Full copies of assessment materials are available in the open-access thesis by Amerongen Maddison (2016).

To evaluate whether Shroomroot (SR) improved students' ability to achieve the target learning objectives within the Introduction to Soil Science course, both the pre- and post-test included 24 individual items about mycorrhizal content (e.g., how the mycorrhizal symbiosis benefits the fungus in multiple different ways). To better isolate how effectively Shroomroot delivered content, seven of these items (29% of all content items) covered mycorrhizal content not included in Shroomroot (i.e., not referenced during gameplay nor in Rewards content). The content knowledge portion of the assessment was therefore grouped into items that were "SR-addressed" or "not SR-addressed."

To evaluate Shroomroot's effect on student engagement with ecological content, a set of four items (on a Likert 5-point scale) were included on both the pre- and post-test. Two of these items related to the mycorrhizal content addressed by Shroomroot (e.g., "Mycorrhizae and mycorrhizal networks are interesting" and "I would like to learn more about mycorrhiza and mycorrhizal networks"). Two additional items were related to basic plant nutrition-related content that is presented in the early levels of Shroomroot (e.g., "Plant nutrition is interesting" and "I would like to learn more about plant nutrition"). For the purpose of this study we considered responses to these statements to reflect student "content engagement" (i.e., students' self-reported interest and desire to learn more about mycorrhizal ecology and plant nutrition).

The pre-test and post-test also evaluated other factors to explore potential confounding variables. Unique to the pre-test were two demographic items (gender, program major) and three items related to previous game experience and content experience. Unique to the post-test were four additional Likert-style items that directly assessed whether students felt they learned information from playing Shroomroot, and whether they felt their interest in the target topic areas increased.

○ Data Analysis

Content Knowledge Acquisition

The difference in pre- and post-test content scores was assessed using the nonparametric Kolmogorov-Smirnov (KS) test due to non-normality of the data. The two-sample KS test generates a "D" statistic and examines the null hypothesis that two distributions of data (ordinal or continuous) share the same underlying continuous distribution. It should be noted that the KS test is a rather conservative test, and p-values presented are likely to be underestimates of actual effects. Differences between cumulative pre- and post-test scores were calculated for each item and grouped by how well Shroomroot was expected to address each item based on the concepts presented.

After observing during the intervention that students seemed to put a limited amount of time into reading content in the Rewards section of the Shroomroot, a second analysis was performed in which items were further subdivided into three categories: (1) "not SR-addressed" for content not included in Shroomroot; (2) "rewards only" for content only presented in Rewards section and not through game play; and (3) "gameplay and rewards" for content presented in both Gameplay and Rewards sections. The change in content knowledge within each group was compared using a Kruskal-Wallis test (due to non-normality of data), followed by post hoc analysis using the Dunn test.

Content Engagement

All 5-point Likert items were scored from 1 to 5, "Strongly disagree" to "Strongly agree." Scores on content engagement items were compared between the pre- and post-test individually using a KS test.

Other Factors

Other potential covariates, such as previous game experience, gender, and class section, were evaluated for their relationship to changes in knowledge or attitudes (in separate analyses) using ANOVA where assumptions were met, or a Kruskal-Wallis test where a non-parametric test was more appropriate. When a change in scores is reported, it is in mean raw difference between the pre- and post-test, and all means are reported ± standard deviation. All scores were normalized before comparison, and all analysis was done in R Studio, version 3.2.2 (R Core Team, 2016).

○ Results and Discussion

Summary Statistics

About 60 percent of students were in attendance across both sections on the day of the intervention (Table 2). Of the tests recorded, 48 pre- and post-tests (21% of the class across both sections) could be unambiguously paired by the username students provided, and were students who did not look up mycorrhizal content in between assessments; hence, only these 48 tests were included in the final analyses of this study as a matched pre/post design.

Content Knowledge Acquisition

Shroomroot-addressed (SR-addressed) content knowledge scores significantly increased between the pre-test (raw score of 5.9 ± 3.4) and post-test (raw score of 8.6 ± 3.4) ($p = 0.018$, $D = 0.313$, Figure 3, Table 3), with a relatively strong effect size (Cohen's $d = 0.79$). Non SR-addressed content scores did not significantly increase between the pre- and post-test ($p = 0.249$, $D = 0.208$, Figure 3). When splitting SR-addressed items into "game-play and rewards" and "rewards only," content knowledge percent improvement on "game-play and rewards" items (19.4 ± 27.4) tended to be higher than "rewards only" percent improvement (4.7 ± 22.3, $p = 0.05$), and both "game-play and rewards" and "rewards only" had significantly higher percent improvement than "not-SR-addressed" items (–3.3 ± 21.5, $p < 0.0001$ and $p = 0.04$, respectively) (Figure 4). Students also tended to self-report that Shroomroot increased their understanding of mycorrhiza and mycorrhizal networks, as well as plant nutrition, with the majority of students (77%, $n = 37$ students out of 48) reporting that they "Agree" or "Strongly agree" with the statement "I learned about mycorrhizae and mycorrhizal networks from Shroomroot."

Shroomroot appeared to increase knowledge acquisition of targeted learning objectives about mycorrhizal ecology. Because there was no traditional instruction group as a comparison, we emphasize that this positive outcome does not demonstrate an improvement over traditional instruction methods, but that Shroomroot presents exciting potential as a complementary educational tool about mycorrhizal ecology. Shroomroot offers an interactive and visual experience with mycorrhizal systems, utilizing some of the characteristics of motivating and experientially rich digital games (Garris et al., 2002; Huang et al., 2013).

Shroomroot increased content knowledge acquisition with a relatively simple digital intervention structure—gameplay occurred during one 50-minute lecture period with little to no content-based instructor support (such as guided questions or group discussion). After playing Shroomroot in this relatively unguided context, students on average answered correctly about half (52%) of the SR-addressed items. Other successful game-based interventions have stressed the importance of instructor and digital support mechanisms (Barko & Sadler, 2013), and many studies have demonstrated the positive influence of guidance on game-based learning (Lim et al., 2006; Basu et al., 2011; Erhel & Jamet, 2013). Positive results from these other studies suggest that Shroomroot may have the potential to facilitate greater mycorrhizal learning in the context of greater classroom support.

One relatively simple form of support of Shroomroot within an undergraduate classroom context would be to pair questions with Shroomroot gameplay, to give students an explicit target of content to focus on. As an example, multiple-choice content items from the assessments used in this study (Table 4) could be answered by students in tandem with gameplay, marked by groups, and returned to provide individual students with feedback about correct answers. In particular, one could use a mixture of basic questions regarding

Table 2. Summary statistics of participants who completed matched pre- and post-tests (*N* = 48). LFS = Faculty of Land and Food Systems.

Value	Number (percent) of participants
Total number of paired tests	**Total:** 48 (100%)
Demographics	
Gender	**Male:** 14 (29%) **Female:** 33 (69%) **Blank:** 1 (2%)
Faculty	**Forestry:** 41 (85%) **LFS:** 5 (10%) **Science:** 1 (2%) **Blank:** 1 (2%)
Had taken Forest Ecology course	**Yes:** 3 (6%) **No:** 45 (94%)
Section	**Section 1:** 16 (33%) **Section 2:** 31 (65%) **Blank:** 1 (2%)
Previous game experience	
Previous video game experience	**Not at all:** 18 (37%) **A bit:** 11 (23%) **A moderate amount:** 11 (23%) **Quite a lot:** 7 (15%) **Other:** 1 (2%)
Preferred game devices	**Mobile:** 20 (42%) **Computer:** 22 (46%) **Console:** 20 (42%) **Other:** 2 (4%)
Device used on game day	**Computer:** 41 (85%) **Android:** 6 (12%) **Both:** 1 (2%)
Previous content knowledge	
Shroomroot experience	**None:** 40 (83%) **Heard of:** 4 (8%) **Played before pre-test:** 2 (4%) **Played between pre- and post-tests out of class:** 2 (4%)
Mycorrhizal knowledge	**None:** 46 (96%) **Previous course:** 2 (4%) **In between pre- and post-tests:** 4 (not included)
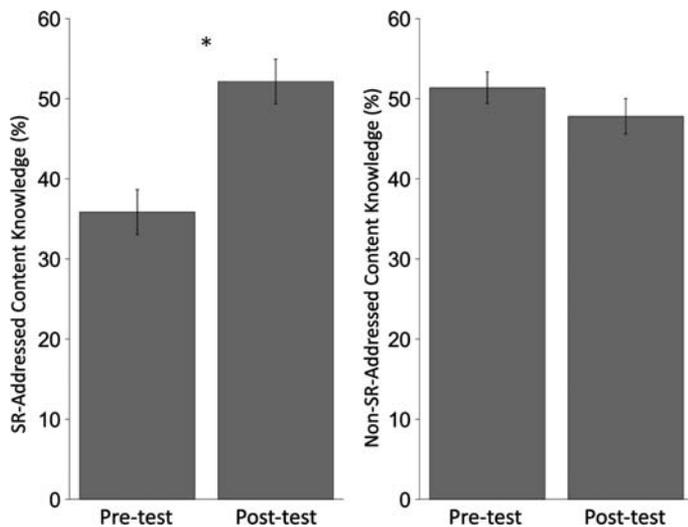
Figure 3. Students' knowledge acquisition about mycorrhizal content for pre- and post-test for **(A)** Shroomroot (SR)-addressed items (scores shown as percentages of 17 items) and **(B)** non-SR-addressed items (scores shown as percentages of 7 items). Asterisk denotes significant difference in scores based on a Kolmorgorv-Smirnov test ($p = 0.018$). Error bars are standard error of the mean ($N = 48$).
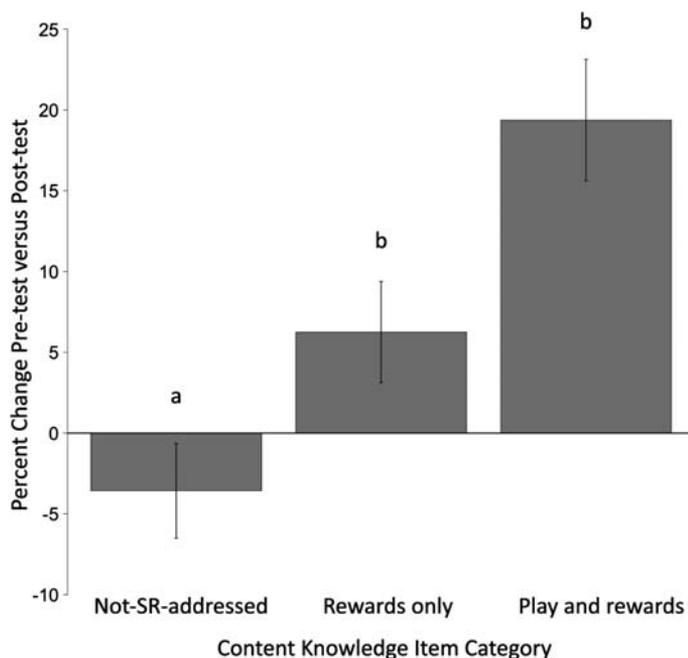
Figure 4. Students' content knowledge improvement (difference in percent of correct responses on the post-test vs pre-test) by item category. "Not-SR-addressed" refers to items categorized as not addressed by Shroomroot; "rewards only" are items addressing content only covered in the Rewards section of Shroomroot; and "play and rewards" are items addressing content covered in both the Gameplay and Rewards sections of Shroomroot. Letters denote significantly different groups based on a Kruskal-Wallis test ($p < 0.0001$) followed by a post hoc Dunn test. Error bars are standard error of the mean ($N = 48$).

the mycorrhizal symbiosis (most basic: content questions 1 and 2; intermediate: 3, 4, 5, and 6) and higher-order questions that require more synthesis of information and prediction of system behavior (questions 7, 8, and 9) with Shroomroot. For an explicit framework to facilitate higher-order, synthesis-type discussion among students, a potential avenue is the Generate-Evaluate-Modify (GEM) framework (Khan, 2007; 2008).

In addition to the importance of support, the classroom context of gameplay can significantly influence a game's impact on knowledge acquisition. Informal feedback from students and our observations suggested that students were unable to fully concentrate on the progression of the game and the information delivered sequentially during Shroomroot's in-game tutorials. It is possible that solitary or at-home playing would have been more effective. De Grove et al. (2012) found that students who played a first-person adventure game found higher self-reported learning and enjoyment, and they attributed it to having enough time to play and master the game. Ability to focus and develop mastery of a game can also contribute to achieving a state of "flow," a desirable state of high concentration and enjoyment more likely to be conducive to learning (Keller et al., 2011).

The overall significant increase in students' knowledge acquisition suggests that Shroomroot, a plant-ecology-focused, action-based game, was successful at addressing some learning objectives in mycorrhizal ecology at the postsecondary level. Greater gains in knowledge acquisition may have been possible if students were to play at home and were provided with additional support such as guided questions, small group discussions, or an integrated framework of instruction with technology such as GEM.

Content Engagement

None of the content engagement items had significantly different scores between the pre- and post-test based on the KS test ($p > 0.05$, Table 5). One of these items ("Mycorrhizae and mycorrhizal networks are interesting"), however, showed a possible trend toward increasing between the pre- and post-test ($D = 0.250$, $p = 0.10$, Figure 5), with an average rating of 3.7($\pm$ 0.8) on the pre-test, which is between "Neutral" and "Agree," and an average rating of 4.1($\pm$ 0.7) on the post-test, which is approximately at an "Agree" rating. Students also tended to self-report that Shroomroot increased their engagement with mycorrhiza and mycorrhizal networks, as well as plant nutrition, with the majority of students (77%) reporting that they "Agree" or "Strongly agree" with the statement "Shroomroot increased my interest in mycorrhizae and mycorrhizal networks."

These results suggest that Shroomroot may have mildly increased student engagement with mycorrhizal content, but not to a substantial degree. This could be connected to the structure of Shroomroot as a relatively simple game that utilizes an action-based gameplay combined with a reward system, as opposed to a more cognitive-based, intrinsically motivating style (Connolly et al., 2014). However, pre-test scores for both mycorrhizal items were already close to an "Agree" average, and the impact of Shroomroot may not have been strong enough to significantly change students' content engagement. No other factors (gender, course section, etc.) were significantly related to any content knowledge or content engagement metric (data in Amerongen Maddison, 2016).

Table 3. Effect of Shroomroot on students' content knowledge acquisition about mychorrizae (_N_ = 48). SR-Addressed = "Shroomroot-addressed". α = 0.05. D is the test statistic for the Kolmogorov-Smirnov test.

Variable	Points possible	Pre-test mean	Post-test mean	Mean change	_df_	_D_	_p_-value
Overall	24	9.5 ± 3.5	12.1 ± 3.5	2.6 ± 3.6	47	0.313	0.018
SR-Addressed	17	5.9 ± 3.4	8.6 ± 3.4	2.8 ± 3.5	47	0.313	0.018
Not SR-addressed	7	3.6 ± 1.0	3.4 ± 1.1	−0.2 ± 1.5	47	0.208	0.249

Table 4. Content-oriented questions from assessments. Correct responses are marked in bold; some questions have multiple correct answers. Responses marked with an asterisk (*) are not Shroomroot-addressed.

1. Which of the following best describes mycorrhizae?
Choose only one:
a. They are symbiotic associations that occur between a fungus and a plant root.
b. They are specific plant organs in roots that collect nitrogen and phosphorus.
c. They are symbiotic associations that occur between a decomposer fungus and a soil algae.
2. Which of the following best describes a mycorrhizal network?
Choose only one:
a. A single plant with its mycorrhizal fungi that are spread through the soil.
b. Multiple plants and multiple mycorrhizal fungi that are connected together.
c. Many species of fungi growing in the same patch of soil.
3. For PLANTS in mycorrhizal associations, what are the potential benefits of being in a mycorrhizal association?
Select all that apply:
a. They may receive phosphorus and/or nitrogen from the fungus.
b. They may receive water from the fungus.
c. They may receive resources from neighboring plants via the mycorrhizal network.
d. They may have increased defense against non-mycorrhizal fungi and bacteria.*
e. They may have increased ability to access resources in the soil.
4. For PLANTS in mycorrhizal associations, what are the potential costs of being in a mycorrhizal association?
Select all that apply:
a. They may give carbon to the fungus.
b. They may lose nitrogen to the fungus.
c. They may spend defense resources interacting with the fungus.*
d. They may have an increased risk of infection from other fungi and/or bacteria.*
5. For FUNGI in mycorrhizal associations, what are the potential benefits of being in a mycorrhizal association?
Select all that apply:
a. They may receive carbon from the plant.
b. They may have increased ability to digest plant material in the soil compared to decomposer fungi.*
c. They may have increased defense against external pathogens compared to decomposer fungi.*

(continued)

Table 4. Continued

| |
|---|
| **6. For FUNGI in mycorrhizal associations, what are the potential costs of being in a mycorrhizal association?** |
| *Select all that apply:* |
| **a. They may give nitrogen and phosphorus to the plant.** |
| **b. They may lose carbon to the plant.** |
| c. They may be dependent on the plant for water. |
| d. They may have increased risk of attack by pathogens.* |
| **7. In which of these situations might a plant "choose" not to be mycorrhizal?** |
| *Select all that apply:* |
| a. When the soil is rich in organic resources (such as organic forms of nitrogen). |
| **b. When the soil is relatively moist.** |
| **c. When the soil is rich in inorganic resources (such as inorganic forms of nitrogen).** |
| **8a. Considering a group of plants connected on a mycorrhizal network, which one of the following plants would be most likely to receive resources from neighboring plants via the mycorrhizal network?** |
| *Choose only one:* |
| a. A medium-aged tree in a local patch of *organic*-nutrient-rich soil. |
| b. A medium-aged tree in a local patch of *inorganic*-nutrient-rich soil. |
| **c. A young tree in a local patch of heavy shade.** |
| d. A young tree in a local patch of moist soil. |
| **8b. From the question above (8a), which resource would the selected plant most likely receive?** |
| *Choose only one:* |
| **a. Carbon.** |
| b. Water. |
| c. Inorganic nutrients. |
| d. Organic nutrients. |
| **9. Within the field of mycorrhizal network ecology, what kind of tree does the "mother tree" concept primarily refer to?** |
| *Choose only one:* |
| a. An older tree from which carbon flows through the mycorrhizal network to nearby relatives *more* than to nearby non-relatives. |
| **b. An older tree that is more greatly linked on the mycorrhizal network, from which resources tend to flow to younger seedlings.** |
| c. An older tree that provides many functions in the forest for multiple organisms, especially animals. |
| d. An older tree that is a canopy dominant and has dispersed seedlings more widely than other trees. |

○ **Limitations**

There were some limitations to this study. First, as a quasi-experimental pre- and post-test design, there was no comparison to traditional instruction. Also, the assessments were arguably limited in scope and sensitivity, and the main response variables of content knowledge and content engagement were measured with multiple choice questions, making them closed (as opposed to open-ended) and quantitative. This format was chosen to simplify the evaluation process and create a broad-reaching assessment appropriate for the time constraints of the intervention. This approach, however, means that interpretation of results can only draw on a basic quantitative understanding of the knowledge and engagement scores and informal comments from students and instructors, and lacks the depth of assessments that include open-ended questions and qualitative analyses such as focus groups, classroom observations, and interviews.

Table 5. Effect of Shroomroot on students' mycorrhizal content engagement (N = 48).

Item	Maximum score	Pre-test mean	Post-test mean	Mean change	D	p-value
"Plant nutrition is interesting."	5	3.8 ± 0.8	4.0 ± 0.7	0.1 ± 0.6	0.063	1
"I would like to learn more about plant nutrition."	5	3.8 ± 0.9	4.0 ± 0.8	0.2 ± 0.6	0.083	0.996
"Mycorrhizae and mycorrhizal networks are interesting."	5	3.7 ± 0.8	4.1 ± 0.7	0.3 ± 0.8	0.250	0.1
"I would like to learn more about mycorrhiza and mycorrhizal networks."	5	3.9 ± 0.7	3.9 ± 0.8	0.0 ± 0.8	0.063	1
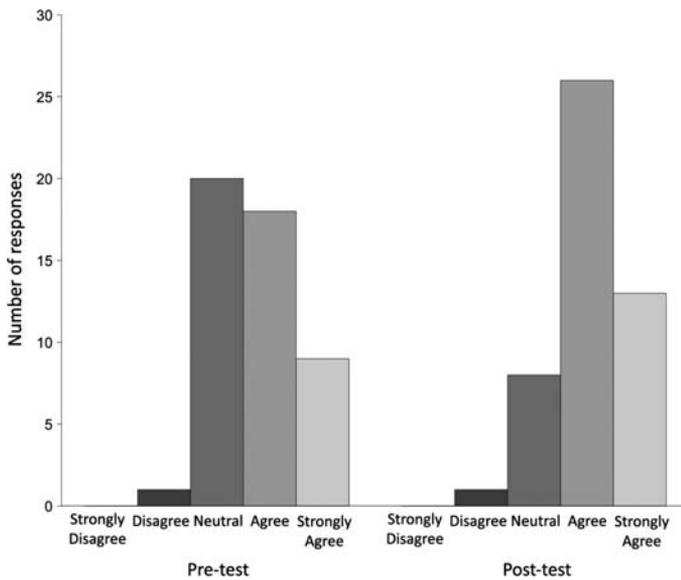
Figure 5. Distribution of student responses to content engagement item "Mycorrhizae and mycorrhizal networks are interesting," as numbers of students responding with different levels of the Likert scale. 60% (n = 29 out of 48) of students Agreed or Strongly Agreed with the statement on the pre-test, 81% (n = 39 out of 48) Agreed or Strongly Agreed on the post-test, after playing Shroomroot.

Conclusions

Intervention with Shroomroot was successful at increasing undergraduate students' knowledge acquisition to meet mycorrhizal ecology learning objectives, and tended to have a positive impact on student engagement with mycorrhizae and mycorrhizal ecology (content engagement item "Mycorrhizae and mycorrhizal networks are interesting" saw 60% of students reporting "Agree" or "Strongly agree" on the pre-test versus 81% reporting "Agree" or "Strongly agree" on the post-test). Students also self-reported that the game increased their learning (77% "Agree" or "Strongly Agree") and interest in mycorrhiza and mycorrhizal networks (also 77% "Agree" or "Strongly Agree"). The potential for digital games to have positive learning and affective outcomes is well-documented, but it is unique to see significant knowledge acquisition for a plant-focused action-based game. Both learning and affective outcomes may have

been even more pronounced had more explicit classroom support (e.g., guided questions) been included in the intervention format.

Shroomroot has the potential to be useful for other soil science, forest ecology, and biology courses that deal with the invisible components of below-ground biological systems. This study also emphasizes the importance of the creative collaboration between game developers and science instructors in developing the educational digital gaming context.
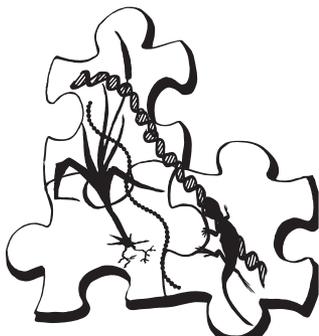
Acknowledgments

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