frontiers | Frontiers in Education

TYPE Original Research
PUBLISHED 01 August 2023
DOI 10.3389/feduc.2023.1186270

Prairie Protector: student development of systems thinking habits in the context of agroecosystems

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RECEIVED 06 April 2023
ACCEPTED 13 July 2023
PUBLISHED 01 August 2023

CITATION
Ingram E and Keshwani J (2023) Prairie Protector: student development of systems thinking habits in the context of agroecosystems. *Front. Educ.* 8:1186270.
doi: 10.3389/feduc.2023.1186270

Introduction: The Great Plains ecosystem offers an opportunity for young people to gain knowledge about intricate systems through practical learning. The spread of woody plants into grasslands, known as the "Green Glacier," poses a risk to biodiversity and animal production. Although effective management strategies exist, some land managers are reluctant to use them. It is critical to cultivate a scientifically literate population that can think systematically and make informed decisions based on STEM principles to address such complex agroecosystem problems.

Methods: In this study, semi-structured focus group discussions with high school students were analyzed to determine whether Prairie Protector, an educational game, and its associated resources led to evidence of systems thinking habits in student conversation.

Results: Analysis of the focus group transcripts revealed that the students developed systems thinking habits through their experience playing Prairie Protector while developing empathy for land managers and others involved in the Great Plains agroecosystem. In general, students found the game enjoyable and a useful tool for learning about agroecosystems, conservation land management, and the spread of invasive species.

Discussion: Analysis of the student statements led to the development of a guiding framework to assess and analyze students development of systems thinking habits that could be used to scaffold student learning experiences to explore, understand, and interact with complex systems. Providing simulated environments for students to interact with complex systems should be explored in additional scenarios to support student development of systems thinking skills.

KEYWORDS

systems thinking, agroecosystem, game-based learning, STEM education, science literacy

Introduction

Ensuring thoughtful involvement of individuals from a variety of perspectives is critical to successful strategic discussions around challenging systemic problems such as pandemics and climate change. To foster meaningful conversation, it is crucial to provide learning opportunities that enable individuals to understand and analyze complex systems. In its simplest form, a system consists of elements, interconnections, and a function or purpose (Meadows, 2008). The Great Plains ecoregion of the United States is an example of a system. The elements of the Great Plains ecoregion include grasses and shrubs, prairie chickens, prairie dogs, people, and cattle, among many other aspects and components (Augustine et al., 2021). Interconnections of the Great Plains ecoregion include the food chain of producers (such as grasses) being eaten by primary consumers (cattle and rabbits), being eaten by secondary consumers (owls and coyotes), being eaten by decomposers (vultures, insects, bacteria, and fungi), and returning organic matter to the soil to start the cycle all over again. Similarly, humans are interconnected within the prairie system through family and social networks in rural communities and by raising and selling cattle from rangelands to support economic vitality. One function or purpose of the Great Plains ecoregion is to support the biodiversity of life and livestock production (Freese et al., 2014).

The ability to identify and analyze the elements, interconnections, and purpose of a system is known as systems thinking (Meadows, 2008). Addressing challenges that arise in complex systems requires systems thinking skills. As an example, in recent decades, the Great Plains region of the United States faces the threat of the "Green Glacier," an invasion of woody plants spreading across the landscape, which has traditionally been dominated by grasses and wildflowers (Engle et al., 2008). From a systems perspective, we can determine that the solution to mitigate the impacts of the "Green Glacier" is complex and will require adjusting more than one element in the system. For example, simply convincing land managers to remove invasive trees from grasslands is only one aspect of addressing the negative impact of the "Green Glacier." Other aspects to consider include the financial costs of tree removal, the impacts of climatic events like drought on available management strategies, regional policy decisions that impact land use, and urban homeowner's decisions to plant invasive trees for aesthetic reasons. A comprehensive understanding of complex agroecosystem issues, such as the "Green Glacier," necessitates a science-literate citizenry equipped with systems thinking and STEM-informed decision-making skills, capable of analyzing the historical, social, financial, political, and cultural aspects of the dynamic prairie ecosystem. Only by considering the "Green Glacier" within the broader context of a complex and evolving system can we effectively determine appropriate land management practices for its sustainable stewardship.

The history of Eastern red cedar in the US Great Plains is complicated. Eastern red cedar is native to the grasslands of the Great Plains and plays an important role in the prairie ecosystem under normal conditions (Van Haverbeke and Read, 1976). Only in the past few 100 years have the human impacts on prairies resulted in the invasive spread of Eastern red cedar across the Great Plains. When European settlers arrived and implemented Western agricultural practices, the omission of fire from land management strategies resulted in a significant decline in the biodiversity of flora and fauna (Umbanhowar, 1996). As a result, Eastern red cedar became invasive due to the lack of fire mitigating its spread (Bragg and Hulbert, 1976; Briggs and Gibson, 1992; Engle et al., 2008). The transformation of grasslands to forests has negative impacts on carbon sequestration, biodiversity, and other ecosystem services (Engle et al., 2008; Keyser et al., 2022; Wilcox et al., 2022).

Equipping learners with systems thinking skills provides a foundation to consider and critically analyze complex systems, such as the Great Plains ecoregion and the threat posed by the "Green Glacier." Systems thinking is literally a system of thinking about systems (Arnold and Wade, 2015). Systems thinking habits can equip learners with pro-environmental sentiments, such as belief in and concern about human-driven global warming (Ballew et al., 2019). Systems thinking is a complex skill that involves moving back and forth between gaining knowledge and then using that knowledge (Arnold and Wade, 2017). Mental models are a key component of systems thinking and serve as personal representations of reality used to understand phenomena (Mental Models—InstructionalDesign.org, 2023). The development of mental models allows learners to gain literacy of new topics (Tham et al., 2021). Inadequate mental models limit the ability to understand and manipulate complex systems (Garrity, 2018). The Waters Center for Systems Thinking has defined 14 specific habits to be developed when equipping a learner to be a systems thinker (Waters Center for Systems Thinking, 2020). The Waters Center Habits of a Systems Thinker include skills such as "Changes perspective to increase understanding," "Pays attention to accumulations and their rates of change," and "Considers how mental models affect current reality and the future."

Playful games can provide a low-stakes setting for developing systems thinking strategies related to complex issues. The act of play facilitates learning by allowing individuals to temporarily ignore real-world limitations (Vygotsky, 1966). Games provide an avenue for players to practice making decisions in an environment outside of the game (Shaffer, 2006) and provide a scaffold for non-experts to interact with scientific models by engaging both expert and non-expert players in exploring and experimenting with management solutions to a game-based environmental situation (den Haan et al., 2020). Educational games focused on climate change promote empathy and engagement in community planning and development meetings (Wu and Lee, 2015) and pro-environmental behavior (Wolf, 2020). Educational games can be effective learning tools that lead to improved systems thinking and policy support, particularly for participants with less science education (Sajjadi et al., 2022). In this study, we assess evidence of high school students developing systems thinking habits related to complex agroecosystems after experiencing an educational game known as Prairie Protector.

Research problem

Prairie ecosystems offer a practical learning environment for comprehending and exploring intricate systems. Initially, prairie models included four sub-models to describe aspects of the biomass system: abiotic (photosynthesis), producers, consumers, and decomposers (Patten, 1972). The complexity of the prairie ecosystem increased with the introduction of the "Green Glacier," across the Great Plains ecoregion of the United States (Engle et al., 2008). The encroachment of woody plants into grasslands poses a threat to ecosystem biodiversity and animal production systems. However, effective management strategies, such as prescribed burning and mixed-species grazing, during the early stages of spread can mitigate the issue (Wilcox et al., 2022). Despite the potential benefits of fire as a management tool, land managers are often hesitant to implement prescribed burning due to factors, such as social impacts, legal liabilities, and economic concerns

(Kreuter et al., 2019). Acceptance of fire as a management tool is essential on a regional scale to preserve productive rangelands (Wilcox et al., 2022). By maintaining productive rangelands, the biodiversity and overall health of the prairie system will also be preserved. The educational game Prairie Protector was developed to introduce the challenge of the "Green Glacier" and strategies used to mitigate the impacts of woody encroachment on prairie grasslands.

The goal of this qualitative study was to determine whether students develop systems thinking habits after playing Prairie Protector and experiencing supporting educational resources. The central research question of the study was how do students express systems thinking habits after the Prairie Protector intervention? Research sub-questions include the following:

- How did social interaction with peers play a role in the development of students' systems thinking?
- In what ways did students develop systems thinking habits related to empathy and perspective taking that translate from the game environment to real-world situations?

Evidence was analyzed to create a model of how students develop systems thinking habits through educational activities. Specifically, we analyzed student quotes from focus group discussions to identify and categorize examples of student understanding of each of the 14 Habits of a Systems Thinker.

TABLE 1 Systems thinking habits aligned with Prairie Protector gameplay experiences and lesson plan reflection questions.

Habits of a systems thinker (Waters Center for Systems Thinking, 2020)	Prairie Protector game and lesson connections
Surfaces and tests assumptions	Player outcomes allow players to test strategies and receive prompt feedback.
Observes how elements within systems change over time, generating patterns and trend	Eastern red cedar trees grow and spread across the landscape in alignment with research-based models.
Recognizes that a system's structure generates its behavior	Tree age determines spreading pattern; mitigation tools cannot be used in dense tree stands surrounded by trees.
Makes meaningful connections within and between systems	Player treatment options have different impacts on tree spread and different costs, reflection questions ask students to compare gameplay with real-world ecosystems.
Identifies the circular nature of complex cause-and-effect relationships	Gameplay experience allows trees to continue to spread and regrow after treatments are applied.
Changes perspectives to increase understanding	Player opportunities to learn from peers and computer-controlled neighbors; reflection questions on how cultural beliefs around fire have changed over time.
Seeks to understand the big picture	Reflection questions encourage students to explore the nuances of real-world land management decisions.
Uses understanding of system structure to identify possible leverage actions	Gameplay strategy development encourages use of treatments with highest return on investment.
Checks results and changes actions if needed: "Successive approximation"	Quick gameplay, feedback, and results/score allow players to iteratively improve their strategy.
Pays attention to accumulations and their rates of change	Eastern red cedar trees grow and spread across the landscape in alignment with research-based models.
Recognizes the impact of time delays when exploring cause-and-effect relationships	Reflection questions to identify trends in wildfire regimes in the US and related factors.
Considers short-term, long-term, and unintended consequences	Development of gameplay strategy; reflection questions on treatment selection and efficacy, benefits and drawbacks of using fire balanced with health and safety.
Considers how mental models affect current reality and the future	Reflection questions on mental models prior to playing Prairie Protector that impact game decisions.
Considers an issue fully and resists the urge to come to a quick conclusion	Reflection questions on the acceptance of fire as a land management tool and related beliefs or assumptions that impact acceptance and implementation.

Materials and methods

Prairie Protector game

Our team of undergraduate students, graduate students, staff, and faculty developed the Prairie Protector game (Ingram et al., 2022; Prairie Protector, 2023). Players take on the role of land manager for a section of land and make treatment decisions to eradicate Eastern red cedar from their land using limited financial resources. Initial findings suggest that using Prairie Protector as an educational tool for middle school students allowed players to experience meaningful interaction with selecting land management strategies and exploring the complex system interactions of prairie ecosystems (Ingram et al., 2022). The goal of Prairie Protector and the associated educational resources is to provide players with a low-stakes and interactive environment to test systems thinking habits (Table 1).

Prairie Protector players are given a plot of land that has been impacted by woody encroachment. A player wins the game by eliminating Eastern red cedar from the land in the fewest number of years. Players can choose from five treatment options (small fire, large fire, ax, chainsaw, or bulldozer) with varying efficiency and cost to contain the Eastern red cedar on their land. Trees spread across the landscape according to research models that show the likelihood of spread given tree age and location (Donovan et al., 2018). Advanced levels allow players to manage a section of land adjacent to computer neighbors to simulate the impact of societal decisions on land management. Each standalone game takes <10 min to complete to allow students to try again with a new strategy or game scenario. There are six levels in the game representing different ecological situations, such as drought. In addition, players can choose a custom game with a randomly assigned distribution of trees with three difficulty levels (increasing starting density of trees) and three map sizes. Players can also choose to add up to three computer neighbors in the custom game option. Prairie Protector is available to play freely online (prairieprotector.com).

Program participants and implementation

High school students from a high school in central Nebraska were recruited to participate in the study during the spring 2022 semester. The school is considered semi-rural with 20% minority enrollment and 36% economically disadvantaged students (US News Best High Schools, 2023). The guardians of every student in the three classes that participated in the Prairie Protector educational experience received informational emails from their student's teacher and provided informed consent to allow their student to participate in the study. Student participants completed assent forms in addition to receiving parental consent in accordance with the approved IRB protocol (IRB Approval #: 20211121464EP). A total of 52 of the 55 students from three classes participated in the study. Students were in grades 9–12 and were enrolled in an animal science course. Animal science is an elective course taught by agricultural education teachers.

The intervention consisted of five, 60-min instructional periods during which students played the digital video game, Prairie Protector (https://www.prairieprotector.com/), and engaged in supporting educational activities including systems modeling using Loopy, an online systems modeling tool (https://ncase.me/loopy/), and completing discussion and reflection exercises to support the development of systems thinking habits after playing the game. Lesson plans are provided in the Supplementary material. Students played the game independently on school-provided Chromebooks but were given the freedom to discuss their experiences and strategy while playing.

Data collection

Eligible students were invited to participate in focus groups conducted during the school day at their regular class time. Focus groups were selected as the data collection method primarily to accommodate student class schedules and the ability to coordinate time to discuss their experiences. In addition, focus groups allow group dynamics, or in this case class dynamics, to be visible to the researchers to reveal "shared lived experiences" such as playing Prairie Protector in a classroom setting (Liamputtong, 2011). The authors led the focus group discussion with all eligible students during a class period combined into one discussion of 15–20 students. Each of the three focus group discussions lasted ∼50 min. Focus groups followed a semi-structured interview format with questions focused on the gameplay experience, the impact of existing mental models on gameplay, and the development of empathy for land managers. The focus group protocol was developed in alignment with the research questions to discuss the aspects of the game and lessons expected to impact the development of systems thinking habits (Table 1). Focus group questions are provided in the Supplementary material. Discussions were digitally audio-recorded and transcribed by Rev.com. The authors manually corrected transcripts as needed based on the audio recordings for data analysis.

Data collection and analysis

Qualitative analysis of the data was conducted in two key phases: a priori coding and analytic coding (Merriam and Tisdell, 2015). Given that the purpose of the study was to determine students' systems thinking habits, we used the Waters Center for Systems Thinking (2020) as a classification scheme to create an a priori code list (Merriam and Tisdell, 2015). During the first round of coding, investigators Ingram and Keshwani read the transcribed discussions separately and identified responses that provided evidence of student development of each of the 14 systems thinking habits and applied a priori codes to meaningful data segments. The research team then compared coded transcripts, discussed discrepancies in the application of codes to data segments, and co-created a codebook of exemplars and operationalized definitions of each of the a priori codes aligning to the 14 systems thinking habits. Investigators completed a second round of a priori coding using the codebook as a guide. The research team once again compared coded transcripts, discrepancies were discussed, and final additions and refinements were made to the coding framework. The process continued until the two researchers reached a consensus. Once it was determined that no new insights or understandings were emerging from the a priori coding process, the research team engaged in analytical coding in which the a priori codes were consolidated into broader systems thinking themes based on patterns identified in the data.

Results

Analysis of the focus group transcripts revealed that the students developed systems thinking habits through their experience playing Prairie Protector. Student statements on mental models suggest that they also developed empathy for land managers and others involved in the Great Plains agroecosystem. In general, students found the game enjoyable and a useful tool for learning about agroecosystems, conservation land management, and the spread of invasive species.

Evidence of systems thinking habits

Focus group transcripts were coded to identify statements that aligned with each of the Habits of a Systems Thinker identified by the Waters Center. Statements were identified for each Habit suggesting that the gameplay experience aligned with systems thinking concepts. In this section, we define how we categorized each Habit and provide sample student responses that exemplify each of the Habits of a Systems Thinker.

Makes meaningful connections within and between systems

We defined this code as evidence that a student identifies two or more system components and the relationship between them or the impact that one has on the other. This code appeared in transcripts from all three classes. An example of a temporal connection within the system is "*the ax just made it so it (young tree)* *would stop growing.*" [Class 1] The student identifies the impact of the management tool (ax) on the change in the trees (they stop growing).

Students also identified spatial examples of system connections, "*Well, like, so like if you had like deer or like opossums or like raccoons or coyotes, like you can't use this treatment on this part of the land because there's these animals here.*" [Class 2] In this example, the student identified that management tools can only be used on certain areas of the land due to competing factors in a real-world scenario, such as the presence of animals.

Recognizes that a system's structure generates its behavior

For transcript analysis, we defined this habit as a student discussing how a feature of the system influences the behavior of the system. This code appeared in transcripts from all three classes. For example, "*So I looked at the trees and saw like how many years they had left and the lower, the lower the years, the more I like tried to get rid of them.*" [Class 1] This student identified a feature of the system structure, that older trees that would soon transition to dense forest and have a more negative impact on the land than younger trees, that influenced their strategy through the decision to act by focusing management efforts on older trees. The student was acting as a part of the system, and the impact was the influence on their player behavior.

Identifies the circular nature of complex cause-and-effect relationships

The circular nature code was identified when a student discussed a cause-and-effect loop as a cyclical pattern within a relationship. This code appeared in transcripts from two of the three classes. Students using phrases such as "this leads to X... which leads back to Y..." were coded as an example of circular nature. For example, one student commented,

> "*I mean, there wasn't really, we were just burning trees, but I was like, we were all talking about like, if you added cattle, like just like the little, little cows in the spaces that don't have trees and like the cows go away when trees grow back or when trees die, cattle comes in.*" [Class 3]

The student identified that cows go away when trees take over a grassland and then when the trees die the cows come back, showing the circular nature of the relationship in the system.

Observes how elements within systems change over time, generating patterns and trends

We focused on the ability to recognize change over time but does not indicate a quantifiable change as the key feature for applying this code. For example, noticing that carbon changes to carbon dioxide within the system. This code appeared in transcripts from all three classes. An example of this code in the transcripts includes, "*Didn't realize like how many methods of clearing there were and like how some of 'em would cause spreading a lot faster than the others*" [Class 1]. In this example, the student articulates that trees spread within the system and that some trees spread faster than others depending on the type of management tools used.

Pays attention to accumulations and their rates of change

We defined this code as a student's ability to identify quantifiable changes and was identified when students express that a system element changes and indicates a quantifiable change in accumulation or rate. Specific numbers or units (e.g., month and year) must be mentioned by the student for a statement to meet this criteria. This code appeared in transcripts from all three classes. For example, "*It actually takes time to burn down the trees in years instead of just outta one whole month*" [Class 3]. In this example, the student identifies the amount of time it takes to manage trees with fire as being longer than 1 month.

Seeks to understand the big picture

For this habit, we defined the code as evidence that the student discusses a broader context for making decisions, either within the game or in real-world land management scenarios. This code appeared in transcripts from all three classes. In one example, a student stated, "*And if they have like cattle, they're having to watch the land and the cattle and there's a lot that goes on*" [Class 3]. The student shows an understanding of the balance between land management and livestock production being the reason behind why trees on a grassland must be managed. Examples of this habit could also focus on the nuance of complex agroecosystem problems. For example,

> "*Well, I feel like we shouldn't just like promote, killing all the [trees]. [Laughter] I got to thinking about that and I was like, oh gosh, what are we getting into? But like, like I feel like I get like cutting down invasive ones. Like that makes sense. Yeah. And like, but I do think that like with like our greenhouse emissions and things like that, we do need trees and especially with how many trees get cut down a year for things that aren't protecting anything. It's just for gain of like wealth and stuff, especially with different forests. But I think that we need trees, but maybe make more of an emphasis that the game is based on cutting down invasive trees.*" [Class 3]

This quote shows a student has a nuanced understanding that the killing of trees should not be indiscriminate and must consider the type of tree and location. The student understands why some trees are invasive and should be managed while others are non-invasive and do not pose a problem to the system.

Changes perspectives to increase understanding

We operationalized this code as student responses in which they note gaining new knowledge or changing their mind about the system, either in the game or in the real world, after encountering a perspective other than their own. The new perspective encountered could be that of a classmate, a non-playable neighbor character in the game, the game tutorial, or the provided educational resources.

This code appeared in transcripts from all three classes. One example of a student demonstrating this habit is found in the following quote:

> "*At the beginning of one of the levels I didn't know that we were supposed to clear off. What do you call like the smaller groups of trees first until at the beginning of one of the levels, it kind of like gave you a hint on how you're supposed to do it. And then that helped me throughout like all the rest of the levels.*" [Class 3]

This student demonstrated their ability to use the information provided in the game to improve their ability to manage the land successfully.

Considers how mental models affect current reality and the future

We defined the code for this habit as the student acknowledging any awareness of self or others' mental models and the impact these models have on a system. This code appeared in transcripts from all three classes. The awareness of mental models could relate specifically to the game or related experiences in life. For example, one student stated,

> "*Or like the person's like belief, something, they think something like a certain tool is really, really bad. So they don't use that even though like maybe they think the wrong thing about something.... [Like what?—interviewer] So like fire, like I know some people think that's super bad, so maybe like they're not educated and know that it's good, but they have to like know like when [to] use fire, like it's too dry or something like that.*" [Class 2]

The student comments show evidence of understanding why a land manager may choose to use or not use fire based on their mental models of the usefulness or danger of fire in a grassland ecosystem.

Surfaces and tests assumptions

This habit relates to the awareness of individual assumptions that lead to behavior such as gameplay strategy. We defined this code as the student referencing a decision made in the game based on assumptions. This code appeared in transcripts from two of the three classes. For example, one student described their game strategy as follows:

> "*I thought that the money like mattered a lot. So like when I first started playing, I was trying to do cheaper options cause I thought if I clicked to the next year, that money would carry on and then I realized that it didn't. Yeah. So I was like 12 years in and a bunch of trees [and] have the same amount of money.*" [Class 3]

The student assumed that money would carry over from year to year in the game. However, they learned from playing the game that the money (coins) reset every year.

Uses an understanding of systems structure to identify possible leverage actions

We defined this habit as a student identifying how a player's choice, such as a management tool or treatment location within the game land area, has different impacts, either positive or negative, on the system. This habit also closely links to gameplay strategy development and expression. This code appeared in transcripts from all three classes. For example, one student commented that they "*didn't realize like how many methods of clearing there were and like how some of them would cause spreading a lot faster than the others*" [Class 1]. This student identified that their choice of management tool could have a positive impact on the system through the effectiveness of removing trees from the system.

Considers short-term vs. long-term consequences of actions; and recognizes the impact of time delays when exploring cause-and-effect relationships

We combined two of the Habits of Systems Thinkers into this code after our initial analysis of the transcripts. For this habit, we defined the code as a student discussing trade-offs and the related impacts on decision-making in either the game or real life. This code appeared in transcripts from all three classes. One example includes the following:

> "*I feel like I respect him [a land manager] to like more like a lot more. Cause you know, we get like more than one try, we get many attempts at this [in the game] and like, if we fail, we can always just restart. But like if they fail and like the entirety of their land is just covered in trees, that's gonna be a lot more difficult than just restarting. So it's kind like, I don't know. I just think a lot more about like the circumstances now.*" [Class 1]

Sometimes students' responses focused on the impacts of a time-dependent behavior or response event. For example, one student comments, "*Controlled burning, like with the fire was incredibly useful in like two ways. Cause it, it got rid of the, the trees, but it also prevented them from growing for a little bit*" [Class 1]. The short-term consequence was removing the trees, and the long-term consequence was preventing growth for a period of time due to reduced reproduction via seed spread.

Students may focus on using knowledge of the impact of a time delay to guide their decision-making and strategy development. One student commented on time delays when asked about their gameplay strategy, "*There were hints like at the beginning of the level that you could read. That was kinda helpful. I noticed like the, uh, transition period, like how long until the seed spread. So that was kind of where I went as far as strategy... Like the fire said like would like, like even have trees grow back for like 3 or 4 years*" [Class 2]. This student used their knowledge of how long the fire management tool would prevent seeds from spreading as well as prevent trees from coming back for a period of time to plan their gameplay strategy.

Consider unintended consequences of actions

We defined this habit as evidence that students recognize that decisions made in the game or the real world may cause unintended damage or unforeseen circumstances. Students suggested changes or additions to the game design that would better reflect unintended consequences. This code appeared in transcripts from two of the three classes. For example, "*I feel like it would be cool if there were like certain instances where you used a tool and like, like if you used the fire, like there would be a chance that it would get outta control*" [Class 1]. While this student did not necessarily articulate their concern for wildfire, their comments suggest that they understand unintended consequences could result from treatment strategies under real-world conditions.

Considers an issue fully and resists the urge to come to a quick conclusion

The code for this habit was defined as a student discussing multiple facets or perspectives that should be considered when making a decision. This was often discussed in conjunction with broader societal situations. This code appeared in transcripts from all three classes. For example, students were asked to contrast their gameplay experience which encouraged eliminating invasive trees with highly publicized tree-planting initiatives to combat climate change. One student expressed that not all trees are created equal, "*It just depends on what type of tree you plant. Cause like if you plant like a tree that spreads a bunch of seed, like cedars, then that's gonna be a big problem. But if you plant a tree that doesn't produce that many seeds, that would be beneficial*" [Class 2].

This student articulates how Eastern red cedar's higher rate of reproduction leads to invasiveness while other tree species with lower reproductive potential may prove to be beneficial to an ecosystem.

Checks results and changes actions if needed; "successive approximation"

We defined this code as a student experiencing something within the game that leads them to change their strategy. This habit was closely tied to competition within the game and with other students. We applied the code when student comments included comparative language about strategy effectiveness or efficiency to align with this habit. This code appeared in transcripts from all three classes. One example of competition between an individual and the game itself is highlighted in this student comments, "*Whenever you failed one [game scenario], it kind of made you like want to do better and like whenever you like accomplished and like beat one [game scenario] made you want to beat your score*" [Class 1]. Students also aligned with this habit when describing improving strategy through comparison with their peers. For example, "*I felt like I was using like the ax and like, not like not fire a lot. And then I talking everyone around me, they were saying the fire works so good. Cause then I was like, oh, I need leave this one [tool or strategy] and try the fire*" [Class 1]. In these two examples, the students were looking at their results of achieving a certain score or comparison with their peers and deciding to change their actions to improve their results.

General feedback on the game experience

Student feedback on the gameplay experience suggested that Prairie Protector felt like a real game. For example, student comments suggest they were compelled to succeed in the game by the opportunity to "win." One student noted "*Winning the game was super rewarding… that like your strategy paid off*" [Class 1]. Similarly, failing to achieve game goals caused emotional distress:

> "*Like on certain levels it was so frustrating. Cause you wanted to use a bulldozer, but it costs more money. Then you had to like either not spend all your money, which like* [Classmate] *said earlier, wasn't really worth it. Cause then it wastes more years. But, or you could like not do it, try something else, but that might not work as well.*" [Class 1]

Of course, not all students agreed that the game was a positive experience and some suggested that gameplay could be improved by including additional components and interactions in the prairie system. One student said, "*It was kind of like repetitive, like it was just burning down all the trees. Like there was nothing really else to do, but just like burn the trees and then you win the level. Okay. I feel like it, there needed to be like more to the game instead of just like burning down the trees. Yeah. Maybe like you grow plants for the animals. If you have animals, like you grow certain plants or what happened to those plants if like a pest was on it or something. Okay. Yeah. Or like, um, something like add in like a way to like lose money or something. If you like, I don't know, like your house, like you need to fix something in your barn house or like one of your animals got sick or something. Maybe <laugh> one of your animals got sick. So you lose like a couple of coins or like, just like something that doesn't make it so like you're just running down trees*" [Class 3].

Students naturally gravitated toward talking with each other about game strategy while celebrating wins and commiserating losses. One student discussed talking with friends to develop a strategy for a game scenario involving dense tree cover, "[Classmate] *was telling me about one of the strategies she used for, um, the dense one and I got it done in like five years or something. So it was super good to like, have it done really like quick, cause like you get like extra awards for having done a specific period of time and it was like cool to get stars.*" Another student commented on enjoying learning from peers to improve their strategy, "*It was fun to figure out like what other people were doing, cuz like I would be stuck and then I would be like,* [Classmate], *what did you do for this? I don't know and she'd be like, oh, I just did that. Or like when I was done, she would be like, what'd you get? I told her like 7 years or something. She'd be like, I got six. So I was like how? She basically just showed me*" [Class 1].

Student interaction with Prairie Protector modeled the exploration of other games. Eventually, they discovered "cheats" that made the game easier. One student shared that developing their strategy helped them shift from feeling clueless to feeling like they were gaming the system.

> "*So when I first played, I was like clicking each individual square. I was like placing something down or if it was like, you can't place here. I was like, okay. So I just kept on like clicking random squares until I found where it was supposed to be. And*

> *then, um, I just started like, like dragging it to where it was like just a like small section. And then over time I'm gonna be honest. I just kind of like did the whole square and then just like placed fire on it. And if I had any leftover money, I'd just use it for something else. Okay. And just kept on doing that.*" [Class 3]

Overall students were genuinely surprised that they were able to learn so much from a game. They saw the potential for a game like Prairie Protector to help others learn about complex systems and management strategies.

> "*I think there's a lot of people that have no idea about that stuff [and the] game could like help teach them. Cause like, I think that some people like have no idea about even a problem the game, like shows, I guess I kind of didn't realize like it was a problem. Like I knew like it, like they burn for and stuff, but I didn't realize how big of a problem. Cause like we plant trees like on our land for like wind blocks and stuff, but that we don't put Cedars and stuff, but I never really knew like the back story of that stuff.*" [Class 2]

Discussion

The purpose of this study was to determine whether playing an agroecosystem educational game and engaging with supporting educational activities would result in student demonstration of systems' thinking habits. Specifically, we looked for evidence in the focus group data of student understanding of the Waters Center Habits of a Systems Thinker. Focus group data allowed for analysis of student responses to open-ended questions, which provided opportunities to identify student language in alignment with the Habits. Examples were identified in the transcripts for each of the 14 Habits, suggesting that the gaming environment and associated curricular activities provide students with experiences to explore, understand, and interact with complex systems and develop their systems thinking.

Model of systems thinking habits

During the analytical coding process, three subgroupings of how students expressed systems thinking habits (Figure 1) emerged from the data: Conceptualize the System, Analyze the System and Our Conceptions, and Catalyze Action. The model provides a guiding framework to assess and analyze student's development of systems thinking habits that could be used to scaffold student learning about complex systems. The subgroups do not indicate a sequential progression through the systems thinking development process. It is not necessary to achieve a level of competency in one subgroup prior to moving into another subgroup. Some students started by focusing on actions they could take, which eventually led them to consider the elements within the system. Others began by exploring their own mental models before pinpointing the leverage points within the system.

Theme 1: **Conceptualize the system** includes a group of habits that focus on understanding the key elements that make up a system, the ways these elements interact, and the dynamic behavioral effects these interactions have on system function. For the agroecosystem scenario, the basic aspects could include identifying interactions relevant to the system such as "*the ax just made it so it (young tree) would stop growing*." In this example, the student identified a meaningful connection between two components of the system, namely the management tool (ax) and impact on tree growth. The dynamic effects include both elements changing over time and accumulations and rates of change. For example, a student might say that trees were "*spreading a lot faster*" or "*it actually takes time to burn down the trees in years instead of just outta one whole month*." The habits within this theme respond to the definition of a system (Meadows, 2008) by identifying the elements, interconnections, and purpose of the system.

Theme 2: Analyze the system and our conceptions includes a group of habits that can be split into two layers. One aspect is introspective and includes considering the assumptions and mental models we bring to assessing a system. The other aspect involves finding new ways to look at a system—either considering the bigger picture or changing the viewer's perspective within the system to gain understanding. These habits dig deep into the broader context. Student development in this systems thinking theme suggests learning at a deeper level (Tham et al., 2021). Awareness of personal and societal mental models with the ability to consider alternative mental models provides opportunities to anticipate and explain phenomena (Garrity, 2018).

Theme 3: Catalyze action consists of a group of habits that recognize that humans can be agents of change within a system and that we can engage in a continuous process of working within and through the system to bring about change and that our actions may at times be aspirational. Considering the impacts of time delays and unintended consequences aligns with the foundational goal of identifying leverage points to achieve desired outcomes in a system. The development of this group of habits particularly benefits from the gaming environment, which supports learner agency in exploring decisions and their related outcomes in a fictional environment without fear of cost or consequence (Gee, 2003).

Games as Playful Pathways to Systems Thinking games offer a playful context to explore systems thinking, leading to a variety of entry points and systems-based conversations. Student comments after playing Prairie Protector suggest that for many students the gaming experience meets the four criteria of play: flexibility, intrinsic motivation, positive affect, and non-literality (Krasnor and Pepler, 1980).

During gameplay, students were allowed to flexibly select among a variety of game-based scenarios to match their individual skill level and interest. This flexibility supported student choice and likely increased intrinsic motivation. During associated learning activities, systems thinking concepts could be flexibly incorporated, allowing for individual strengths to be built upon, and a diverse range of thinking styles to be embraced, including empathetic, time-based, and dichotomous thinking. The non-literal nature of the game allowed students to engage in low-stakes decision-making about land management. Even though students were aware that their game-based choices had no tangible impact on the real

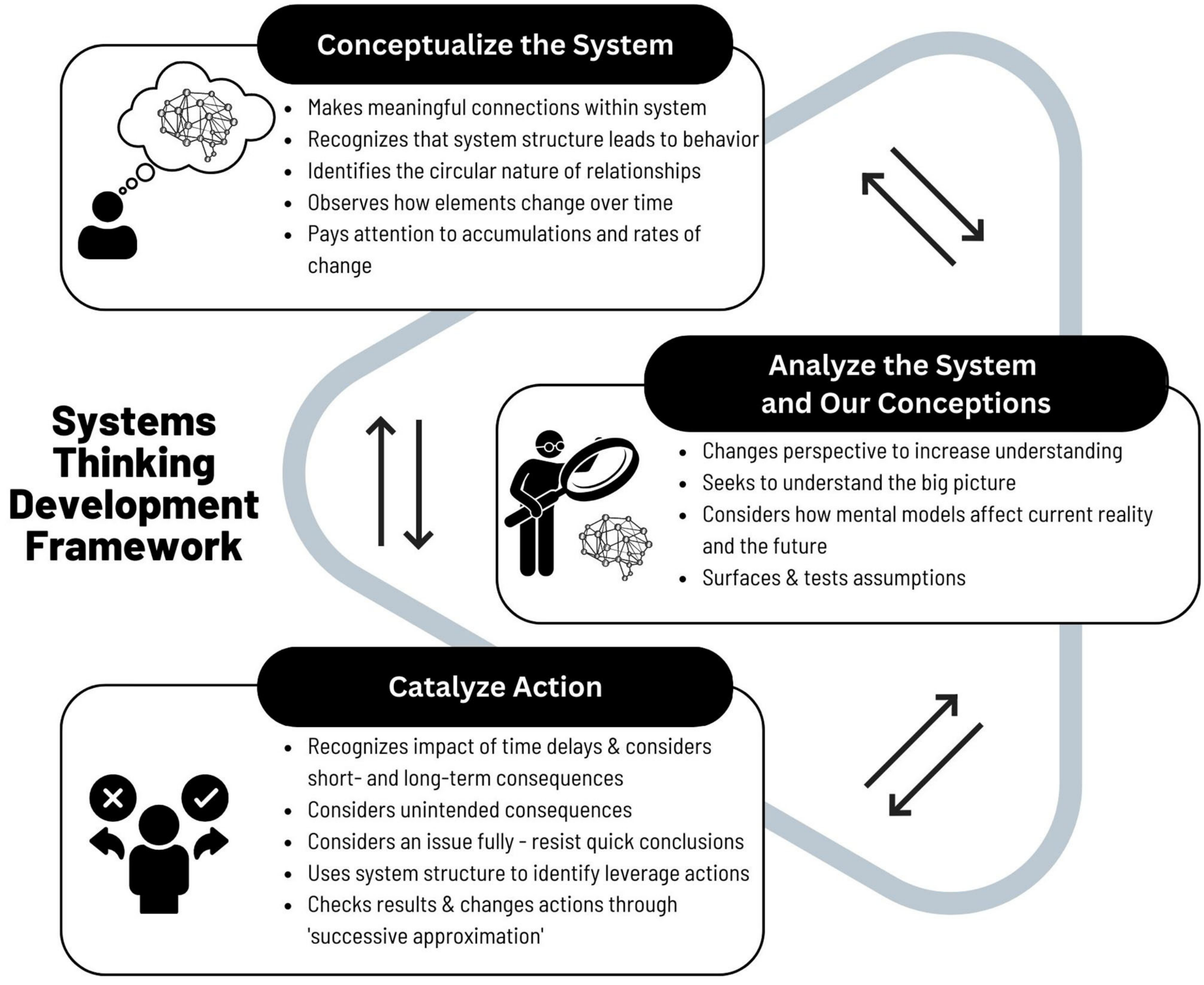

FIGURE 1
Systems thinking habits organized in a development framework. The triangular shape indicates the interconnected nature of the systems thinking habits that allow for multiple entry points. Arrows point in both directions indicating the non-sequential nature of the habits.

world, they expressed positive affect when describing gameplay as rewarding when their strategies led to winning. Even in cases where students did not win and expressed frustration, the game likely buffered negative affect because the cost of failure during gameplay is minimal compared with real-world experiences (Gee, 2003) and failure is even encouraged in gaming to aid the learning process (Kapur, 2008; Plass et al., 2015).

Social learning implications

Multiple learning theories including social constructivism (Vygotsky, 1966) and social learning theory (Bandura and Walters, 1977) view social interactions as fundamental to the learning process. Indeed, student responses indicate that social interactions related to gameplay were essential to the development of systems thinking habits. Peer-to-peer conversations focused on gameplay decisions, and these interactions provided opportunities for students to share strategies, successes, and frustration. It also allowed students to ask for help when they became confused about the game's objective or why particular actions were not successful. Through social knowledge construction (Steinkuehler and Tsaasan, 2020), during the intervention students brought together different perspectives based on their gameplay experience, forming connections through the web of systems thinking habits. Bringing the social aspect into exploring technical content is an interesting parallel to how ranchers and land managers observe and discuss their neighbors' land management decisions and outcomes across fence lines or in the local coffee shop.

Empathy transcends game to real world

Games have been shown to support players in developing empathy (Papoutsi and Drigas, 2016). Students commented on the empathy they developed through the game for both land managers and animals connected to grassland ecosystems. Students often credited the gaming experience for increasing their awareness of the labor and dedication required by land managers to care for their land. Even in the fictional game environment, student empathy for animals impacted their game-based management decisions. For example, one student stated "*Don't put an owl in a tree and make me burn it—that would destroy me*." Interestingly, students expressed empathy for woodland wildlife when destroying their tree habitat but did not express similar empathy for grassland wildlife whose grassland habitat was destroyed due to encroaching trees and land manager inaction. We assume the emotional impact of actively eliminating trees in the game directly relates to student mental models of the importance of trees in providing habitat for wildlife and perhaps a "blind spot" in overlooking the importance of grassland habitat for wildlife in prairie ecosystems.

Educational implications

This research and organized framework provide guidance for educators hoping to instill systems thinking skills in their students. Providing opportunities through games or other experiential learning experiences to spend time understanding a system, its broader context, and its inner workings are essential to student development of systems thinking skills. Relating content to personally relevant scenarios, in this case an invasive species in the student's local environment, is also key. Student conversation, both formally and informally, allows students to process complex systems and practice moving through the systems thinking habits.

Conclusion

This study investigates the development of systems thinking habits in high school students after playing Prairie Protector, an online agroecosystem game. The key takeaway from our study is that research-based educational games are a useful tool for developing systems thinking habits in high school students. After experiencing the game and supporting resources, student comments indicated evidence of all 14 Habits of a Systems Thinker. Three subgroupings of systems thinking habits emerged during the analysis of the data: Conceptualize the System, Analyze the System and Our Conceptions, and Catalyze Action. Providing simulated environments for students to interact with complex systems should be explored in additional scenarios to support student development of systems thinking skills.

Future work

We intentionally avoided discussion of the 14 Habits of a Systems Thinker with the students that participated in the focus groups out of concern that they would artificially find connections between the game and systems thinking. However, in future studies, it would be interesting to prompt student thinking by providing terminology to describe systems thinking habits. Each of the habits could be explored in an engaging and playful manner prior to playing the game to encourage students to become aware of their existing systems thinking tendencies and areas where they have room to develop as a systems thinker.

Focus group conversations supported other studies suggesting students struggle to describe the movement of carbon through biological systems such as prairie ecosystems (Zangori et al., 2017; Düsing et al., 2019). Student comments indicated beliefs that trees are better for the environment than grass, only trees release oxygen into the atmosphere, and that animals prefer to live in a wooded area over a grassland. These mental models are strongly entrenched and difficult to counteract with additional information as seen by tree-planting campaigns that have been employed across the Great Plains for over 100 years despite the negative impacts on carbon sequestration and biodiversity (Keyser et al., 2022). These beliefs are supported by prior study showing students struggle to identify mitigation strategies that address climate change impacts (Bofferding and Kloser, 2015). Further study is planned to expand the Prairie Protector game to address the alternative conceptions regarding climate impacts, carbon sequestration in grasslands, and role of trees and grass in developing animal habitats, by making these invisible system components observable to students and relevant to gameplay.

Students often expressed an interest in a more complex gaming system than what we provided through Prairie Protector. For example, students wanted the impacts of animals included in the game. They suggested adding owls and other woodland creatures to show the positive impacts of the presence of trees and cattle to show how expanded grassland allowed for increased profitability. The game design team deliberately limited the complexity of the game to improve playability. However, future iterations may add more of a storyline including animals to better connect with students.

Limitations

The participants in this study were limited to one high school in a town in central Nebraska, which limits the generalizability of the findings to students in similar scenarios. However, we believe our findings give insight into the progression of the development of systems thinking habits through game-based learning experiences.

The participants in our study were from a rural region of the state, and many indicated a connection to agriculture through friends and family. Cultural implications, including access to prairies, affinity for gaming, prior hands-on experiences in agriculture or natural resources management, and living in a rural community may have contributed to students' understanding of the Great Plains ecosystem. Future study should explore the impact of the agroecosystem-focused game on developing systems thinking abilities in urban students and other populations that may be less familiar with the prairie ecosystem.

Pre-intervention data were not collected. It is possible that students held the same beliefs and strategies prior to experiencing Prairie Protector. We worded questions during the focus group to encourage comments on how they felt the experience had impacted their understanding of invasive species and land management strategies through the lens of systems thinking.

Audio recording and transcription did not allow for the confident identification of individual student voices in the data.

Therefore, quotes were identified only by class section in the results section. During the focus group, the authors encouraged all students to participate in the conversation and contribute their perspectives.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by University of Nebraska-Lincoln Institutional Review Board. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

Funding

This study was supported by the National Science Foundation (grant number: 1639478) and the United States Department of Agriculture (grant number: M1903198).

Acknowledgments

The authors wish to thank the following for their contributions to this study. Dirac Twidwell, Dan Uden, and Dillon Fogerty for providing content expertise during game development and the game development team including Deepak Keshwani, Conner Lunn, Chloe Lehnert, Quinn Lanik, Ben Buckwalter, Mac Ozanne, Lizzie Erikson, Calvin Shafer, and Uri Herszbaum for their technical expertise and creativity that brought the Prairie Protector game to life. Participating teachers for implementing the game and associated learning activities with their agriculture education classes and participating students for providing feedback on the game and their gameplay experiences.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feduc.2023.1186270/full#supplementary-material

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