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How Can Participating in a Forest Community and Citizen Science Program Support Elementary School Students' Understanding of Socio-Ecological Systems?

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Abstract: In the face of the climate crisis, sustainability education must include a focus on understandings of socio-ecological systems (SES) and applying systems thinking (ST) skills. This study investigates a Community and Citizen Science (CCS) program designed for elementary school students to collect forest data to better understand their SES and gain insights into wildfire management in a California region recently ravaged by wildfires. We examine the development of fourth-grade students' systems thinking skills and understandings of SES, seeing these as crucial components toward fostering agency with science to support climate resilience. We found that students were capable of recognizing the intricate impacts of wildfires on interconnected human and ecological systems and demonstrated varying levels of proficiency in systems thinking skills. This place-based CCS program cultivated knowledge and skills in young learners that may contribute to better socio-ecological resilience and proactive sustainability efforts.

Keywords: Community and Citizen Science; systems thinking; socio-ecological systems; forests; environmental science agency

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1. Introduction

As education is a key component of the Sustainable Development Goals (SDGs), educational systems and programs should focus on knowledge, skills, and actions that learners can take to support sustainable human and ecological systems [1–3]. Approaching such educational programming with a socio-ecological systems (SES) lens can encourage learners to consider the complex interconnections between natural and human systems [4] and foster agency [5,6]. Community and Citizen Science (CCS) as a participatory approach to conducting scientific research and monitoring has been proposed by scholars. CCS has the potential to empower participants to take ownership of the scientific data, develop a deeper understanding of their local environments, and, ultimately, take action to make changes for sustainability [7]. For young people in schools, this potential may be even more impactful; however, empirical research is still limited. We report here on a study of a CCS program for elementary school students that aimed to deepen their knowledge of their local forests and collect data to help support forest management decisions to mitigate wildfire risk, which, in turn, can foster resilience in the SES to absorb unpredicted disturbances, like fire, while retaining the current state or phase [8–10]. As more students around the world experience the effects of climate change, such as catastrophic wildfires, their understanding of and commitment to managing resilient ecosystems becomes even more crucial.

1.1. Sustainability, SES Resilience, Systems Thinking, and Education

Scholars argue for the need to understand the dynamic relationship between socio and ecological systems to support the adaptive capacity to accommodate change and sustainable management practices [4]. Resilience is at the center of this shift to seeing socio-ecological systems (SES) as linked and nested, centering on how SES might mediate, adapt, and learn from change [10]. To achieve sustainability, understanding what practices might foster resilience understandings and thinking within SES is vital moving forward [10–12]. Walker and Salt [12] categorize three broad drivers of unsustainable practices: (1) people without choice due to extreme poverty, (2) people with intention due to unsustainable desires, and (3) non-intentional practices or those due to misinformation and ignorance. Fortunately, the third category—ignorance and misinformation—can be addressed by generating new knowledge and educating people to understand the system [3,10]. Scholars [3,12] argue that education should support knowledge development around what one needs to understand about the underlying socio-ecological systems to better inform how we manage resources to achieve sustainable goals. This is not to say the only way to combat the ignorance and misinformation is through education, such as the environmental education (EE) program; as Bhandari and Abe [13] argued, EE did not make a leap regarding change due to the issues of "poverty, population, and environmental degradation and discrimination" in the Asia-Pacific region (p. 57). Also, we acknowledge that moving from the possession of environmental knowledge to transforming it into pro-environmental behavior is a complex process that is influenced by both external factors, such as economic and sociocultural factors, and internal factors, [14]. such as attitudes and emotions [15–17]. For example, Pihkala's [17] article stated that there was evidence of positive outcomes after incorporating emotional activities in environmental educators' professional development trainings in Finland. However, we agree with Kollmuss and Agyeman [11] that knowledge can serve as a modifier of learners' intrinsic motivations, such as pro-environmental attitudes and values, and can ultimately foster learners' pro-environmental behavior. Also, we argue that there's a difference between the possession of knowledge and actively constructing new knowledge. As several scholars argue, it is important to generate both new understanding [12] and, also, new ways of thinking through education and learning [2,10] to embrace the constantly evolving and changing state of the socio-ecological system to foster resilience [10,18].

Climate change, biodiversity degradation, and energy transition are a few examples of complex socio-ecological challenges requiring sustainable development and societal transformations [19]. Scholars argue that cultural evolution can only happen when group-level collective endeavors are supported and facilitated [20]. One important process of achieving the endeavors to make societal, cultural, and behavioral changes is to foster new knowledge and new ways of thinking. By connecting students to their local SES impacted by climate change, like forests, students can connect their own knowledge to support complex scientific reasoning [21].

Environmental education (EE) and education for sustainable development (ESD) have long centered on knowledge and practices to engage in SES resilience thinking and behaviors [10]. As Krasny et al. [10] emphasize, EE and ESD support discussions "focused on creating opportunities for ongoing, responsive, and transformative learning leading to new insights and abilities, rather than on promoting more proscribed environmental behaviors" (p. 463). While there are many components to understanding SES resilience, one that is central is the role of systems thinking (ST) [22–24]. While research has shown that students as early as elementary school can engage in ST [25], there is an ongoing need to better understand how this systems thinking translates to broader connections to SES resilience and sustainability.

Despite the importance of understanding the complex SES, as well as engaging in systems thinking to make informed choices, students at all levels struggle with understanding the concepts and applying the skills to practice [26,27]. Particularly, students often narrowly focus on superficial components of the systems rather than investigating the underlying mechanisms [22]. Several studies partially focused on teaching socio-ecological systems to students, from elementary students to college students, through a model-based approach that was content-driven [24,28,29]. As global changes become an urgent issue that we are facing together, it is not scientists but all humans, including young people, who need to regard themselves as capable stakeholders to address the urgent global climate change disaster. To do so, we need to go beyond "textbook" scientific knowledge and support students' adaptive capacity to embrace change through participation, relevance, and interconnectedness when engaging learners in climate and environmental education [30,31].

1.2. Engage Students in Community and Citizen Science as a Participatory Approach to Achieve Sustainable Development Goals

Though Citizen Science is a term that is more widely used and recognized in the field, we agree with Fan and Chen [32] that Citizen Science bears multifaceted, politically loaded controversies that might exclude and deter a certain group of people from participating in the CS program, especially in East Asia, with an array of multiple political models. Instead, we use the term Community and Citizen Science (CCS), with the intent of de-emphasizing the problematic aspect of the term "citizen" and centralizing the local community-driven effort. CCS includes participatory approaches to research and monitoring primarily driven by scientists (often called Citizen Science) and, also, includes community-driven endeavors (often called Community Science). CCS projects are co-created with members of the community and focus on community needs and interests; they incorporate local knowledge and expertise and community members are involved in defining research questions and determining how findings are generated and disseminated [14]. As scholars explore the educational benefits of CCS for science learning [33,34], we find there are many overlapping activities between EE or ESD and Community and Citizen Science (CCS). Lorke et al. [34] identified some key activities that both EE and CCS have in common, specifically when learners participate in exploring, observing, and/or identifying. However, Lorke et al. [35] argued that what differentiates CCS from EE programs is when participants are engaged in recording data to be used for scientific research, especially when the data collected by participants are used by scientists who are collaborators and partners in the CCS program.

Through engaging non-professionals in authentic scientific research processes, de Sherbinin et al. [36] argue that Citizen Science and other participatory approaches to science can serve as critical channels for broadening participation in scientific research and promoting equitable access to scientific data. Citizen Science and related approaches can allow scientists to collect larger volumes of data across a wide geographical area, which could otherwise be an impossible task [37], and simultaneously open up opportunities for laypersons to directly engage with research to advance scientific knowledge [38], in formal education settings [39] as well as informal settings [5]. However, many scholars argue that to realize the potential of CCS and strengthen the reciprocal relationship between scientists and citizens, CCS programs must go beyond data collection and engage participants in the full process of generating scientific knowledge.

Student participation in CCS can be a highly impactful experience. However, special attention must be paid to the design of CCS programs to provide opportunities for students to be involved in and position themselves as actors in the many steps of the scientific process [40]. Previous research has explored this to understand better what might enable or constrain student participation [41–44]. Together, these authors found three factors to be important: (1) contextual factors, like facilitators and available roles [41]; (2) setting norms and cultures (i.e., how are participants positioned) [42]; and (3) clear communication of program goals and objectives [43]. Well-designed programs have been found to impact students' development of science identity, self-efficacy, and interest [42,45], as well as learning and agency [5].

As we look at the intersection of CCS and students' understandings of SES resilience, agency provides a valuable lens into how CCS practices might support learning and the development of behaviors that contribute to SES resilience [5]. We draw our understanding of agency from cultural anthropology and sociology, seeing individual, or in this case, student agency, as students' directed actions towards personal and/or social, cultural large-to-small scale goals and/or values [21,46]. We further narrow this definition, drawing from Basu et al.'s [47] concept of critical science agency to explore the role that environmental science agency (ESA) plays in SES resilience development [5]. ESA provides a lens into how "young people use science learning and participation as a foundation for action related to environmental sustainability" [5] (p. 67). ESA, overall, includes the development of three aspects: (1) environmental science content knowledge and skills, (2) self-identification with roles within environmental science, and (3) the agency to apply environmental scientific findings to enact change in their lives, their communities, or the environment [5]. However, in this paper, we focus largely on how SES resilience and ST, as some of the core environmental science content knowledge and skills, emerge through CCS practices and how they might mediate and support each other.

1.3. Research Problem and Aims

Many in the conservation and sustainability fields believe that educating students will help us to find solutions to our environmental problems, now and into the future. However, we still struggle to understand how and when students develop rich and complex systems thinking about SES issues and apply their understanding for resilience. As climate change rapidly affects our socio-ecological systems, increasing the intensity of natural disasters, like wildfires, CCS may offer a way for young people to concretely contribute to efforts addressing the climate crisis and gain a foundation for making change and developing agency with environmental science. In this study, we ask the overarching question: what science learning happens when students collect forest data to inform wildfire management, a locally relevant socio-ecological issue? To guide the investigation, we ask the following sub-questions:

(1) What systems thinking skills and understandings of socio-ecological systems do elementary school students develop while participating in a forest-monitoring CCS program;
(2) What types of CCS participation might connect to elementary school students' development of their systems thinking and socio-ecological thinking?

2. Analytical Framework

To answer our research questions, we construct an analytical framework by synthesizing the literature to define (1) systems thinking skills, (2) understandings of socio-ecological systems, and (3) ways to participate in the Community and Citizen Science program. The definition for each element in the framework is used to create the coding scheme for the data analysis and to help structure the findings.

2.1. Systems Thinking

ST deviates from the disciplinary nature of modern education and instead looks at the interactions between "system components and patterns that emerge from those interactions" [48] (p. A), which helps students develop higher-order thinking skills that are important for understanding and addressing complex, interdisciplinary problems, like climate change [48]. ST provides, as described by Gray et al. [24], three primary benefits: (1) the ability to identify interactions across pieces of the systems as well as dynamics of the whole system; (2) critical thinking development to support decision making within the system; and (3) multidisciplinary reasoning across both the social and ecological systems. Systems thinking is defined as "a school of thought that focuses on recognizing the interconnections between the parts of a system and then synthesizes them into a unified view of the whole" [25] (p. 520). As a useful way of understanding complex systems, scholars argued for the need to introduce this way of thinking to young students as well. Assaraf and Orion [25] conducted a study to understand whether elementary school students were able to perform systems thinking skills focused on the hydro-cycle.

To operationalize the systems thinking, they broke systems thinking into five components: (1) the ability to identify the components of a system and processes within the system; (2) the ability to identify simple relationships among the system's components; (3) the ability to identify dynamic relationships within the system; (4) the ability to organize the systems' components and processes within a framework of relationships; (5) the ability to understand the cyclic nature of systems. Though Assaraf and Orion's [25] five-component system did not articulate the hierarchy of each component, it is clear that identifying the components of a system is the most entry-level element of applying the systems thinking skill. Similar but different from Assaraf and Orion's study, Danish et al.'s [22] study simplified the components and adopted the "Components-Mechanisms-Phenomena" (CMP) framework to conceptualize systems thinking. Components are the superficial structures that consist of the system and the mechanisms explain how different components interact to produce a particular result. As the highest level of systems thinking, phenomena are observable events within the system [22].

2.2. Understandings of Socio-Ecological Systems

Krasny et al. [10] defined SES resilience as, "the interplay between disturbance and reorganisation, contextualised by system dynamics and cross-scale interactions, and focusing on adaptive capacity, learning, and innovation". This definition aligns with Gray et al.'s [24] study, which categorized the hierarchical components of socio-ecological systems thinking. In Gray et al.'s framework, they listed four components of SES thinking to assess undergraduate students' thinking competence structure (identifying system components and understanding the interconnectedness), function (evaluating the system dynamics and cross-scale interactions within SES), leverage points (generating multiple scenarios to inform a decision-making process around human and natural systems), and trade-offs (understanding the nested and multiple spatial and temporal natures of the systems, recognizing the cross-scale dynamics, and analyzing the trade-offs of a management decision). Given the different knowledge and skill development stages between undergraduate students and elementary school students, we adopted Gray and colleagues' framework loosely and used it as an indicator of defining SES thinking. In this study, we define an understanding of SES as the comprehension of the cycling nature of the socio-ecological system and the intertwined human and natural systems around them [25], particularly how human behaviors can affect the ecological system, how the ecological system can impact human life, and how human society can actively intervene to support forest health.

2.3. Ways to Participate in the Community and Citizen Science Programs

Given the variety and diversity of scope of CCS projects, there are many ways that individuals may be involved. When we look at CCS projects for young people, Lorke et al. [35] found that there were five common steps that students used when participating in biological data collection: exploring (defined as exploring and actively searching the habitat to discover organisms, potentially involving tools such as binoculars or nets), observing (defined as observing organisms in nature, using one's senses to find and study organisms), identifying (defined as putting a name to the organism (e.g., taxon or species) that was observed), documenting (defined as documenting the observations by generating evidence of the observation, such as a photograph or writing on a datasheet), and recording (defined as making the documented observation available for biodiversity monitoring or research purposes, ideally providing the who, when, where and what aspects of a biological record) [35,40,49]. Lorke et al. [35] found that student participants often do not participate in all the steps and that the more common types of participation were exploring, observing, and identifying. Understanding how students participate in CCS projects can give us insight into their level of engagement, interest, understanding of the project goals, and contributions. Therefore, we use these categories for student participation in CCS activities in the Our Forests program to understand what types of participation students were engaging in during different features of the program. This also can help us understand what type of participation might be linked to the emergence of other factors, like ESA or SES resilience.

3. Materials and Methods

3.1. Program Context/Description

Historic fire suppression in the western United States has led to higher fuel loading, which, in the long run, has led to changes in forest structure and frequent high-severity fires [50]. As a result, and alongside the effects of climate change, rural and semi-rural communities situated in forest ecosystems need to mitigate the risk of these catastrophic, high-severity wildfires. In this context, the Our Forests program was developed as a collaborative educational CCS project designed for 3rd- to 5th-grade students, led by a watershed organization, forest managers, and educational researchers, to monitor their local forests through data collection about forest health to help mitigate wildfire risk. Each grade level had a different focus, with some topics in common, which, taken together, constituted a complete set of data about each forested plot for the forest managers (Table 1). The program, across all grade levels, had an emphasis on how the forest and human systems were intertwined, with students learning about practices such as cultural and prescribed burns and the causes and impacts of fire in human and forest communities. Furthermore, the Our Forests program was developed around three design features building from previous research on youth-focused CCS [5,51]: (1) youth collect place-relevant environmental data, (2) youth engage in facilitated meaning-making with their own data embedded in larger data sets, and (3) youth share findings and interact with community stakeholders.

Table 1. Program focus by grade level.

Grade Level	Topics Covered
All Grades	Conceptual models of forest health, Forest stand density (trees per acre), Forest layers (understory, overstory)
3rd Grade	Tree Recruitment (counting mature trees, saplings, seedlings, and seeds)
4th Grade	Tree and plant species diversity
5th Grade	Forest fuels (dead and downed woody debris)

This paper focuses on the learning outcomes and participation of the fourth-grade students participating in the Our Forests program. Students in the 4th grade collected data over 4 all-day field trips, “forest investigations,” at a nearby or on-campus forest site (see Table 2) and one classroom-based session, with each investigation focusing on a different goal. During these forest investigations, students used various tools, like quadrats, tree species identification guides, and Biltmore sticks, to collect understory plant diversity and abundance data and tree stand density data. Students learned about how to analyze tables and graphs to understand forest and fire history with data from Yosemite National Park as a model and, then, were guided through analysis involving creating and analyzing data tables and graphs to make sense of their own forest density and health. Students then shared their findings with a local forest manager paired with each class, referred to as community partners (CPs). These CPs were forest scientists and technicians who worked for local governmental or non-profit agencies and were responsible for managing the forested site the students studied. At a final “share-out” event, students shared various information with the CP, including temperature data in the shade and sun; abundance and diversity data on understory plants; the importance of native plants; the presence and impact of invasive species; photographs of their plots; the effects of fire on the forest; reasons why they found particular types of plants in our plots; and recommendations on how they can better take care of their forest.

Table 2. Fourth-grade field investigation goals and activities.

Field Investigation Lesson	Topics Covered
Forest Investigation 1	• Students made initial conceptual models of forest health. • Students learned about making and recording accurate measurements by collecting air temperature, soil temperature, and soil moisture data in a forest plot using scientific tools. • Students used bar graphs to visualize their data at the end of the day.
Forest Investigation 2	• Students generated a map of the study site that included their own interpretation of the site and set physical characteristics. • Students gained a working definition of "disturbance" in forest ecosystems. • Students practiced using visual representations of data to support the communication of findings.
Forest Investigation 3 (Classroom-based)	• Students explored the benefits of forest fires on the landscape and how forest management can help prevent destructive fires. • Students learned and practiced data analysis and interpretation skills using Yosemite National Park data. • Students watched a video of their forest manager Community Partner and wrote letters to their CP around questions they had about forest health.
Forest Investigation 4	• Students collected forestry data, including identifying tree species, measuring tree diameter, counting trees, and calculating stand density. • Students described patterns and compared several plots' data.
Forest Investigation 5	• Students learned more about the site history of their forest plot and then compiled their data and observations of plant diversity and abundance, the site history, and the forest health model to outline their findings and recommendations to share with their Community Partner
Community Partner Share-Out	• Students shared their findings with their Community Partner through in-person slide presentations and letters.

3.2. Participants and Data Collection Methods

We studied 3 of the 4th-grade classes (students were approximately 9 years old) that participated in the year-long program. The three teachers and classes were recruited by the watershed organization (whose staff served as educators during the program) and the school district, whose administrators sent information to their teachers to recruit participating schools and teachers. We then hosted an informational meeting for any teacher who might be interested in participating and all those teachers who wanted to participate became part of the program. Within the pool of all participating classes, the educational researchers then first observed all classes on the first field trip and selected 10 classes as focal classes based on criteria such as the number of consenting students and site access. Within each class, we collaborated with their teacher to select four to six students per class for a total of fourteen focal students based on consent and selection criteria for a range of students, with respect to their gender, performance in school based on grades, and their responses to a short survey regarding initial interest in and confidence in conducting science, being in nature, and experiencing outdoors. While no demographic data were collected for the focal students, all classes were from a rural county, with 60% of students receiving free and reduced lunch services. All fourteen focal students experienced catastrophic wildfires and evacuations living in the area before participating in the program.

For these focal students, we collected observational field notes of student participation in all five field investigations and post-program semi-structured interviews. During each field investigation, one researcher-observer collected ethnographic fieldnotes, audio recordings, and photographs, taking an "observer as participant approach" [52]. To document student participation, the observers followed focal students for the duration of the field investigation to capture student actions/interactions. To maximize the number of focal student observations, field observations lasted 20 min for each focal student and rotated so that each focal student was observed multiple times throughout the day (similar to Lorke et al. [35]). While this means some student participation in the CCS activities that occurred outside of our observation intervals may have been missed, our methods aimed to capture as much in-depth observation of any individual focal student as possible. For each class, the observer wrote one set of observational field notes for the class that included all four to six focal students.

Semi-structured photo-elicitation interviews with each focal student were conducted after the last field observation of the Community Partner share-outs. The interviews were conducted in person at the focal student's school, were audio recorded, and lasted approximately 30 min. Interviews followed a semi-structured protocol that aimed to capture (1) the overall narrative from students about their experiences with the project, (2) the impact and reflections of CCS program design features/activities with photo prompts taken during field day observations, and (3) evidence of learning and the development of ESA with respect to participation and the design features.

3.3. Data Analysis Methods

We analyzed the observational field notes and post-program semi-structured interviews from fourteen focal students (ages 9–10). Our qualitative analysis of field notes and interviews followed the Miles et al. (2014) two-cycle analysis method-applying codes for the first cycle and identifying patterns for the second cycle. We first imported all the data into Dedoose 9.0.107 (a qualitative data analysis software) to prepare the data analysis [53]. Then, we created one dataset for each focal student as one case, which included five field observational notes and one interview transcript. In the first cycle, we first coded one dataset from one focal student using the codebook structured under three categories (see Table 3): (1) focal students' methods of participation in the CCS program, according to the types identified by [35,40], which include exploring and discovering, identifying, observing, documenting, and recording; (2) the aspect of environmental science agency identified by Ballard et al. [5] that focuses on the knowledge, skills, and norms of environmental science. To ensure validity and reliability, four researchers kept reflection journals to document individual coding processes, including confusions and questions. We then collaboratively reflected on the coding process to check the researchers' biases and discussed the disparities and similarities in the coding process to establish a shared understanding—the size of a codable block and the definitions of codes. Then, each coded three to five datasets, checking intermittently to ensure agreement. Each researcher also kept reflection journals to document the patterns observed after coding each dataset and then discussed, as a group, the overall patterns observed.

In the second round of coding, we further identified the patterns to answer the second research question. We coded the data sets for both "socio-ecological systems" and included evidence of excerpts that displayed the focal students' systems thinking ability using an analytical framework adapted from two prior studies' work on systems thinking—Danish et al.'s work [22] and Assarf and Orion's [25] work described in the Analytical Framework in Section 2. We examined the co-occurrences in Dedoose between "engaging with complex socio-ecological systems" and/or "systems thinking," as well as the 5 types of participation in CCS activities. We found a rich co-occurrence between systems thinking and the types of participation but not between SES and participation. To ensure the validity, we triangulated amongst the observational field notes and interview data for each student to examine how their whole story of participation may clearly relate to their perspectives; we could see what each student actually completed and participated in and what they talked about in their interviews related to their understandings of SES resilience.

Table 3. Codebook for fieldnotes and interviews analyzing Environmental Science Agency 1—disciplinary knowledge and scientific knowledge and practice regarding systems thinking and understandings of socio-ecological systems.

Codes	Definition	Examples
Systems Thinking [22,25]	• **Identify the components** of a system and processes within the system.	**Ace** [1]: "*For* [2] *(whether) the forest is healthy, I think it's yes because there is a lot of wildlife that I can hear and . . .there's just the right amount of trees. . .. I think the forest density is good*".
	• **Identify the mechanism** (simple or dynamic) of a system—how different components of a system interact with each other to present system characteristics.	**Colby**: "*. . . fires can help by making small fires so they can burn down overgrown [plants], and then [the fire is] not too big. . . If there's no room for other things to grow, it [fire] can help our forest by burning the trees, the stuff like the plants that we don't need, and all the undergrowth. Then..animals can hunt*".
	• **Observe the phenomena** as the result of mechanisms within the system.	**Jack**: "*. . .if the fire is big, like, really big and destroying more, like thousands of trees, then we should stop it. But if it's medium and it's killing down some dense areas, then I say we should keep it*".
Understanding of how Socio-Ecological Systems relates to Forest Ecology [24,25,44]	Understanding the **cyclical nature of the socio-ecological system.** It involves young people observing, considering, and acting within intertwined human and natural systems around them. Instances might include: • Consider how disturbances, such as human behaviors and management, affect ecological systems, such as biodiversity, fire behaviors, etc.	**Chase**: "*Like, it's actually like people aren't allowed to cut down redwood without a whole license without asking the whole community if they could cut down. At least one, at least if you like to cut down like one, without asking, without a license? You're gonna get at least a $10,000 fine*".
	• Consider how the ecosystem impacts human life or the place they (or their family members/friends) live.	Ella: "*helping our forest is . . . our priority. . . If we keep on helping places around us, our surroundings, we could get better*".
	• Consider how human society can choose to actively intervene and manage to make the forest healthier.	**Carl**: "*Controlled fires can help with fires happening. And, um, the dead trees, if you moved some of those (dead trees) out, that could help not have big fires*". **Finn**: "*I learned that some forest fires are beneficial and there are cultural burns that some people do. When they do that they obviously have a hose nearby in case it gets out of hand that they need to put it out*".

[1] Pseudonyms are used for instructors and focal students to protect their identity. [2] We used italics to indicate students quotes.

4. Results

Here, we report the ways in which students demonstrated one aspect of environmental science agency—developing disciplinary knowledge and practices specifically around systems thinking and understandings of socio-ecological systems—as a result of engaging in a CCS program collecting forest-monitoring data to inform forest management.

As an overview (see Table 4 for summary), in examining our first sub-research question (What systems thinking skills and understandings of socio-ecological systems do elementary school students develop while participating in a forest-monitoring CCS program?), we adopted the systems thinking and socio-ecological system analytical frameworks as coding schemes for analysis. We found that all 14 focal students demonstrated some aspects of systems thinking (ST) skills and 12 of them also demonstrated various levels of understanding of socio-ecological systems (SES). In answering the second sub-question (What types of CCS participation and curricular activities supported elementary school students' development of their systems thinking and socio-ecological thinking?) after analyzing the data through the CCS participation framework, we found that the CCS practices of identifying and observing were particularly co-occurring with students demonstrating systems thinking skills and understandings of socio-ecological systems. In the following sections, we report the details of these findings.

Table 4. Summary of key findings.

Research Questions	Key Findings
RQ 1: *What systems thinking skills and understandings of socio-ecological systems do elementary school students develop while participating in a forest-monitoring CCS program?*	• All focal students demonstrated some aspects of systems thinking (ST) skills. • Twelve students (86%) also demonstrated various levels of understanding of socio-ecological systems (SES). • Qualitative analysis revealed a strong link between the development of systems thinking skills and the understanding of the socio-ecological systems.
RQ 2: *What types of CCS participation might connect to elementary school students' development of their systems thinking and socio-ecological thinking?*	The CCS practices of identifying and observing were particularly co-occurring with students demonstrating systems thinking skills and understandings of socio-ecological systems.

4.1. Systems Thinking

In our analysis of the evidence of students demonstrating systems thinking skills as part of ESA development, we found that all fourteen focal students demonstrated an understanding of at least one of the several aspects of systems thinking, including various components and mechanisms that occurred within the ecological system, in this case, the forest ecosystem, particularly with respect to fire. We identified two themes in the ways students demonstrated or explained their thinking about systems thinking: (1) what makes up a healthy forest; (2) fire can be beneficial to support forest health.

4.1.1. The Components of a Healthy Forest Ecosystem

As described above, a driving question of the program was asking students to consider what constitutes a healthy forest in order to provide context and a foundation for understanding why and how they were collecting forest data. In that context, nine students discussed what they saw as important components of the system to support a healthy forest. They listed multiple components that they saw as crucial for a healthy forest and explained how they fit into the forest ecosystem, including biotic and/or abiotic factors. For example, when asked "what makes a forest healthy", Lester explained, "*Well, what makes the forest healthy is. . . it has to be a place that really gets rained on a lot, but not too much. . . And you have to have an open space for other plants to grow, so they can get as much sunlight and water as they need. . . And you also need bees, or something to pollinate flowers and other plants*". In this excerpt, Lester described the specific components they thought were important for a healthy forest ecosystem and the relationships between them, including pollination.

Another way students explained the components and relationships in a healthy forest ecosystem focused on the relationship between forest stand density and biodiversity. In varying ways, they each described that forests with a lower stand density, or number of trees per unit area, can allow for more biodiversity or those with a higher stand density can discourage biodiversity. We saw this demonstrated during the fifth forest investigation; when another student reflected that different spots in the forest had different tree densities, Zane responded by arguing, ". . .*but there was more diversity in Plot 1*". The educator followed up and asked whether there was a correlation between the tree density and the diversity of other plants and animals; Zane explained that even though Plot 1 had a lower stand density, it had higher diversity since lower tree density means more space in the area for different kinds of trees to grow. Lastly, some students considered invasive species as a component of the system that has negative consequences for the other parts of the system. For example, Finn mentioned in the interview that the program "*helped me to understand which plants are invasive and which plants I should look out for. . .. and which plants take up a lot* *more space in there, and sort of invasive to other endangered plants*". In this excerpt, Finn first identified different types of plants (invasive and endangered), and provided rationale on the simple relationship between two components.

4.1.2. Fire as an Important Mechanism of Supporting a Healthy Forest Ecosystem

The second and most common way that we saw students express systems thinking skills was in their explanations of the role of fire in the ecosystem as a driving mechanism in the system. Overall, nine focal students started developing an understanding that fire as a disturbance can have a positive effect on the forest ecosystems' health for various reasons, an important finding in light of the fact that all the students experienced evacuations and some experienced loss due to wildfires in their area recently. Those students described the role of fires in increasing biodiversity and reducing competition depending on the size of the fire. They discussed aspects of the forest stand development driven by fire, such as regeneration ability, tree mortality, and tree age. While these concepts were generally learning goals for the Our Forests program, we highlight here that students particularly made meaning about how characteristics of the fire as a driving mechanism affected other components of the system.

Several focal students mentioned the relationships between fire and biodiversity, especially that fire can help reduce invasive species like scotch broom (*Cytisus scoparius*). For example, when asked about fire suppression, Finn argued that, since scotch broom is more flammable than native plants, fire could create space for desirable plants to grow: "*I would tell them that some (fires) are beneficial to get rid of plants . . . as in like some plants, . . . the numbers are going down because of . . . invasive species such as scotch broom. . . (The) oils in it. . . It can catch fire very easily. . ..*". Finn further explained that "*if we suppress the fire, like I keep saying. . . there would be a lot of invasive plants that would just take over all the other plants and then we would only see the invasive species and none of the other species*". In this excerpt, Finn demonstrates an understanding of how fire as a mechanism in the system can help burn down flammable invasive species to leave space for desirable (native) plants to grow in the forest.

One of the most predominant relationships students mentioned was between fire and tree density. From the observations and interviews, we found that some students described the interactions simply, such as during the fifth field investigation; when asked in a group discussion, "*How could forest density affect the resources of our forest*?", Zane replied, "*since (there are) more plants, there's more fire hazard,*" and Jason answered, "*because there's a dense forest, there's a high fire risk*". Though lacking explanations, both Zane and Jason stated that high forest density could become a fire hazard. Other students explained more nuanced systems thinking, for example, in the activity when each student shared their data and findings about their plot with students from other plots, Chase explained that, "*density is good but density helps fires spread. If the underbrush [is dense], it can spread fire. We don't know if density is good or bad. It's probably both*". In this case, Chase identified that different attributes of the understory vegetation (their term "underbrush", a mixture of shrubs and understory grass) could influence fire behaviors.

Another way in which students expressed systems thinking around fire is their understanding that wildfire does not have equal impacts on all forests. They shared that the impact of wildfire depends on the size of the fire. When the interviewer asked what Zane thought about forest fires, Zane shared, "*I know that if it's too big it would be not really good, but if you had a small one, you let it go through, it'd stop the big one from happening. Because they would burn each other out*". These explanations reflect students' understandings of what factors within the system influence whether or not it can be a destructive disturbance in the forest ecosystem.

Many focal students also described the fire as a mechanism that influences tree regeneration ability and forest stand structure. For example, during the interview, Julio explained that "*forest fire is. . .not just a bad thing, it's actually good because some trees, they need forest fire, like to drop their acorns and for the acorns to open up. And to clear the brush. And* *it's not just a destructive thing*". In this case, they saw fire as being important to allow trees to reproduce. Chase, in another case, made connections between fire behavior and tree mortality, saying, "*If, if it's (a tree) dead, they are easier to catch on fire, but if it's alive, if it has a lot of green in the middle, then that's probably just like first born, and those green parts have tons of moisture so they're super hard to light on fire*". When asked what data Chase would like to collect to investigate the forest health, they mentioned tree age, because, "*. . . if we could tell the age of them, and how long they could last and how strong they could withstand the fire. If one was like, about 300 years old, that would be like. . . You can count the rings. . .That tree would be. . . probably the hardest one, but it could (burn)..*". In these two excerpts, Chase explained in detail how fire as a driving mechanism can affect the components of the system and, potentially, its resilience to fire.

4.2. Understanding and/or Engaging with Socio-Ecological Systems

As evidence of the knowledge gained importance for the development of ESA, we found that twelve out of the fourteen focal students gained a clear understanding of the ways the human and ecological systems influenced each other in their local forests; although, the nuance or complexity of the students' articulation of their understanding varied. Among those who discussed aspects of SES, we identified three key ways that students explained how human systems impact forest systems and the impacts on humans of forest wildfires.

The first category we heard students explain was about the interconnectedness between humans and the forests, including the value and responsibility humans have to protect the forest. In the interview, Ella described their lived experience to explain this interconnectedness: "*If they're [fires] really big, then they can cause, like, really bad things to happen to the earth. . .. Recently, there was a fire around where my dad lives, and everybody had to evacuate. There was police officers by the roads that were blocking them off. So I think that that was a pretty bad wildfire that happened from too much [forest] density*". Here, Ella showed her understanding of the role that fire played in mediating between the social and ecological systems.

The second category of the students' understandings of SES and wildfire focused on how disturbances from human behaviors and management affect ecological systems. One aspect of this was to describe the negative impact human behaviors can have on forest ecosystems. During the third forest investigation that introduced forest history and data analysis, Zane offered their own lived experiences in a forested landscape as part of their explanation of why a graph showed tree density changing over a particular time, saying, "between 2000 and 2020 where there's a big drop (in the graph of tree density), it's because [the local energy company] cutting down trees on power lines. I remember lots of power outages". Zane's comment connected how human actions to support social systems (in this case, to maintain electrical lines) affected the ecological system (in this case, tree density). Furthermore, they situated themselves and their personal experiences within that system—living in a rural, forested region, there are many planned power outages to mitigate wildfire risk. Zane saw individual human behaviors as impacting the system.

The other aspect of the second category is about how *human society can choose to actively intervene and manage to make the forest healthier*. In several cases, students suggested management actions that their community partners and the community can take to make the forest healthier (and presumably more resilient to fire). For example, many focal students suggested prescribed fire/controlled burns or cultural burns (indigenous practice of the "purposeful use of fire by a cultural group (e.g., family unit, Tribe, clan/moiety, society for a variety of purposes and outcomes" [54] (p. 2)) to promote forest health. In the last field investigation, Julio recommended controlled burns for their forest site because "*. . .plants need fire. It's efficient and plants need fire. It takes care of the leaf litter*". Similarly, when asked about the role fire plays in the forest that people should know about, Emma referred to cultural burning as a recommendation: "*Cultural burning would help open up the forest more so we could plant new trees and help them grow*". Alternatively, Graham recommended their community and the community partner to clear out the dead trees manually to reduce fire hazards: "*Yes. About forest fires, they need to chop down a lot of dead trees or this forest could go down with a big fire*". Everlee referred to the tree density data they collected in the fourth field investigation and articulated their thoughts on the forest management approach: "*My thought was (our plot was) super dense, and then some of the other plots had almost no trees. So . . . we could've thinned that out maybe a little bit because there was one giant fallen tree there, too. So then we could've planted more in the other plots".* In these examples, focal students not only demonstrated their understanding of the interaction between biotic and abiotic resources, forest growth, and fire but they connected these immediately with how local human forest management can take actions to positively influence the system to be more resilient or healthy, as they understood it.

4.3. The Connection between ST and SES

We also examined the relationship between students' demonstrated systems thinking skills and their understandings of social-ecological systems; we then examined the relationship between the two in order to completely answer our first research question. We found that thirteen out of fourteen focal students demonstrated both SES and systems thinking skills, by comparing student comments and observed behaviors, and found some exciting ways students connected the two.

After comparing excerpts from ST and SES, we found four out of thirteen students, who demonstrated both ST and SES, started developing fairly nuanced ways of connecting the two and made sophisticated suggestions and trade-offs for managing forested ecosystems. When discussing the data we coded as both systems thinking and SES, focal students discussed the dynamic relationship between social and ecological systems (how human and ecological systems can influence or support each other) and several students also considered the tensions and costs or trade-offs within some decisions or actions within the SES. This type of consideration was regarded as the most sophisticated type of systems thinking within the socio-ecological context [24]. We see this specifically reflected in several of the facts presented by the majority of focal students, who recommended the use of controlled burns (prescribed fire) or cultural burns to thin out the forest and mitigate catastrophic wildfires and who further described some potential tensions or trade-offs. For example, while Chase suggested that the controlled burn method was beneficial to promote forest health and should be adopted, they also shared that the trade-off of a controlled burn in the forest is air pollution, saying, "*The thing is that it leaves a ton of ashes on the ground which could also lead to ash being in the air if it blows around*". He then took a step further and connected how air pollution could affect human health: "*if the ash got in there [local river], it would just make it if you accidentally sucked in even a little water, you would probably have to go to the hospital to get all that out*". In this excerpt, Chase brought in how the human health system might be affected by the ashes produced by the controlled burns. At that moment, Chase critically evaluated the potential costs of using controlled burns to human health, which not only showed their understanding of the interconnectedness of the two systems but also the trade-offs of the forest management approach. In another case, when asked about whether they learned anything about forest fires, Colby responded, "*Oh yeah, like forest fires and controlled fires and cultural burns*"; explaining further, the researcher prompted Colby to elaborate and Colby said, "*. . . That forest fires can help, make small fires so they can burn down. . . the, uh, so then, overgrown. . . and like, and then, so, it's not too big. And then like, there's no room for other things to grow*". Though students did not use the term resilience, their responses described how controlled fires could be disruptions that establish resilience in the socio-ecological system but also have trade-offs.

4.4. Participation in Community and Citizen Science Links to Systems Thinking and Understanding Socio-Ecological Systems

To answer our second research question, we analyzed the co-occurrence of the five types of participation in the CCS activities (see Table 3) focal students were engaged in when they were also demonstrating systems thinking skills and/or understandings of socio-ecological systems across all fourteen focal students' individual datasets. We found that while not all students engaged in all the CCS activities, nine students engaged in documenting the data, six students participated in recording data, and two students showed evidence of exploring; nearly all students engaged in observing (*n* = 13) and identifying (*n* = 13) and these were two main ways students participated in the CCS activities while also demonstrating either ST and/or SES.

4.4.1. Participation in Community and Citizen Science and Systems Thinking Skills

We found that when students engaged in making explicit and detailed observations about the forest, this elicited conversations around the different components of the system and how they interacted. For example, when Lester discussed how animals and insects were an integral part of a healthy forest ecosystem (see Section 4.1.1), they also described (when prompted) how they used those components to evaluate the forest they observed, stating, "*there were some parts that were really cramped, and some parts that were a good open space*", and provided observational evidence of insects, stating, "*We did see that some animals were moving in. . .. I'm not sure if it was a bunch of bees or a bunch of wasps we saw, it might be bees*". In this case, Lester used observational evidence and the components of a healthy forest to evaluate their local forest system.

In one case, we also saw the ways in which making careful observations about the forests not only facilitated students' thinking about their own local forest ecosystem but also comparisons with other forests and management actions that might impact their forest. Ella shared that "*. . .we saw in plot 3, that we were seeing diseases. I'm pretty sure it was the Cedar, it get dark like you got struck in lightning, when it doesn't have enough space . . .it needs because the water is being taken by the other trees also, so . . . it's not getting enough water*". Then, Ella shared their management suggestion: "*I would love to grow some trees in the less dense areas, because that could help nutrition for the forest".* Instead of stopping here, they continued with what phenomena they observed in their trip to Maui to back up her suggestion: "*I went to Maui recently, and I saw the 100-year-old mango tree and I thought, wow, that must have had a lot of fertilizer and stuff like that. But I realized there are a lot of other plants around it, and I kind of wondered, how come it's so dense if it lasted 100 years? That made me really wonder*". In this case, Ella drew on their observations during the Our Forests program and their lived experience on their Maui trip and added this new information to their own conceptual model of the forest.

We also found that when focal students learned to *identify* forest plant species, giving names to what they observed, they were then able to connect and articulate how the pieces of the system fit together. Julio, for example, identified how the bark beetle can infect trees and impact forest health: "*The bark beetles, if there is a drought they would infect that tree, and then the tree next to it, and then that tree, and that tree*". Julio discussed the importance of monitoring the forest to make the forest healthy, sharing that, "*we were taking data on the trees and about thinning. Well, for our plot, mostly thinning, the space on the ground and the width of the trees,*" and explaining that this monitoring can support the forest health because they were evaluating the conditions that could cause disease: "*we had these little black fungus mold on the Cedar trees and somebody said that that was because the Cedar trees, they didn't have enough sunlight and they were too grouped together.* " In both cases, identifying the species—bark beetles and black fungus mold on Cedars—allowed them to discuss how those observations helped them evaluate how healthy their forest was, either in drought conditions or when impacted by high stand density, respectively.

4.4.2. Participation in Community and Citizen Science and Understandings of Socio-Ecological Systems

Based on our analysis of the complete data set for each focal student, we found that, of those who expressed understandings of SES, as described above, thirteen out of fourteen of them referred to experiences during the program when discussing SES that we traced to their participation in identifying and observing CCS activities.

Students used more reasoning practices that were indirectly linked to those concrete experiences. In Chase's interview, they rationalized how underbrush (a term Chase created to refer to both brush and understory) was a fire hazard and suggested clearing them out to reduce the probability of a big fire: "*My thinking is: the density could also be causing more fire because the more denser places the more fire there is, and the underbrush, we might need to clear that out. Because the underbrush can easily catch on fire and just start a whole huge forest fire like the one that we had like a couple years ago. It was super big*". In the fourth field investigation, we observed how Chase and the other students in their group actively engaged in collecting understory abundance and diversity data. In the investigation, Chase and their partner, Colby, used a quadrat (1 m $\times$ 1 m size) plot and flags to observe and identify the types and amounts of understory plants. Chase, in particular, constantly observed and identified new understory plants in the quadrat and, then, double-checked their data for accuracy. These observations then supported them to reason through the density of the understory plants they observed and identified at their forest site to the management recommendation they suggested in the post-program interview. In another example, Everlee (in Section 4.2) referred to the tree density data in the interview and suggested thinning out the forested plot and increasing tree density in other plots. When we triangulated Everlee's interview with the observational data, we found how Everlee not only actively engaged in identifying and recording the matured tree density data but also had an in-depth understanding of the protocol. To collect the mature tree density data, Everlee and their partner had to first identify trees that were over 4.5 ft tall; then, they had to use a Biltmore stick to estimate the tree trunk diameter and Everlee became adept at judging whether the tree "counted" or not.

5. Discussion

In this study, we investigated what science learning happened when fourth-grade students collected forest data to inform wildfire management as a locally relevant socio-ecological issue. Our findings indicate that engaging students in a CCS program has the potential to foster specific aspects of environmental science agency—their systems thinking skills and understandings of socio-ecological systems and how systems thinking and SES resilience might emerge as a mediating factor or outcome. We also found that specific CCS activities, identifying and observing, might cultivate students' systems thinking skills and support their understanding of socio-ecological systems.

In answer to our first research question, we found evidence that using a participatory or CCS approach can cultivate both a variety of systems thinking skills to understand the forest ecosystems [25] and the understanding of socio-ecological systems [10,31] for elementary school students. While we focused on knowledge and skills, we argue alongside Walker and Salt [12] that it is important to engage the stakeholders, including youth, to actively generate new knowledge to be able to enact change. In this way, developing disciplinary knowledge and skills, such as systems thinking and understandings of SES, may be building blocks or precursors to fully developing environmental science agency and moving towards more agentic actions. We also suggest that, just as Ballard et al. [5] found, engaging with complex socio-ecological systems is a key practice to support ESA development through CCS participation and we see the CCS activities as opportunities for students to act responsibly using systems thinking skills and deeper understandings of their own socio-ecological systems, to be more motivated to inform natural resources management and cultivate stewardship towards more resilient systems. We saw this in the discussions from several focal students who engaged in more sophisticated SES resilience thinking by considering the trade-offs and costs of different forest management approaches, which went beyond rote memory of the fixed knowledge created by scientists and other authority figures and positioned themselves as the stakeholders of the forest management. Instead of treating elementary school students as learners who were taught about the pre-determined knowledge generated by scientists, this program was able to position students as knowledge co-creators who have the capacity to rationalize, think critically about the information, and serve as active stakeholders capable of making management decisions [10,31].

In answer to our second question, our findings suggested that participation methods, such as identifying and observing, may be particularly important ways to support students' learning through CCS participation. Our findings showed how identifying and observing as two predominant participation methods can foster aspects of students' environmental science agency, in this case, their scientific skills, such as systems thinking skills, and disciplinary knowledge, such as understandings of socio-ecological systems resilience. This finding demonstrates that these two ways of participation provide concrete and direct experiences to students with the forest ecosystems. It also aligns with Lorke et al.'s [35] and Ghadiri Khanaposhtani et al.'s [40] finding from Natural-History-Museum-led CCS projects that observing and identifying are often predominant or important ways that young people participate in short-term BioBlitz and long-term monitoring CCS programs (respectively). These practices of observing and identifying may provide foundations for other types of participation for students in our study, as Lorke et al. [35] found. Furthermore, our findings that link observing and identifying with SES understandings align with Assaraf and Orion's [25] argument that hands-on or outdoor learning environments can provide sensory experiences to contextualize phenomena, which can help develop students' systems thinking skills and then serve as the building block to understanding larger SES. Importantly, the Our Forests program provided additional context and content to students about forest management, such as prescribed burning, that were complementary to the CCS practices of data collection students engaged, such that, of course those practices are not the only sources of influence on students' SES understanding.

Given our evidence, we suggest that systems thinking skills might serve as a building block to understanding the interactive and dynamic relationship between social and ecological systems for elementary students. We suggest that there is potential to build upon students' systems thinking skills that support their understanding of the ecological system and to also move towards understanding the interactions within the larger socio-ecological system [22,24,25]. In the cases we presented, there was a very fine line between performing systems thinking skills and understanding SES. Fire and fire management seem to serve as the mediator to understanding the interaction between social and ecological systems. This suggests a parallel argument to Assaraf and Orion's [25], where they claimed that systems thinking in the hydro-cycle context provided the first step to help elementary school students understand the system on a larger scale, including the role of human beings, or, in another term, the socio-ecological systems interaction. More importantly, we were excited to see students start identifying themselves as stakeholders within the SES by sharing how forest systems (e.g., wildfires) and management approaches (e.g., planned power outages) were things they personally experienced.

We are aware of two potential limitations of this study. First, our result might be confounding factors, such as students' prior-existing knowledge and skills. Our research method design did not include pre-program interview data, which might have provided evidence about focal students' pre-existing skills and knowledge. This may have confounded our claims about the influence of the forest-monitoring CCS program on student learning; although, we rely on students' direct comments about how aspects of the program influenced their thinking when we can. Second, we might have limited power to argue what other factors in the program might support the development of the systems thinking skills and understandings of SES. Even though we examined the data from both the field observations and the transcript data, we were not able to observe the entirety of the students' participation in the program and heavily relied on the students' recall.

6. Conclusions

In conclusion, we argue that the contribution of this study is threefold. First, this study showed the empirical results of engaging students in community and citizen science programs that are participatory and locally relevant and how supporting the understanding of interconnectedness [30,31] can support science learning outcomes, such as an aspect of environmental science agency development-system thinking skills and understandings of SES, which can be building blocks to empower students to inform resource management decisions and cultivate stewardship towards achieving sustainable development goals. Second, our findings support that this CCS approach has the potential to educate students to make changes in their attitude, knowledge, and actions to achieve the goal of 'sustainable development', combating climate change, rather than simply about 'sustainability' as knowledge to learn [10,31]. Third, this study also calls out the importance of empowering learners. Our study showed that, if we aim to foster SES resilience and consider young people as stakeholders in managing resources to deal with change and achieve sustainable goals [10,11], we might need to also rely on the power of engaging students in hands-on participatory monitoring [55] and knowledge production activities [38] to allow students, along with communities and scientists, to generate new understandings of the socio-ecological systems to better manage the resources [12].

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