CITIZEN SCIENCE: THEORY AND PRACTICE

An Emerging Theory of School-Based Participatory Science

ESSAY

P. SEAN SMITH
CHRISTINE L. GOFORTH
SARAH J. CARRIER
MEREDITH L. HAYES
SARAH E. SAFLEY
*Author affiliations can be found in the back matter of this article

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ABSTRACT

Participatory science conducted in formal K–12 settings has many benefits, including the potential to engage teachers and students authentically in the scientific enterprise and to make learning more meaningful. Despite these benefits and others, school-based participatory science (SBPS) is not widespread. In this essay, we put forth a theory of SBPS that is emerging from a four-year study of efforts to integrate participatory science in elementary classrooms. The theory captures the complexity of SBPS and describes factors that shape the experience teachers and students have with participatory science. First, we describe the landscape of SBPS. Second, we describe our study and the data we have collected on teachers' efforts to implement SBPS. Next, we describe the emerging theory and illustrate it with vignettes constructed from our data. Finally, we discuss recommendations for participatory science projects that wish to gain a foothold in K–12 classrooms and for research that can further test the theory of SBPS.

CORRESPONDING AUTHOR:
P. Sean Smith
Horizon Research, Inc., US
ssmith62@horizon-research.com

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INTRODUCTION

In this essay, we discuss participatory science (also known as citizen science or community science) that is conducted (in whole or in part) in formal K–12 school settings as part of ongoing science instruction, or school-based participatory science (SBPS). The benefits of participatory science outside of school are well estalished: Scientists can collect and analyze far more data than they could otherwise (Cooper 2016; Forrester et al. 2015; Lewandowski and Specht 2015), and participatory scientists can expand their science knowledge and literacy (Bonney et al. 2009; National Academies of Sciences, Engineering, and Medicine 2018). SBPS has added benefits for teachers and students (Aristeidou, Lorkee, and Ismail 2023; Kenyon, Christoff, and Wisdom 2020). Perhaps most compelling is the potential to engage teachers and students authentically in the scientific enterprise. Despite this, efforts to apply participatory science in school settings have been uneven, and although some studies of these efforts are present in the literature (Pizzolato and Tsuji 2022), research on the presence and impacts of SBPS has been limited (Ballard 2023). Pizzolato and Tsuji (2022) sought to characterize participatory science in schools through a literature search. Across the 77 articles reviewed, the authors described types of participatory science projects, grades in which they were present, availability of training, and frequency of participation. However, it is not clear whether the findings are representative given that they are based only on published literature. We have been studying SBPS for four years, and a theory is emerging from our work. In this essay, we sketch the landscape of SBPS, describe our study, explain the emerging theory, illustrate it with vignettes, and discuss implications for the field.

AN OVERVIEW OF SCHOOL-BASED PARTICIPATORY SCIENCE

Participatory science in school contexts has many of the benefits of participatory science conducted in other contexts. For example, in many projects, schoolchildren can expand scientists' data collection capacity just as adults can. In addition, SBPS has the potential to engage students and teachers in inquiries that involve collecting, reporting, and making sense of data, something that is often missing in K–12 science instruction (Banilower et al. 2018). Immersing students and teachers in authentic scientific inquiry creates opportunities for students to learn science by doing science. It also has the potential to increase STEM engagement and civic engagement (Condon and Wichowsky 2018), as well as STEM content knowledge and skills (Kermish-Allen, Peterman and Bevc 2019). We believe that, at its best, SBPS is characterized by two equally important elements:

1. Students collecting and reporting data over an extended period of time.
2. Students using those data (combined with data collected by others) to learn science concepts by applying the practices of science.

These opportunities closely align with project-based learning, the benefits of which include deeper learning of science concepts (Harris et al. 2015; Krajcik et al. 2023). SBPS also aligns well with the Next Generation Science Standards (NGSS), which emphasize the interweaving of science concepts and science practices (NGSS Lead States 2013). Forty-nine states and the District of Columbia have adopted the NGSS or NGSS-like standards for K–12 science instruction (*Science Standards, NSTA* n.d.), and the science practices described in the NGSS are integral to participatory science. They include asking questions, planning and carrying out investigations, analyzing and interpreting data, and using mathematics and computational thinking. National data suggest K–12 students have limited opportunities to engage in these practices during science instruction (Banilower et al. 2018).

The benefits of SBPS are in tension with its challenges. One major challenge is that relatively few participatory science projects provide materials to support teachers' implementation, and when materials are provided, their quality and utility to teachers vary greatly. When we filtered the 1,400 total projects on SciStarter (scistarter.org) by availability of classroom materials, only about 20% remained. Many projects offering teaching resources refer teachers to the same data collection tutorials they offer their non-school participants rather than sharing resources explicitly designed for classroom use. When lesson plans are offered, they often do not list the alignment with standards that many teachers require to justify their participation. Many participatory science projects have brought their work directly into classrooms (Colombari and Battisti 2023; Saunders et al. 2018; Yan et al. 2023), but even these visits by scientists or other project staff can be focused on data collection rather than analysis and sensemaking. Interestingly, many resources and programs that incorporate deep sensemaking opportunities have come out of museums and other outreach organizations, such as the Citizen Science Toolkit (https://www.calacademy.org/educators/citizen-science-toolkit) by the California Academy of Sciences and the Driven to Discover (https://extension.umn.edu/environmental-education/driven-discover) program by University of Minnesota Extension. The Cornell Lab of Ornithology, often seen as a leader in the field of participatory science, offers nature-based inquiry guides for grades K–12 (https://www.birds.cornell.edu/k12/sas/). These resources provide a tangible guide to bringing participatory science into a classroom setting beyond data collection and include reform-based educational best practices, such as science inquiry, flexibility in approach for educators, and opportunities for students to pursue their own questions with the data they collect. For example, the Driven to Discover materials include a sequence of several lessons structured around the Nature's Notebook project (https://www.usanpn.org/nn) that range from constructing a testable question, to collecting and interpreting data, to drawing conclusions and reporting them.

Teachers' own backgrounds and instructional practices present other challenges. Although middle school and high school science teachers tend to have relatively strong backgrounds in their disciplines, less than a third regularly engage their students in project-based learning (Banilower et al. 2018). In the elementary grades, most teachers must teach all subjects but generally do not consider themselves well prepared to teach science (Plumley 2019). In addition, accountability pressures to teach English language arts (ELA) and mathematics often crowd out science instruction. Across grades K–5, science instruction averages about 20 minutes a day, compared with an hour for mathematics and an hour and a half for ELA (Plumley 2019).

Roche et al. (2020) present several challenges in incorporating participatory science into classroom settings, highlighting the potentially competing needs of scientists and educators and the burden for project leaders with limited K–12 educational experience to create and maintain quality resources for teachers. They also note that, because students in classroom settings have been volunteered to participate rather than choosing to do so themselves, the success or failure of a project in a classroom setting depends almost entirely on the teacher's commitment to the project. They, like others (e.g., Atias et al. 2023; Ballard 2023; Harris et al. 2020), suggest that co-created projects that involve students in more aspects of the scientific process and nested inquiries in which students situate their data collection within the larger dataset or in their own communities can produce the most effective SBPS experiences.

OVERVIEW OF OUR STUDY

We are a group of researchers interested in the potential of SBPS to improve science instruction in the elementary grades (K–5). Our team's expertise includes formal and informal K-12 science instruction, participatory science, outdoor learning, teacher professional learning, curriculum development, and education research methods. We believe participatory science can transform K–12 science instruction from an all-too-often passive experience to one in which students learn science by doing science. With a four-year grant from the National Science Foundation, we have been studying how elementary teachers incorporate two participatory science projects in their instruction. One project focuses on collecting daily precipitation measurements (the Community Collaborative for Rain, Hail, and Snow, or CoCoRaHS; cocorahs.org), the other on conducting periodic searches for ladybugs (Lost Ladybug Project, or LLP; lostladybug.org). Both have been operating for over 20 years. The purpose of our study is to understand how well-developed teacher support materials, designed explicitly for each project, influence teachers' experience.

We spent the first year of the study creating the support materials in collaboration with a small group of current elementary teachers. Briefly, the materials consist of monthly activities in which students take stock of the data they have collected that month and use the data to answer questions. In one month, students examine ladybug habitats and compare their LLP observations with those of another location in their state as they explore each location's features (e.g., weather, geographic location, vegetation). In CoCoRaHS, students graph their daily readings for one month and try to explain the shape of the graph in terms of weather events that occurred that month. As the school year progresses, lessons build on previous months' activities and the increasing body of data students have collected. They also leverage data collected by other participatory scientists. In the second year, we piloted the support materials in the classrooms of our teacher collaborators and revised them based on teachers' feedback. In the third and fourth years, we recruited approximately 50 more teachers to use the materials in their classrooms for a full school year. All attended professional development sessions and completed beginning- and end-of-year surveys about their experience with the projects. They also submitted weekly instructional logs. We have followed 15 of them more closely through monthly classroom observations and post-observation interviews, as well as three focus group interviews with students near the beginning, middle, and end of the school year. We are still collecting and analyzing data from these teachers, but our data suggest an emerging theory of SBPS.

THE THEORY

Our theory is adapted from work on the relationship between teachers and their instructional materials (Remillard 2005). That relationship, mediated by several factors, transforms the written curriculum into what happens in the classroom. Depending on the teacher and the mediating factors, what students experience may bear little resemblance to the instructional materials as written. Our perspective on SBPS is similar. Teachers have a relationship with a participatory science project, and that relationship is mediated by many factors. The mediated relationship determines how students experience the project and what they learn. We group these factors into the following categories:

- the participatory science project;
- the teacher;
- the teacher's context (e.g., students, school, community, school district); and
- teacher support materials that accompany the project.

THE PARTICIPATORY SCIENCE PROJECT

Factors associated with the participatory science project itself influence SBPS. For teachers, perhaps the most important factor is whether the project aligns with a topic they are responsible for teaching. The project's appeal to students is also important but somewhat unpredictable. In our work, searching the school grounds for ladybugs has sustained students' interest for an entire school year, even in cases where the students found almost no ladybugs. Reading a rain gauge each day and reporting the data may not seem particularly engaging (especially during long periods without precipitation), but we have seen classes of students participate enthusiastically throughout the year. They are eager to read the rain gauge, enter the data, and compare their readings to others across the nation. The fact that students can see their data alongside data entered by others seems important for engagement, an observation supported by Harris et al. (2020). Ease of data collection is important for students and teachers. When data can be collected quickly with minimal demand on instructional time (e.g., reading a rain gauge), it is most likely to take place frequently and regularly. Taking an entire class of students outside to search for ladybugs is likely to happen less often due to the preparation required and data collection time. Age appropriateness is inherent in several of these factors. Reading a rain gauge to hundredths of an inch is difficult for young children, but even young children can find and identify ladybugs with appropriate support (e.g., an easy-to-read field guide).

THE TEACHER

Nationally representative data on the use of participatory science in K–12 science instruction are not available, but there is considerable data on teachers themselves from which inferences can be drawn. Each teacher comes to participatory science with a unique blend of knowledge, skills, attitudes, and beliefs. Teachers vary widely in their science background. High school science teachers frequently have the equivalent of a major in the subject they teach (Banilower et al. 2018), positioning them well for the content demands associated with implementing participatory science. In contrast, only about a third of elementary teachers have taken at least one course each in Earth, life, and physical science. Elementary teachers in general feel ill prepared for science instruction (Plumley 2019). At the same time, most elementary teachers teach ELA, mathematics, science, and social studies, creating opportunities for interdisciplinary connections that make learning more meaningful. Depending on their science background, some teachers will be adept at supporting students to analyze data they have collected; others will not. Some teachers are comfortable taking their students outdoors to collect data, while others worry about managing student behavior. Teachers differ widely in their beliefs about what constitutes good science instruction. Many see the primary purpose of science activities as confirming what students have already learned. Others believe students should grapple with firsthand data to learn concepts (P. S. Smith, A. A. Smith, and Banilower 2014). Teachers also vary in what they believe about students. One widely researched example is beliefs about whether intelligence is malleable (Dweck and Yeager 2020; Yeager et al. 2019). Some teachers believe young children are not capable of scientific thinking, despite much evidence to the contrary (National Academies of Sciences, Engineering, and Medicine 2022). Each of these factors can shape a teacher's relationship with a participatory science project. For example, teachers who view their students as fixedly incapable of collecting and making sense of data are unlikely to embrace SBPS.

THE TEACHER'S CONTEXT

All K–12 teachers work in settings that strongly influence how they teach. Students are central to that context. Their backgrounds, assets, and challenges, combined with teachers' beliefs about students, strongly influence the choices teachers make about SBPS. The school site is another consideration. Both projects in our study require data collection on the school grounds. Most of our teachers can easily take their students outside to search for insects in a variety of settings (a school garden, a playground), but this is not the case in all schools. For some, going outside presents considerable safety concerns, or perhaps the campus lacks vegetation. Installing a rain gauge is straightforward at some schools but requires formal approval at others. The priority a school gives to science also influences how easily teachers can implement participatory science. Particularly in public elementary schools, science instruction typically receives much lower priority, and thus less instructional time, than ELA and mathematics (Plumley 2019). Many school districts have curriculum pacing guides that dictate when and for how long teachers teach certain science concepts, making integrating a year-long participatory science program a challenge, sometimes an insurmountable one. School administrators can facilitate or inhibit SBPS. We have seen administrators encourage SBPS by calling attention to public displays of data students collect (e.g., daily precipitation charts in a school hallway). An administrator who visits a classroom to observe a teacher and finds the class is outside searching for insects might either be pleased by the teacher's innovation or discourage it going forward.

TEACHER SUPPORT MATERIALS THAT ACCOMPANY THE PROJECT

Our work hypothesizes that teacher support materials have the potential to improve teachers' and students' experiences with participatory science. By support materials, we mean content developed with the explicit purpose of helping teachers integrate a particular participatory science project into their instruction. Our work suggests that some features of support materials are particularly important. First, the materials should be educative (Davis and Krajcik 2005); that is, they should support student learning *and* the teachers' own understanding of the related science content and instructional practices. This is especially important for elementary teachers. Support materials should show teachers how the participatory science project can help them teach the science content they are responsible for teaching. Because almost all states now share a common framework for K–12 science instruction, this has never been easier. Support materials should give teachers concrete descriptions that help them visualize classroom implementation. Such descriptions have proven to be particularly effective (Davis et al. 2017). Finally, support materials can help teachers sustain engagement with a project by structuring year-long explorations of the data students collect, providing opportunities for students to make sense of the data. These explorations can offer options that make it easy for classes to get started and give teachers ample opportunities for adapting and extending the experience to best suit their context and their students.

REPRESENTING THE THEORY

We conceptualized our emerging theory as a four-legged stool (Figure 1), where four sets of factors—the

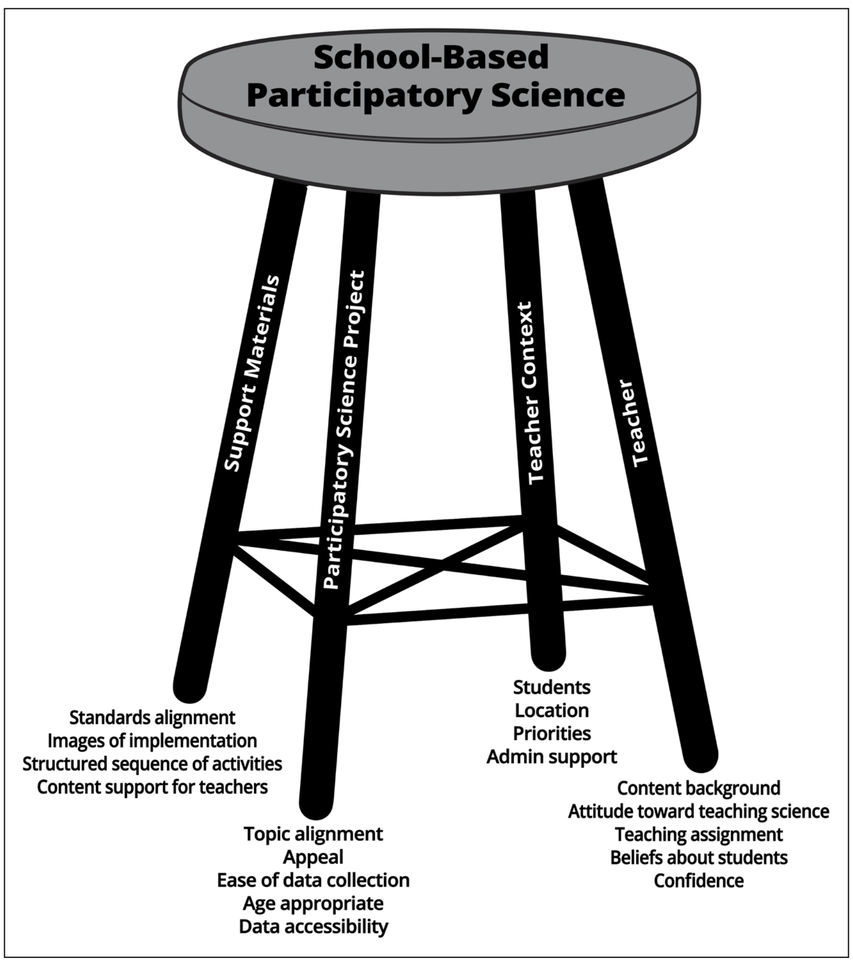

Figure 1 A model of school-based participatory science (SBPS). Image credit: Emma Smith.

participatory science project, the teacher, the teacher's context, and the teacher support materials—support effective SBPS. (Factors shown in each category are illustrative, not exhaustive.) It is possible that without support materials, a resourceful teacher might have a positive SBPS experience. However, our data and our collective experience suggest that each of these four components shapes the SBPS experience. The theory also highlights relationships *among* these factors. Each component can strengthen or weaken the others. Support materials can make a project more feasible by showing teachers how it aligns with their standards. Teachers' attitudes toward science influence the enthusiasm a participatory science project fosters in their students. A school's priorities affect how often students are allowed to collect data on the school grounds and how much class time they devote to making sense of the data. When all four components align and reinforce each other, the foundation for SBPS is strong, and the potential for an experience that optimizes the benefits for teachers and students is high.

VIGNETTES

In this section, we offer three vignettes of SBPS to illustrate the theory—two describing considerable success with SBPS and one describing limited success. Each is constructed from data collected through teacher surveys and interviews, student focus groups, and observations in schools. The vignettes do not fully describe or explain the SBPS experience. Our goal is to unpack the theory with concrete examples, not to fully explain each case. We have replaced all names with pseudonyms.

ALL FACTORS ALIGNED FOR SUCCESS

To say that Ms. Parsons is enthusiastic about ladybugs is an understatement. She wore a ladybug costume on data collection days, and her classroom was full of ladybug-themed gifts from students. She prominently displayed a map noting locations students had found ladybugs, alongside photographs of ladybugs. Her students became equally enthusiastic, eagerly searching for ladybugs on their school grounds (and sometimes at home, or even on vacation in France!) and graphing and analyzing their data. Her students relished their opportunities to learn outdoors and were amazed they could contribute to ladybug research by simply finding ladybugs at school. Their work culminated in a class presentation—in costume and supported by their own data—to their school's board of directors. The result: the board agreed to allow their most productive habitat, a grassy patch that had been mowed to turn it into a sports field, to regrow so the ladybugs could rebuild their population at their school.

Ms. Parsons's experience with LLP was overwhelmingly positive. She initially joined our study so she could teach outdoors more often, and knew her varied school grounds (a mix of landscaped athletic fields, school gardens, and fields bordered by woods) were an excellent learning space. Her charter school, catering to the social and emotional learning of relatively affluent students, proved to be a superb environment for LLP. It helped that Ms. Parsons saw her students as bright, eager to learn, and capable of collecting high-quality data, submitting and interpreting their findings, and presenting their work with a high level of understanding. She was not disappointed.

Ms. Parsons is a highly experienced teacher respected by her peers and school administrator. The latter was particularly impressed by the students' LLP work, especially when she saw their deep learning and how invested they were in the project. The administrator trusted teachers at the school to take children outside to learn and to be creative in their approach to teaching the standards. The administrator also appreciated that the students were so eager to learn through LLP and that the accompanying support materials were explicitly aligned with the state standards. Ms. Parsons loved the teacher support materials, sharing that the curriculum correlations, year-long engagement in the project, links to resources, and narrative descriptions of implementation were helpful as she developed her lessons. She was able to quickly read the materials and confidently develop her lessons with little need for additional resources. She particularly appreciated the flexibility of the supports; she likes to do things her own way rather than following a strict lesson plan developed by others.

The high level of student enthusiasm, varied grounds, culture of the school, and administrative support, combined with the ease of data collection and availability of a range of support materials made Ms. Parsons's work with LLP positive and highly successful. Her classes demonstrated the possibilities when the participatory science project, support materials, teacher's context, and attitudes and experience of the teacher come together to support SBPS.

OVERCOMING BARRIERS

In the last week of the school year, Ms. Baca's class finally found a ladybug. All year, they had searched regularly, exploring their school grounds outside and in, with no luck. Despite this, Ms. Baca and her students were consistently engaged and invested in the project throughout the year. Ms. Baca taught monthly science lessons using the supports, modifying them to accommodate the wide range of learners in her class. She made interdisciplinary connections, incorporating ladybugs into literacy, mathematics, and even music and art. Toward the end of the year, when they still had not found ladybugs, Ms. Baca facilitated class discussions about ecosystems, agriculture, and pests, and the class came up with hypotheses for the lack of ladybugs. The project culminated with small group presentations to herself and an assistant (role-playing as school administrators), explaining the students' concerns about pesticides used by the school and neighboring farms and suggesting actions the school could take to become a better habitat for ladybugs. Ms. Baca said the year-long project was powerful in improving her students' pride, confidence, and science content knowledge, even attributing their higher-than-normal state science scores to their participation.

Ms. Baca's successful implementation of LLP, despite factors that could have inhibited success, can be explained by our emerging theory. The major barriers were contextual factors. Her schoolyard, though large, accessible, and containing a variety of habitats, was inhospitable to ladybugs due to pesticide use. Her students, all of whom lived in a rural farming community, had their own challenges. Several were categorized as having physical, mental, or social disabilities, and almost all were economically disadvantaged. However, factors related to the supports, the participatory science project, and the teacher combined to mitigate the barriers and even turn them into facilitating factors. LLP's data collection appealed to Ms. Baca's students, who reported being very comfortable outdoors. The supports provided content (much of which did not depend on students finding ladybugs) that Ms. Baca used for a year-long progression of learning, which sustained students' interest in the project through months of fruitless ladybug searches. Furthermore, Ms. Baca made the project relevant to the students by connecting it to their lives in a farming community. She regularly used anecdotes from her own farm to illustrate concepts and encouraged students to share examples from their farms or gardens. In particular, their lived experiences relying on agriculture for income, paired with their firsthand knowledge of the unusual lack of ladybugs around their school, allowed the class to have nuanced discussions of the pros and cons of pesticides. This is one example of how Ms. Baca consistently demonstrated her belief that all children can succeed in science. When needed, she modified the supports for her students (e.g., rewriting an article for a lower reading level), then she expected—and joyfully celebrated—student success. The teacher factor, in particular, along with the supports, the project, and the context combined to turn challenging factors into successful implementation of SBPS.

LIMITED USE

Ms. Cronin teaches in a small town with one stoplight. When Ms. Cronin introduced LLP to her students, she asked if they were scientists and received a mixed response. Ms. Cronin told students that they were all scientists and told them they would be looking for ladybugs. For the last 10 minutes of the class period, she took the students outside, limiting their searches to one small area of the schoolyard. Before going outside, she told students not to hurt others, kill insects, or destroy school property. Some students searched for ladybugs, while others found other insects or socialized. Occasionally, a student found a ladybug. Similarly short ladybug searches were repeated at the end of each monthly lesson. Although the students were enthusiastic about the project's outdoor time, Ms. Cronin said she found it difficult to make time for ladybug searches. This perception of limited time for data collection, combined with her decision to limit ladybug searches to one small area of the expansive schoolyard, contributed to students finding few ladybugs. When ladybugs were found, Ms. Cronin occasionally took a photo, but she did not submit photos to the project website or discuss with students the habitat where the ladybug was found. During one observation, the indoor portion of the class session was devoted to students using a ladybug identification sheet from the support materials to identify the species of photos projected on the presentation screen. Students yelled their guesses, often focused on the number of spots on the ladybug (an unreliable indicator), with limited discussions about the body shape or markings on the thorax. In another classroom session, Ms. Cronin explained to students that it is important for scientists who do not find ladybugs to report those "zero" findings. However, because Ms. Cronin did not ask students to record or report their searches resulting in no ladybugs, this remained an abstract concept.

Ms. Cronin was initially drawn to the project to build her own science content knowledge and provide students with science experiences, but she said time constraints limited her use of the project in her instruction. She said that her students were behind academically and described her class as "tough" and with "poor socialization skills." Her concerns about student behaviors and academic levels, along with her principal's expressed goals that the project should positively impact students' science test scores, shaped her decision to limit the class time she spent on the project and instead have students practice for the test. Ms. Cronin saw limited connections between the project and her state's science standards on ecosystems, but she was able to connect ladybugs in her lecture on predator-prey relationships. Although the concept of habitats was part of her ecosystem unit, Ms. Cronin made only indirect connections to a ladybug's habitat, likely because her class's ladybug searches were restricted to a raised garden in the schoolyard. When plants in the garden were cut back by groundskeepers, the students turned to nearby manicured grass areas, limiting their perspective of a ladybug's habitat. In her first year working with the project materials, Ms. Cronin's teacher-centered and testing-focused approach, influenced by accountability pressures and a lack of confidence in her students, limited her use of the support materials and overall engagement with the project.

CONCLUSIONS

Although the three vignettes are of elementary classes, we believe the theory applies equally well across formal education contexts K–12. The same factors are at play regardless of grade level, but they play out differently. For example, the structure of the school day (a context factor) is different in elementary schools and high schools and exerts a different influence, but it is a factor in both. High school science teachers generally have the equivalent of a bachelor's degree in the subject they teach, while elementary teachers rarely have more than a few courses scattered across disciplines. Content knowledge influences SBPS in both grade ranges, but the influence is different.

We find the theory represented in Figure 1 useful for explaining SBPS experiences, yet we characterize it as emerging for a few reasons. First, although our current study is generating considerable evidence that supports the theory, we did not design it to test all factors and relationships represented, but rather to identify and explore them. Second, each leg of the stool is not a single factor but a collection of factors. The participatory science project, like the teacher, their context, and the support materials, represents many associated influences. We likely have not considered all associated factors for each of the four legs. We are planning additional studies to test and refine the theory, as SBPS is a complex system, and understanding it fully will require many studies in diverse contexts. We are particularly interested in how support materials for teachers influence SBPS, but we can imagine other studies focusing on features of participatory science projects or teacher-related factors.

We believe the theory has implications for participatory science project leaders who want their projects to take place in schools. We offer a few examples here, but the common theme is acknowledging the teacher and the teacher's context. Regardless of a project's inherent appeal, teachers must be convinced it is worth their instructional time. Teachers also need guidance on how to use the project with their students. We took the approach of packaging this guidance in a set of sequenced activities with ancillary resources teachers could draw on at their discretion. Involving experienced teachers in creating these materials proved invaluable (Carrier et al. 2024). For new participatory science projects with SBPS intentions, consulting with teachers in the design phase can help ensure that the protocols for collecting and reporting data are both age appropriate and feasible in school settings. Teachers in our study also reported greater confidence in the quality of our materials because they were reviewed and used in classrooms by our teacher consultants before sharing them with our study teachers.

Recognizing that teachers need more than awareness of participatory science projects is a first step toward increasing the spread of SBPS, but only a first step. For the full potential of K–12 SBPS to be realized, project designers should create robust accompanying materials that draw on teachers' unique pedagogical strengths, support their varied backgrounds, and acknowledge their contexts. Our emerging theory of SBPS highlights the importance of all four components: the participatory science project, the teacher, the teacher's context, and support materials. It also emphasizes the relationships among each component, illustrating how a successful SBPS depends on all components working together.

ETHICS AND CONSENT

The study on which this essay is based was approved by the Institutional Review Board of Horizon Research, Inc. (00005913). All study subjects gave active consent to participate.

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COMPETING INTERESTS

The authors have no competing interests to declare.

AUTHOR CONTRIBUTIONS

PS, CG, SC, and MH conceptualized the study on which this essay is based. PS led the writing, with all other authors contributing.

AUTHOR AFFILIATIONS

P. Sean Smith orcid.org/0000-0002-1680-5044
Horizon Research, Inc., US
Christine L. Goforth orcid.org/0009-0005-8087-1387
North Carolina Museum of Natural Sciences, US
Sarah J. Carrier orcid.org/0000-0002-6902-812X
North Carolina State University, US
Meredith L. Hayes orcid.org/0000-0002-7923-6715
Independent Consultant, US
Sarah E. Safley orcid.org/0009-0007-6575-753X
Horizon Research, Inc., US

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