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ORIGINAL RESEARCH

Boundary Crossing in Student-Teacher-Scientist-Partnerships: Designer Considerations and Methods to Integrate Citizen Science with School Science

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Abstract

Student-Teacher-Scientist Partnerships (STSPs) provide opportunities for students and teachers to participate in citizen science and engage with scientific concepts and practices, thereby bridging school learning with issues of importance to society, such as climate change. But STSPs require partners to cross boundaries between the cultures of science and schooling, which is extremely difficult. This three-year case study illuminates how successful designers tackled boundary crossing challenges while creating a scalable STSP for environmental education. Analysis of data gathered from three sources – designer-generated documents, interviews with designers, and researchers' observations of the designer work - through an in-depth participant-observation approach revealed how designers (curriculum writers and partner ecologists) made it possible for middle school students and teachers from partner schools to contribute climate-related data to the ecologists' research and to other citizen science programs, while accommodating teacher preferences and curricular constraints to pursue educational goals. Findings about how designers used specific methods and created curriculum supports to aid processes of boundary crossing are discussed in light of relevant literature, highlighting their considerations about specific stakeholder needs related to pedagogical, curricular, and scientific goals of the partnership. Further, distilled from the empirical findings and in light of relevant literature are three guidelines in designing for STSPs to foster student inquiry, to support teachers, and to provide multiple benefits through the STSP. These findings and guidelines can help designers anticipate and attend to boundary crossing challenges in STSPs designed for environmental education, with broader implications for science education in general.

Keywords Student-Teacher-Scientist-Partnerships · Citizen science · Curriculum design · Case study

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Citizen science initiatives enable non-scientists as members of the general public to partner with professional scientists and participate in organized scientific research, for which they may gather and analyze large amounts of data and report findings (Bonney, Ballard, Jordan, McCallie, Phillips, Shirk, & Wilderman, 2009; Bonney et al., 2015), often focused on environmental matters (Dickinson & Bonney, 2012). The term citizen science itself is a more recent coinage within a much older tradition of public engagement in science that dates back to the 1800s (Bonney et al., 2015; Dickinson & Bonney, 2012). Owing to their potential to engage non-scientists in developing scientific knowledge, citizen science projects have gained popularity around the globe in promoting science learning (e.g., Aivelo & Huovelin, 2020; Harlin, Kloetzer, Patton, Leonhard, & Leysin American School high school students, 2018; Kelemen-Finan, Scheuch, & Winter, 2018; National Academies of Sciences, Engineering, and Medicine, 2018; Paige, Hattam, & Daniels, 2015; Sagy et al., 2020). Although commonly implemented in informal science educational settings, citizen science can move into school classrooms within formal science education programs, where teachers play a pivotal role in integrating citizen science projects with their science curricula (Roche, Bell, Galvão, Golumbic, Kloetzer, Knoben, Laakso, et al., 2020).

The present study, conducted in the United States, focuses on student-teacher-scientist partnerships (STSPs) as a specific model for integrating citizen science with science learning in formal precollege education (see Zoellick, Nelson, & Shauffler, 2012 for a similar conceptualization of STSPs and school-based citizen science). Whereas student and scientist partnerships have existed for a long time in higher education and in other scientific research settings, the potential of designing such partnerships for K-12 school settings came to the fore in the 1990s to serve the learning needs of all students (Morse, 1997). STSPs provide a formal arrangement in which students and teachers collaborate closely with scientists to “answer real-world questions about a phenomenon or problem the scientists are studying” (Houseal, Abd-El-Khalick, & Destefano, 2014, p. 86), thus presenting opportunities to bridge school science with pertinent issues in students’ everyday lives and society, such as climate change. In so doing, students and teachers gain first-hand exposure to scientific practices, while scientists can enlist students’ help in gathering data to answer pressing scientific questions (Doubler, 1997). The partnership is driven by mutual goals of scientific knowledge construction and benefits for both science education and scientific research (Morse, 1997).

In this paper, we use the term *citizen science* to refer broadly to public participation in scientific research (Phillips et al., 2018) and the term *STSP* to refer narrowly to the more direct collaboration between K-12 school partners and scientists as they work together on scientific research. This distinction is based on the degree of direct interactions and negotiations between scientists and school partners. In STSPs, the school partners typically receive more direct support from the scientists, and the needs of different stakeholders require careful negotiation to serve both specific learning outcomes for school partners and scientific outcomes related to the scientists’ research (He & Wiggins, 2017; Houseal et al., 2014; Zoellick et al., 2012). Although some citizen science projects include previously developed resources and training workshops that can be used by subsequent groups of school partners to serve stand-alone or larger projects, the extent to which students and teachers interact directly with scientists and to which student-gathered data are actually used for scientific research are variable and in some cases unclear (Trautmann, Shirk, Fee, & Krasny, 2012; Bonney et al., 2015; He & Wiggins, 2017).

Rationale of the study

Benefits and challenges in designing for STSPs: crossing boundaries between science and schooling

Studies indicate that STSPs offer various benefits for students, teachers, and scientists. For example, students have shown gains in their knowledge of scientific concepts and skills (Golumbic et al., 2016; Hedley, Templin, Czajkowski, & Czerniak, 2013), increased positive attitudes towards scientists (Houseal et al., 2014), and development of agency in using environmental science to take action towards conservation (Ballard, Dixon, & Harris, 2017). Studies also reveal positive shifts in teachers' pedagogical choices, such as increasingly supporting students to communicate their understanding and to apply concepts and make connections in various content areas (Houseal et al., 2014). Scientists, too, gain insights into the realities of schools and ideas for public outreach (Drayton & Falk, 1997, 2006).

While STSPs hold promise, differences in the cultures of science and schooling present boundaries which can disrupt the collaboration. In addition to organizational boundaries, there are other salient differences between these communities of practice. For example, teachers bring to their practice broad content knowledge and are tasked with nurturing interest among their students, all the while working in resource-limited settings. On the other hand, scientists draw on specialized knowledge of their subject, and bring high levels of intrinsic motivation to their practice in settings characterized by a greater access to scientific and scholarly resources (Tanner, Chatman, & Allen, 2003). Another difference exists in terms of the duration of research projects. Student projects typically last days or weeks, while scientific research often extends over years or decades (Barstow, 1997), making it difficult to obtain meaningful scientific findings in short time periods, which are crucial to maintaining student interest. And although common goals undergird the collaboration, scientists are often concerned with the validity of (student-generated) data for scientific research, while teachers are often concerned with the alignment of the collaboration with educational standards (Doubler, 1997).

Additionally, to advance scientific knowledge, student participation in data collection may be overemphasized at the expense of other scientific practices such as data analysis. However, standardized data collection protocols may be implemented selectively and with interruption in schools due to curricular requirements and time constraints, yielding incomplete and inconsistent data with reduced scientific value (Means, 1998). The resulting low quality of student-gathered data, despite the provision of simple methods and detailed protocols, thus necessitates specialized in-person or remote trainings for school partners prior to fieldwork (Castagneyrol, Valdés-Correcher, Bourdin, Barbaro, Bouriaud, et al., 2019).

Further, the background knowledge required to understand scientists' research may be too far in advance of the students' and teachers' understanding (Drayton & Falk, 1997, 2006). This is complicated by the fact that many schools must adhere to topics specified in their curricula and assessments (Moreno, 2005), whereas scientists focus on topics relevant to (sometimes rapidly changing) real-world issues. As a result, scientist partners are tasked with identifying content that will engage students in real-world problems while developing their understanding of the fundamental concepts and practices that will be assessed in schools (Moreno, 2005). Finally, direct interactions with scientists and clarity on using student-generated data for science are important to sustain the interest of school partners, but such interactions are time-intensive for scientists and need careful orchestration (Means, 1998).

More recent literature also highlights similar and additional issues (see Roche et al., 2020). For example, in addition to curricular and scheduling constraints, teachers are tasked with nurturing engagement among students who may lack motivation to participate in the project. This contrasts with general citizen science projects in which the participation of non-scientists is voluntary. And it is especially difficult when teachers lack the content knowledge to facilitate students' fieldwork. Finally and more pertinent to recent times, with the rapid explosion of citizen science initiatives over the last two decades, teachers may struggle to choose among available options that would enable them to align scientific goals and needs of the projects with specific educational goals and needs of their own settings.

Problem Statement

To address these issues, it seems clear that STSPs must be designed to help all partners acquire insight into work outside of their own domains, a practice referred to as boundary crossing (Tsui & Law, 2007). In crossing boundaries, individuals seek to establish actions or interactions across practices of collaborating sites that are characterized by different norms, goals, tools, etc. (Bakx, Bakker, Koopman, & Beijaard, 2016). In the context of STSPs, this means that students, teachers, and scientisist collaborate across the domains of school and scientific research, bringing to bear their own interests, focus, and expertise as shaped by those domains, while pursuing mutually agreed upon objectives.

Specifically, it is vital that partners in STSPs understand the needs and goals of various stakeholders, so that students and teachers can cross boundaries from school practice into scientific research. By coming to understand better the aims and methods of the scientific research program, which may be less easily accessible initially to students and teachers, the school partners can contribute towards it directly by gathering, analyzing, and reporting specific kinds of data. Similarly, understanding stakeholders is important to help scientists cross boundaries in the other direction from scientific research into school science education. By coming to understand better the needs and requirements of their school partners, which may be less familiar initially to the scientists, they can contribute towards intentionally fostering students' interest and content knowledge. Through crossing boundaries between the domains of scientific research and science education, signifying respectively science as practised by professional scientists to construct knowledge and instructing students in those practices, STSPs can thus contribute towards developing scientific knowledge through the participation of non-scientists, while making scientific knowledge more accessible to the public to nurture their motivation, understanding, and action for urgent real-world problems, such as climate change.

Nonetheless, this presents a tremendous challenge to the designers of STSPs, especially because citizen science is still a nascent approach to supporting science learning in schools. While current literature describes boundary crossing processes (Akkerman & Bakker, 2011) and offers guidelines for school and scientist partnerships in general (Houseal et al., 2014; Moreno, 2005), designers of STSPs also require additional information to integrate citizen science with school science. For example, how might designers equip students with the requisite knowledge and skills to contribute to scientific research, and how might they support teachers to help students towards this end (Zoellick et al., 2012)? How might designers select sites for engaging fieldwork when faced with typical school constraints of safety, transportation, and permissions for field visits (He & Wiggins, 2017)? And how might designers promote student ownership of scientific investigations while balancing the needs of teachers and scientists (Houseal et al., 2014)? Further, how might technology be leveraged to help STSPs bridge school science learning with scientific issues of importance to society? Finally, it is vital that curricula support inquiry centered on phenomena of interest to students. But for productive inquiry, students also need motivation to proceed from immediate (ecological) phenomena and connect with global phenomena and more abstract concepts (Feldman, Konold, & Coulter, 2000). How might designers then foster and reinforce local-distant connections through both in-class and fieldwork experiences?

Study goal and significance

The current literature contains some (limited) guidance for STSP designers. For example, designers working across contexts can be informed by research on processes of boundary crossing in different domains of education and work (Akkerman & Bakker, 2011). Additionally, research reports general activities and supports for school and scientist partnerships, the challenges therein, and their outcomes (Houseal et al., 2014; Moreno, 2005). There are also generic models describing methods for instructional design (Gustafson & Branch, 2002) and curriculum design (Thijs & van den Akker, 2009). Finally, there is general guidance available through case studies for teaching instructional design (Ertmer & Quinn, 2007). However, what is lacking are detailed, empirically-derived and theoretically-informed insights into designer considerations and actions for integrating citizen science with school science and for supporting STSP stakeholders to cross boundaries in the mutual pursuit of scientific and educational goals.

Therefore, this study aimed to produce a detailed example of how designers of STSPs perform their work in bringing citizen science to schools and thereby bridging formal science learning with relevant issues in students' local environments and the broader society. Like process-oriented worked examples in other areas (Van Gog, Paas, & Merriënboer, 2004), the present example delineates designer thinking and key methods in tackling important considerations, as exemplified in an emergent STSP design for environmental education. In so doing, the study provides a vital precedent articulating underlying designer rationales and processes (Howard, Boling, Rowland, & Smith, 2012) to aid other designers in understanding and attending to challenges in designing for STSPs.

Context of the study

To tackle questions like these and support the development of future STSPs, a prolonged case study involving a participant-observation approach investigated the evolution of designer thinking and action while designing for a successful STSP for middle schools to promote education about climate change (see Method for more details). To this end, the investigation focused squarely on unpacking the rationales and measures taken by curriculum writers and partner ecologists because they actively created various curriculum supports for the STSP.

Further, as evidenced in the findings, the designers attended to the needs and outcomes of students and teachers in creating these supports, but the school partners did not participate in this study, a point which we revisit in the Discussion section. While this specific case is situated in the USA, designers in international contexts may experience similar challenges to those documented here, and thus also benefit from the insights related to designing for STSPs to integrate citizen science with school science in serving environmental education goals.

Finally, as elaborated in the Methods, Results, and Discussion sections, the ecologists and teachers were both the intended end users of the STSP and stakeholders in developing the partnership. The ecologists (together with curriculum writers) attended to educational and scientific goals and needs, and they contributed ideas and outputs in actively creating various curriculum supports, while the teachers implemented and provided feedback at various points in the design process. Although not a complete representation of participatory design per se, the present case can illuminate how the expertise and experiences of multiple stakeholders are brought together. Used in the field of design more broadly (Baek, Kim, Pahk, & Manzini, 2018; Cipolla & Manzini, 2009; Mosley, Markauskaite, & Wrigley, 2021; Sanders & Stappers, 2008) and in the field of educational design more specifically (Könings, Seidel, & Van Merriënboer, 2014; Penuel, Fishman, Cheng, & Sabelli, 2011), participatory design approaches involve intense collaboration and engagement between professional designers and users from non-design backgrounds to yield high quality usable innovations that are more likely to be accepted, better understood, and effectively implemented in practice (Könings, Brand-Gruwel, & Van Merriënboer, 2007). Such approaches are especially crucial for producing educational interventions because professional designers, practitioners, and students often bring different perspectives to teaching and learning, and a lack of congruence among the perspectives may impede intervention implementation and effectiveness (Könings et al., 2014).

In following participatory approaches, designers are tasked with facilitating dialogue and problem-solving among stakeholders as they collaborate across boundaries of practice (Mosley et al., 2021). For designers wishing to create STSPs through participatory approaches, however, greater clarity is needed on issues such as the following: How can teachers and scientists be supported to contribute during the design process? What activities and tools are used to facilitate communication between school partners and scientists? Finally, how are potential or actual student perceptions and experiences of the intervention accounted for in the emerging design? The present case provides insights to tackle such questions.

Conceptual Framework

As mentioned before, teachers and partner ecologists served as stakeholders in the design process to create the present STSP. The study investigated more specifically how designers attend to three crucial dimensions in creating STSPs: (i) supporting stakeholders (school partners and scientists) in STSPs to understand one another's needs and wishes in relation to boundary crossing processes; (ii) producing curricular supports to help stakeholders engage in the boundary crossing processes; and (iii) employing specific methods during key phases of curriculum design for creating the curricular supports to aid boundary crossing

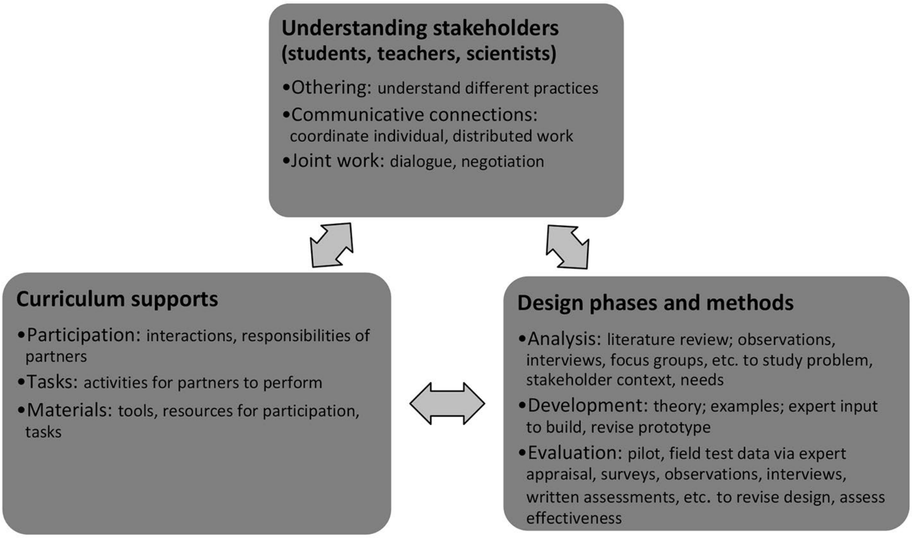

Fig. 1 Conceptual framework highlighting crucial dimensions of STSP designer work.

processes. Previewed in Fig. 1 and elaborated in the remainder of this section, the conceptual framework guiding the study highlights crucial dimensions of STSP designer work, and was synthesized from the wider literature on science education, STSPs, boundary crossing, and curriculum and instructional development and design processes.

The framework focuses on these three dimensions (and not others) because the dimensions together provide a specific and concise structure to systematically investigate and articulate designer rationales and measures that result in specific educational designs. This is consistent with the goal of the study and with calls in instructional design more broadly to relate processes and decisions directly to finished designs (Howard et al., 2012). Designing and thus understanding educational interventions requires detailed consideration of the needs and context of the target users, which in the case of STSPs focuses on the school and scientist partners who are key stakeholders in enacting the partnerships. Furthermore, designer ideals and vision are often embodied in (curricular) products to help end users implement the interventions, thus also requiring a careful analysis of the form of the design. Finally, crucial to understanding any educational design is to unpack the choices made and actions taken by its designers to overcome challenges, address tensions, and tackle trade-offs in creating specific design forms.

The dimensions of the present framework are derived from three classic perspectives discussed in curriculum design theory (Goodlad, 1994). The socio-political perspective refers to the values, interests, and influence of various stakeholders (e.g., students, parents, teachers, curriculum developers, etc.) and serves as a point of departure for the first dimension focused on sensitizing students, teachers, and scientists to one another's concerns through specific boundary crossing processes. The substantive perspective attends to the planned and enacted curriculum, including goals, subject matter content, and tools and materials, and can include the usability of the intervention. This perspective relates to the second dimension focused on what STSP designers create and how these designs support boundary

Leaf Measures

Why you are measuring leaves:

We can look at weather data (collected by entities such as NOAA) to determine whether a year is warmer or cooler than average, but information on organisms' responses to climate change is much harder to come by. This is where you can help!

In much of the country, many plant species drop their leaves to avoid the harsh winter weather. When spring arrives, these species then grow leaves in a process we call leaf out. For understory species and small trees it is important to leaf out earlier than the trees in the forest canopy in order to take advantage of the early spring sunlight.

As you have learned through the <<curriculum>>, timing is an incredibly important aspect in natural systems. Leaf out timing can be influenced by several factors, including temperature. In warmer years, plants often leaf out sooner. By measuring leaves during leaf out **and** after the leaves are fully grown, we can determine how far along leaves were at a certain date. Over time, we can use the data to monitor trends in both leaf out dates and in growth rates over the course of the growing season.

What you will need:

-Measuring device capable of measuring to the nearest millimeter (an ordinary ruler with tape over the "inches" side will suffice)

-Data Sheets (found on the <<curriculum website page>>)

How you will do it:

You will be selecting trees, shrubs or herbs with measurable leaves in the general area of your study site. Be sure to select species that:

-are native species
-are numerous in your study site
-replace their leaves each spring
-do not have compound leaves (such as Ash, Sumac or Locust trees)

-Select six independent plants or trees of the same species. Try to select plants that will not be altered/removed over the course of years.
-Label these plants in a permanent manner. You will need to measure leaves on these plants twice a year for the foreseeable future, so we would suggest using metal tree tags, which we can supply you with. If available, a GPS can be used to note the specific locations, or students can create a diagram of your study site.
-For each plant, randomly select five leaves. We suggest having the measurer close their eyes and feel for one leaf at a time. The person recording data can make sure no leaves are measured twice.
-Measure and record length to the nearest millimeter. Do not include the petiole/ leaf stalk (see Figure 1)
-Measure and record width to the nearest millimeter. Width should be measured at the widest part of the leaf.
-Once the plants have fully leafed-out, return to the same plants and repeat steps 3-5

Fig. 2 Fieldwork protocol for leaf measurement.

crossing in service of learning, teaching, and conducting science. Finally, the technical-professional perspective focuses on methods of engineering, logistics, testing, and refinement for manifesting ideas into specific designs. This perspective is related to the third dimension focused on designer methods during phases of design to iteratively yield the STSP.

Understanding stakeholders

Central to STSP design work is (coming to) understand the needs and wishes of the students, teachers, and scientists involved, and helping them to understand each other's perspectives in crossing boundaries between the cultures of science and schooling. Three processes that have been described in boundary crossing literature (Akkerman & Bakker, 2011) are particularly relevant to STSPs for integrating citizen science with school science. First, *other-*

ing concerns activities through which individuals come to understand the different practices of the collaborating sites. In STSPs, othering could take place when partners examine specific scientific practices for gathering and analyzing data for scientific research purposes, alongside the standards-based content that is specified in science education frameworks with which teachers and students are expected to engage. Whereas the process of othering as defined in the literature emphasizes differentiating explicitly among practices of collaborating sites (Akkerman & Bakker, 2011), the present study focuses on how othering manifests in designer work to help school partners and scientists understand how each other's work is framed by specific needs and expectations, especially in relation to the curricular goals pursued by schools and the specialized knowledge that underlies scientific research, as noted previously in the sub-section on challenges in designing for STSPs. That is, the study unpacks how stakeholders are supported to understand the standards-aligned science content that frames school instruction and the actual research and practices of local scientists, and how these relate to one another.

Second, to ensure sufficient cooperation, it is important that stakeholders establish *communicative connections* so that individual and distributed work through routinized exchanges and dialogue remains coordinated. This process can be performed via boundary objects (e.g., standardized forms and diagrams) or standardized procedures for gathering and recording of information by amateurs (Carlile, 2002; Star & Griesemer, 1989). For example, student-generated data captured on standardized data sheets or represented in graphs and tables serve as boundary objects between fieldwork orchestrated by teachers and the scientists' research institution, thus facilitating a communicative connection between partners.

Third, designers need to ensure that STSP participants are prompted to engage in *continuous joint work*, which provides focus and relevance to their dialogue and negotiation of meaning. To facilitate joint endeavors in STSPs, platforms for communication between teachers and scientists may include online sessions (Means, 1998) and in-person workshops and electronic discussion boards and conferences (Houseal et al., 2014). This may enable scientists to help teachers learn specific science content and tools and change their instructional practice in turn. And teachers may provide feedback to negotiate proposed joint activities, such as modifications to data collection protocols to suit students' abilities while satisfying scientists' criteria for reliable data.

Curriculum supports

STSP designers create supports within the curriculum to facilitate the boundary crossing processes described before. In so doing, designers must ensure that students are sufficiently equipped to perform basic scientific work while aligning their action with both scientists' questions and the learning outcomes specified in curriculum frameworks (Zoellick et al., 2012). Further, curricular supports must make relevant scientific information available for student reading and critique, and facilitate ongoing dialogue with scientists to help students and teachers develop, refine, and conduct school-based investigations (Gray et al., 2012). While educational designers attend to myriad details, most of them relate to participation, tasks, and materials (McKenney & Reeves, 2019; Sandoval, 2014).

Participation

Designers develop and articulate a vision for *participation*, i.e., how students, teachers, and scientists will interact with one another, and the roles and responsibilities they will perform during the partnership. For example, in STSPs, students may be expected to collaborate during fieldwork, and to gather and share specific samples of data. The envisioned teacher role may include providing feedback to scientists about the feasibility of the fieldwork tasks and protocols (Houseal et al., 2014). Further, scientists may be expected to communicate standardized methods of data collection with students and teachers (Saunders, Roger, Geary, Meredith, Welbourne, Bako, et al., 2018), respond to questions, share relevant information, and include student-generated findings in their dissemination efforts (Bonney & Dhondt, 1997).

Tasks

Designers also create the *tasks*, or learning activities, in which students (often together with teachers and/or scientists) are expected to participate during the partnership. The envisioned tasks may involve student projects organized around driving questions (Condliffe, Qunit, Visher, Bangser, Drohojowska, Saco, et al. 2017) and participate in class discussions to construct scientific explanations (Novak & Treagust, 2018). Sample tasks for students in STSPs include generating scientific questions, conducting fieldwork to gather data based on specified protocols, and analyzing and reporting findings in different communities (Houseal et al., 2014). Tasks for teachers in STSPs are attending professional development sessions aimed at helping students generate suitable scientific questions and interpret data (Zoellick et al., 2012). Finally, sample tasks for scientists are formulating questions, research design, and logistics of implementing citizen science projects on school sites (Saunders et al., 2018), participating in online and/or in-person meetings with teachers (and students) to clarify science content and to conduct fieldwork (Houseal et al., 2014; Kelemen-Finan, Scheuch, & Winter, 2018), and teaching classroom-based lessons on specific concepts and practices through interactive exercises and discussions (Miczajka, Klein, & Pufal, 2015).

Materials

Finally, designers create *materials to* support the learning activity in ways that align with the envisioned participation. These include digital and/or analogue tools and resources, such as books, guides, and communication media that enable students, teachers, and scientists to perform specified tasks. Student materials may include written prompts to facilitate data analyses (Songer, 2006). Teacher materials may present learning objectives and desired student responses (Schwartz, 2006), definitions of and rationales for scientific practices (McNeill, González-Howard, Katsh-Singer, & Loper, 2017), educative notes explaining students' typical ideas about scientific concepts (Roseman, Hermann-Abell, & Koppal, 2017), and strategies to engage students in scientific practices (Bismack, Arias, Davis, & Palincsar, 2015). Sample STSP materials are fieldwork protocols and worksheets containing stepwise instructions about scientific practices (The Globe Program), and lesson plans and teacher guides providing inquiry-based strategies (Trautmann, Shirk, Fee, & Krasny, 2012).

Finally, the teacher guides may include personal messages from the scientists for motivating school partners to sustain their investigations (Means, 1998).

Design phases

Educational designer decision-making is a dynamic process which unfolds through iterative phases, each of which features activities and deliberation to realize the underlying vision (Branch & Merrill, 2012; Gustafson & Branch, 2002; McKenney & Reeves, 2019). As van den Akker (2013, p.56) describes, it is “usually a long and cyclical process with many stakeholders and participants; in which motives and needs for changing the curriculum are formulated; ideas are specified in programmes and materials; and efforts are made to realise the intended changes in practice.” While the sequence and duration of the process vary with each project, three main phases are well-described in instructional and curriculum design literature: analysis, development, and evaluation.

Analysis

Designers typically begin with this phase, in which they study the problem (Thijs & van den Akker, 2009) and analyze the needs of the target audience (Edelson, 2002; McKenney & Reeves, 2019). The main methods used in this phase include reviewing the literature to explore how other designers have understood and responded to similar problems and gathering data about the target context and stakeholders. The literature review may focus on learning theories and prior curriculum materials and research to foster teacher knowledge (Kruse et al., 2013; Roseman et al., 2017). The data about context and stakeholders’ needs, wishes, existing practice, and challenges may be gathered through survey questionnaires about their perceptions of the problem and possible solutions (Akomaning, 2019) and through interviews, observations, instructional logs of existing curriculum use (Davis et al., 2014). Accordingly, the tasks and participation structures are envisioned, and preliminary design requirements and specifications are generated to plan the materials. For example, designers analyze ways to balance the research needs of scientists with classroom constraints voiced by teachers, and students’ interests in contributing to authentic scientific research (Zoellick et al., 2012). They may also inventory existing needs to be addressed by the curriculum supports. For example, a common teacher need is addressing gaps in their own knowledge of specific scientific concepts and relevant scientific practices to support their students’ learning (Drayton & Falk, 1997, 2006).

Development

In this phase, designers specify the tasks, materials, and participation structures, and construct and revise prototypes of these elements based on inputs from both the analysis phase and the subsequent evaluation phase (McKenney & Reeves, 2019). The main methods include reviewing theory and inspiring examples to derive specific ideas and gathering input from local expertise (McKenney & Reeves, 2019), such as from scientists (Edelson, Gordin, & Pea, 1999; Songer, 2006) and from teachers to frame science content in real-world contexts (Rivet & Krajcik, 2004). For example, scientists may help identify specific content for which student-gathered data are crucial to advance scientific knowledge while also developing students' own understanding (Means, 1998). Throughout this phase, designers fine-tune both their vision and the materials intended to support the enactment of tasks according to the envisioned participation structures (McKenney & Reeves, 2019). They also return to this phase after conducting additional analyses or evaluating (prototype) designs.

Evaluation

In this phase, data are gathered to inform subsequent revisions to the tasks, materials, and participation structures, and to assess their effectiveness (Branch & Merrill, 2012; Gustafson & Branch, 2002). The main methods include conducting pilots of early prototypes and field tests of more mature versions of the design to generate various sources of data for formative and summative evaluation (McKenney & Reeves, 2019). For example, designers may appraise the accuracy of the science content highlighted in the materials from external experts (Davis et al., 2014), observe student engagement (Edelson et al., 1999), examine student understanding through written assessments (Clarke & Dede, 2009) and interviews (Wiser, Smith, & Doubler, 2012), and obtain in-person or survey-based feedback from teachers, such as on fieldwork protocols (Houseal et al., 2014). Following this phase, designers often return to the development phase to revise the design elements.

Based on the preceding conceptual framework and literature review, the following study question was formulated to attain the goal of generating an in-depth understanding of designer work that is grounded in empirical findings and informed by the wider literature, and to offer insights in designing for STSPs to integrate citizen science with school science:

How do designers attend to stakeholders' (i.e., students', teachers', and scientists') needs, what curriculum supports do they create, and what methods do they employ during phases of the design process in designing for STSPs to integrate citizen science with school science?

Method

Study Approach

To answer the study question, a qualitative interpretive case study (Merriam, 1988) was conducted using a participant-observation approach, which helped capture phenomena that are generally challenging to investigate deeply (Yin, 2014). This approach was chosen because the desired product was a detailed articulation of designer rationales and activities behind specific designs (Howard et al., 2012), in this case, a single successful STSP.

The present STSP involved ecologists investigating climate change at a scientific research institution in the United States and students and teachers from local middle schools contributing climate-related data to the ecologists' research. The STSP was part of a mandate for outreach by the scientific research institution. The shared goal was "linking the science classroom with current science research being conducted by field stations and other scientific institutions," thus "bringing science research closer to the science classroom." As mentioned in their grant proposal, the STSP aimed to provide students with opportunities to experience key scientific practices through data collection on local sites and analyses of their own as well as other existing data sets. In so doing, it was hoped that students would develop "interest in and engagement with science" and "gain a better understanding of science as practiced." The grant proposal also stated that the STSP was warranted by research on the potential of citizen science for science education, and it intended to "contribute to and extend the broad movement of citizen engagement in vital research on climate change and its consequences by making possible the contribution of student-collected data to scientists' understanding of local effects of climate change." The STSP was designed in collaboration with curriculum writers working at an independent STEM educational research and development organization in the United States. The curriculum writers brought knowledge of the relevant science and an "appropriate range of skills, attitudes, and cultural sensitivities" to facilitate the school-scientist partnership. Although curriculum writers were involved in this capacity, the design work focused on the goals, needs, and concerns of the scientists and school partners, who were the stakeholders in the present STSP.

The STSP intended to deepen students' understanding of the central concepts and practices in climate science, including the concepts of weather, precipitation, and temperature, and the practices of fieldwork techniques and analyses of longitudinal data sets. The curriculum consisted of two main components: an in-class unit and fieldwork. The in-class unit was of one week duration to help middle school students (of ages 12–13 years) investigate climate change as it manifested in the local environment. It was aligned with the science education frameworks in the U.S. stressing instruction in disciplinary core ideas, crosscutting concepts, and practices (NRC, 2012). The in-class materials contained guides for teachers and students (see Results for more details).

The unit was also aligned with a standardized vegetation fieldwork component, in which students gathered data on leaf length and width and canopy cover on transects near their school grounds twice over a two-month period each year (ideally) – at first leaf opening, and at full leaf expansion (see excerpt of fieldwork protocol in Fig. 2). Additionally, students measured height and diameter at breast height (DBH) of trees once a year. The vegetation measures had been established by the ecologists through previous collaboration with students to study migratory bird responses to climate change. In addition to engaging students in the present STSP with scientific practices, the vegetation data (as indirect indicator of insect availability) were intended to help the partner ecologists examine over the long term how ecosystem changes, including those in temperature and vegetation, influence bird behavior. As clarified in the curriculum materials, the data on bird biology and behavior collected by the scientific research institution over many decades indicated that migratory birds have changed their seasonal behavior with rising temperatures and are returning earlier. Other regional phenology data, such as frog calling and butterfly range shifts, also indicated that some organisms were responding to the warming climate. To understand better how other local species were changing in measurable ways, the ecologists predicted that trees and shrubs in the local region would respond by leafing out earlier (bud-break and full-expansion), and over time, were expected to grow at higher rates as measured by height and DBH. There were also supplementary fieldwork options involving less standardized data collection (e.g., maintaining a phenology calendar about birds, plants, and insects) to yield more short-term and thus more rewarding results in terms of climate change (Bopardikar et al., 2021; see Results for more details on a menu of fieldwork project options).

Fieldwork materials for students took the form of kits (containing micrometers and DBH measuring tape), written stepwise protocols, and print-based data record sheets created

The goal of this project is to create a transferrable model for students to learn about climate change through collaborative participation in citizen science initiatives and integrated curriculum pieces used by their middle school teachers.

The curriculum is still based heavily on effects of climate change with modifications to explain the relevance of all the field techniques suggested below.

Given the initial observed difficulties of properly/completely collecting the required sample sizes, we are moving in the direction of a menu of several choices for the field work. This gives teachers control over what data they are required to collect and (more importantly) the required allotment of time. Regardless of the teachers' selections, they will still be required to use <<STSP>> curriculum pieces throughout the school year.

The basis of the program is not too different from our original thesis; important links emphasized throughout curriculum and fieldwork choices:

- Physical aspects of climate change
- Biological aspects as indicators of reaction (or not) to rapid physical changes
- Warm temps – earlier leafout – earlier caterpillar/invert. hatch – timing of preadator/pollinator etc. adaptability to the above cascade of altered timing
- Comparison with long-term data bases such as <<scientific research institution's>> migration data, phenology network, etc.
- School data at least potentially useful and shared on <<STSP project>> website and other national websites – your contribution counts! Sum greater than individual parts, etc.

<<STSP>> field work spectrum from less to more time commitment

Things to consider…

Equipment required

Knowledge required

Time commitment/timeframe

Transferability to schools outside <<region in northeastern U.S.>>

Fig. 3 Project document showing preliminary designer ideas for fieldwork menu.

by the ecologists. For teachers, there were also short videos in which the ecologists demonstrated their methods and offered tips for locating suitable sites to gather standardized vegetation measurements. For less standardized fieldwork, there were briefs, background information, and criteria and tips for data collection and reporting to various phenology and scientific programs. Finally, there were webinars for teachers' professional development (PD). The in-class unit, fieldwork, and teacher PD webinars were intended to scale up to involve schools and scientist partners in different regions of the U.S.

Evidence of STSP Impact

We deem this a successful design case, based on project documentation showing a positive impact on student learning. Student responses on written pre-and-post assessments created by the designers showed significant improvements in students' understanding of weather

Table 1 Changes in students' understanding of specific topics

Topic	Percentage of students providing satisfactory, complete, and/or accurate responses on the pre-assessment	Percentage of students providing satisfactory, complete, and/or accurate responses on the post-assessment	Z score and p-value[1]
Distinguishing weather from climate	42%	72%	-5.253, $p<.0001$
Impact of seasons on plant and animal life activities	63%	79%	-2.336, $p=.02$
Species' responses to climate warming	17%	28%	-3.467, $p=.001$

versus climate; impact of seasons on plant and animal life activities; and species' response to climate warming (see Table 1). All of the questions on the pre-post assessments required constructed responses. To assess the responses, initially during the STSP design work, a set of open codes was developed, applied, and refined by the designers through negotiation among members of the design team, with an inter-coder agreement greater than 80%. The codes identified: (i) incomplete or unintelligible answers, and (ii) incorrect answers, in contrast to answers that were (iii) brief but at least partly correct, (iv) correct but incomplete, or (v) correct and full. For the purposes of the quantitative analysis, the designers collapsed all five conditions as described above into two categories: i and ii, vs. a combination of iii, iv, and v. The revised pre-post questions and analytic codes were then used to assess students' understanding during subsequent implementations of the STSP, with two members of the design team coding all responses and resolving differences in codes. Furthermore, feedback from teachers revealed the fieldwork to be of value and the in-class unit to be usable and well-aligned with their curricular needs.

Participants, procedures, and data sources

Four designers participated in this case study. Two of the designers were ecologists from the scientific research institution mentioned previously. While practicing scientists, they had facilitated activities for environmental education previously. As such, they were both designers of and stakeholders in the present STSP. The other two designers were curriculum writers from the educational research organization; they had training in ecology and prior experience with science curriculum design. One of them served as project leader. All participants signed informed consent documents prior to the start of the study, which included granting the researchers access to relevant dialogue, to design documents, and to data gathered by the designers about student learning and teacher implementation[2]. However, whereas the designers provided various data for the study, they did not serve as authors of this paper. Furthermore, whereas the authors gathered data for this study from the designers, they were not directly involved in designing for the STSP, nor were they stakeholders in this partnership. As elaborated below, the first author led the data collection, analysis,

[1] The Z-score was calculated based on a sample of 73 students, with Wilcoxon Signed Ranks test based on negative ranks.

[2] This research was approved by the Institutional Review Board at TERC.

and reporting for the study, while the second and third authors played a supportive role by providing feedback to guide these efforts.

The study took place over a three-year period, during which the first author served as a participant-observer for approximately half of that time and was ‘immersed’ in the regular design work conducted by the participants (Emerson, Fretz, & Shaw, 1995). During this time, multiple overlapping methods were used in conjunction to enable prolonged engagement with and persistent observation of the design work and to yield dependable findings (Guba, 1981). Casual direct observations were made (Yin, 2014), interviews were conducted, and documents were gathered from the middle of the first year, as the designers were preparing for the first cycle of testing to nearly the end of the second year, as the designers were conducting the second cycle of testing. After the observational period ended, document and interview data continued to be collected and analyzed.

Three sources were used to triangulate the data and generate credible and confirmable results (Guba, 1981; Yin, 2014). First, researchers kept observational notes of the design team’s weekly meetings and enactment of standardized vegetation fieldwork at a local school site. The notes were generally drafted immediately upon observing those events to record the complexity of designer reasoning and action (Emerson et al., 1995). Second, designer-generated documentation was collected and analyzed. This included planning documents; email communication; drafts of materials for the in-class unit, fieldwork, and teacher professional development; project grant proposal; written pre-and- post assessments of students’ understanding; and teacher surveys. Finally, the project leader was interviewed three times throughout the project and each of the other participants was interviewed twice, for a total of nine interviews. The interviews were semi-structured and aimed to inquire more deeply into designer thinking and methods behind curriculum supports created to implement the STSP. Sample questions were: *How important is this [boundary crossing process] to your STSP model and why? In helping other scientists and schools to [engage in the boundary crossing process], what factors, requirements, or constraints did you take into account while developing these materials? How did you arrive at these insights/decisions?* The interviews were conducted individually and lasted 80–110 min. Together, the three data sources contributed to understanding evolving designer considerations about stakeholder needs, curriculum supports, and design methods.

Data Analysis

The data were analyzed in two phases. During the observational period of the study, the data from fieldnotes and documents were analyzed to understand designer thinking and activities behind various elements of the curriculum created for the STSP. Grounded in emergent interpretations of the data, this analysis resulted in interim reports describing designer thinking and activity to help the designers to take stock of their work. The first author prepared drafts of the reports, which were discussed and iteratively revised with the co-authors until there was consensus. Member checks (Guba, 1981) were conducted with the participants to verify and revise the reports as appropriate. The interview transcripts were analyzed initially by the first author, then reviewed independently by the second author to verify and extend the interpretations. After the three-year period, guided by the codes described in Table 2, all data were reviewed by the first author to confirm and elaborate a full set of findings about stakeholder needs, curriculum supports, and designer methods to create those sup-

Table 2 Coding scheme to analyze designer work in creating STSPs

Code	Definition	Sample Excerpt
Understanding Stakeholders (Boundary Crossing Processes)		
Othering	Stakeholders understand different practices in relation to one another.	[Excerpt from designer interview]: *Teachers, and through them the students, need to understand more about the science, the meaning of it from the scientific point of view, so they can fit it into their whole curricular purpose. And it's not evident to a working scientist that in order to make sure that the data are collected reliably, the teacher and through them the students need to have a good feel for why these data are being collected, what is gained or lost by the quality of the data.*
Communicative Connection	Stakeholders perform distributed work through routines and procedures.	[Excerpt from designer interview]: *You do have to provide more information for teachers when you are [designing options for fieldwork], and you have to be prepared to provide more protocols and refer them. And you can't just refer to – look at this website, this is how you study insect abundance. You have to very precisely say, lay out the white sheet. Hit the tree. Count the insects down below. Contribute it to the following database.*
Joint Work	Stakeholders engage in continuous dialogue and negotiation of meaning.	[Excerpt from an annual progress report to the grant funding agency]: *In many cases the teachers didn't really know how to conduct field work, and weren't comfortable or knowledgeable about the natural history of their area. The presence of enthusiastic and knowledgeable naturalists as represented by [partner ecologists] meant that the routine of field work was enriched or enlivened by stories, spontaneous comments about other features noted, and interaction with the naturalist "habits of mind" that make field work stimulating and engaging. Moreover, [partner ecologists] provide a warrant for the authentic value of the field work, which was exciting and motivating for students and teachers alike.*
Curriculum Supports		
Participation	Interactions, roles, and responsibilities envisioned for stakeholders.	[Excerpt from newsletter to teachers]: *This year, you will be the ones leading these field sessions, so it is imperative that you understand the techniques and rationale for the data you are collecting. The combination of the protocols, instructional videos, and recorded webinars will provide you with the information you need to master the techniques and relate them to the curriculum.*
Tasks	Learning activities envisioned for stakeholders' participation.	[Excerpt from designer notes in planning documents to envision fieldwork projects]: *Original vegetation sampling both during early spring leaf out and later once leaves are fully grown. Schools must set up and/or maintain one or more transects in a green space near the school. These transects serve as reference points for annual fieldwork.*
Materials	Digital and/or print-based resources to help stakeholders engage with the envisioned tasks.	[Questions in the in-class teacher guide to facilitate a whole-class discussion]: *Which species is most vulnerable to ecological mismatch, and why? How could we use bird data or other data as "bio-indicators" of what's happening to Earth's climate?*
Design Methods		

Table 2 (continued)

Code	Definition	Sample Excerpt
Analysis	Designer work to uncover stakeholder needs and to derive initial design requirements and specifications for creating curriculum supports	[Excerpt from survey administered to teachers about curriculum and fieldwork implementation]: *Question: Were there aspects of the program you would have wanted more training or support on? Responses: orientation to the curriculum, field techniques, data analysis, connecting curriculum to field activities.*
Development	Designer work to determine content and sequence of instructional activities and to craft curriculum materials for supporting the envisioned participation and tasks	[Excerpt of design principles to develop fieldwork projects involving different "effort-levels," as described in an annual progress report to the grant funding agency]: *(i) The field activities at each "effort level" will produce data of scientific interest — to the students as well as the scientists, and suitable for contribution to data sets being collected aggregated by other projects (e.g. the National Phenology Network, Audubon, or regional phenology research).* *(ii) The activities at each effort level should be accompanied by supportive materials for student and teacher linking the content and the practices necessary for the research component to the school curriculum and NGSS.*
Evaluation	Designer work to test and guide revisions to curriculum prototypes	[Excerpt from designer notes about student-generated data from the standardized vegetation fieldwork]: *Although they were provided with seemingly ample tools, no school was successful in collecting a complete set of pre-leaf-out data. No school got out a second time to collect post-leaf-out data. These findings suggest a major shift in our data-collection requirements/methodologies is necessary if we anticipate further program expansion without a serious drop-off in data quality.*

ports. The a priori codes were based on the three dimensions of the theoretical framework. They were applied deductively (Miles & Huberman, 1994), and the code definitions were refined through feedback from the co-authors and the project leader when discussing sample excerpts. Thereafter, a draft case study report was discussed with the authoring team, further refinements to the coded data were made until 100% consensus was reached, and finalized after a final member check with the project leader (Yin, 2014).

Results

This section takes designer understanding of stakeholders as the leading organizing principle and portrays how insights concerning the boundary crossing processes of othering, communicative connections, and joint work emerged over time. Curriculum supports are described in relation to each boundary crossing process, along with the design methods through which the supports were created to aid stakeholders' engagement in those processes. The main findings are previewed in Table 3 as an advanced organizer.

Table 3 Main findings about designer attention to stakeholder needs, curriculum supports, and design methods

	Boundary Crossing Processes		
Understanding Stakeholders	Othering: Clarify standards-aligned science content for student learning, nature of partner scientists' research	Establishing communicative connection: Enable suitable data collection, exchange of fieldwork information between schools and their partner scientists	Continuous joint work: Regular interactions among partners, with substantial dialogue and negotiation of meaning around shared goals
Curriculum Supports	Participation: Students would participate in teacher-facilitated discussions; scientists would motivate fieldwork Tasks: Individual assignments; whole-class, small group discussions; teachers would guide student tasks through questions and specific directions; scientists would communicate fieldwork rationales and theoretical connections through curriculum materials. Materials: Regionally customized curriculum presents relevant readings, authentic data sets for in-class unit; Teacher Guide clarifies learning goals, questions, desired student responses, fieldwork purposes	Participation: Teachers would facilitate fieldwork projects connected to scientific programs; scientists would provide guidance for contributing student-gathered data to suitable scientific programs Tasks: Students would gather data on specific species, contribute data to class discussions, local partner scientists' research, national databases; teachers would guide students through questions and stepwise directions; scientists would identify ecological programs, provide materials for students' investigations. Materials: Hands-on kits; menu of fieldwork options; written protocols; data sheets; video tutorials; briefs, background information; stepwise guidelines for analyses of student-gathered data	Participation: Teachers and scientists would engage in mutual communication towards shared educational and scientific goals. Tasks: Teachers would participate in PD webinars, provide feedback on in-class unit, fieldwork; scientists would assist through in-person, electronic communication Materials: Newsletters; online webinars (recordings)
Design Phases	Analysis: Gathered teacher feedback on interest in enacting data analytic tasks Development: For customization, reviewed information on relevant regional ecosystems; gathered input on locally relevant data sets from scientists	Evaluation: Early pilot trials in local schools revealed standardized fieldwork challenges Development: Reconceptualized scientific research program behind fieldwork; surveyed citizen-science programs, protocols; drafted fieldwork options; refined drafts based on ecologists' input	Evaluation: Observations, teacher surveys from pilot trials revealed benefits of scientist presence, challenges in curriculum enactment, need for supplementary fieldwork, data analysis activities Development: Gathered teacher recommendations for webinar content

Othering: identifying practices of schooling and climate science research suitable for classroom enactment

Understanding stakeholders

Though designers used other terms to describe it, their work clearly supported STSP stakeholders to engage in othering. For example, interviews, design documents, and observations of designer team meetings revealed that to help school practitioners consider disciplinary practices alongside science education standards, the designers attended to teachers' difficulties with enacting data analytic activities in relation to fundamental climate science concepts. While the current science education standards emphasized teaching climate change, teachers lacked adequate supports to enact those standards. This was especially so with the central scientific practice of data analysis. As a curriculum writer explained during interviews, previous in-person discussions with local teacher participants (during *the analysis phase*, prior to commencing this study) had indeed indicated interest in enacting data analytic tasks to facilitate the integration of science and mathematics in their classrooms. However, whereas teachers and students might participate in data collection, they typically resisted sensemaking of the data.

Curriculum supports

Participation. During team meetings, the designers thus formulated a vision for teacher and student participation, centered on teacher-facilitated whole-class and small-group discussions around authentic data sets. The discussions aimed to help students understand patterns in long-term data sets in relation to relevant climate science concepts and to understand the epistemology of science – "how we know what we know." Scientists were expected to motivate students and teachers to conduct fieldwork, for example, by explaining the relationship between fieldwork techniques (e.g., measuring leaf-out to document vegetation changes) and larger ecology concepts in climate science theory related to their research. In formulating this vision, the designers considered the challenges of scientists in communicating their research rationales and data requirements in engaging and accessible ways to middle school students to enable them to contribute reliable scientific data. As a curriculum writer noted during interviews, it was important to help teachers:

> …understand more about the science, the meaning of it from a scientific point of view, so they can fit it into their whole curricular purpose. And so, the science has to be brought towards them, so they can see how for those concerns. And the curriculum developer also needs to think about how much of the science might be unfamiliar to the teacher. So there's translation from the science side in that direction… it's not evident to a working scientist that in order to make sure that the data are collected well, collected reliably, the teacher and through them the students need to have a good feel for why these data are being collected, what is gained or lost by the quality of the data. For the scientist, that's obvious because you don't suggest data collection unless you've got a purpose… so, they need to understand and be patient with the curriculum developer to unpack it in ways that reach the right grade level.

Tasks. To bring this designer vision to life, as drafted in the teacher and student guides early in the STSP, in-class *tasks* for students included completing individual assignments and engaging in whole-group and small-group discussions. These tasks were centered on readings and authentic data sets involving both student-gathered vegetation data and longitudinal bird data obtained from the partner ecologists' research, mainly pertaining to the ecology of northeastern United States region. The discussions also addressed standardized vegetation fieldwork rationales and techniques prior to conducting the fieldwork. The tasks for teachers were to raise specific questions and provide specific directions to guide the flow of these instructional activities in the classroom. Whereas these tasks were to be enacted by students and teachers in the classroom, the task for scientists was to support classroom enactment by clarifying through curriculum materials the scientific rationales behind the fieldwork and its basis in broader climate science theory.

Materials. The teacher guide for the in-class unit included questions and desired student responses around readings and data sets related to climate science concepts and educative notes about students' conceptions regarding climate change. There were also tips for discussing the rationales for the fieldwork techniques and the hypotheses behind the standardized vegetation fieldwork as it pertained to the partner ecologists' ongoing research. Thus, through the written materials designed to enact the vision for in-class participation and tasks, the designers hoped to clarify (and help stakeholders understand) standards-aligned science content that framed classroom instruction and the fieldwork rationales and techniques that framed ecological practice of scientists, delineating how these related to one another. The findings presented below on design phases show how the in-class curriculum was revised later by the designers to customize the content to different geographic regions, thereby geared towards supporting school partners and scientists with respect to this particular boundary crossing process.

Design phases

Development. The original curriculum was designed for schools in the northeastern region of the U.S. and aligned with bird data gathered by the partner ecologists. As described earlier, it situated the standardized vegetation fieldwork within research on climate science to help school partners understand how climate science theory (as conveyed through concepts emphasized in curriculum frameworks in the United States) related to the study of specific aspects of biology conducted by partner scientists in their local region. To extend the STSP later to a geographical region on the west coast of the U.S., the designers sought to adapt the in-class curricular content to continue supporting new school partners to understand scientific practices, especially collection and analyses of longitudinal data sets as embodied in the work of local partner scientists, in light of the science curriculum frameworks. In so doing, adaptations to readings and associated data sets about bird species were crucial. To that end, and as envisioned originally in the grant proposal and explained later during interviews, a place-based learning approach required revisions to make the curriculum relevant to schools and scientific research in that region and also to maintain the motivational value of associating with local environments (and local organisms) to foster student engagement and learning. Through the local environment, the designers hoped to provide students with both an empirical basis to learn about climate change based on what students could see happening around them and an affective connection to local organisms so they would engage more deeply with the content. A curriculum writer reasoned thus about customizing the curricular content to the local ecological context:

> Our conviction [is] that the science of climate change is going to be the most accessible, and possibly the most actionable, for people if they see it happening locally. So that's been the focus of most of our climate change work. So, we developed the curriculum to have the most impact for people in [more specific region in northeastern

> U.S.]. And that was nice because it connected best with the data set from [the partner scientific research institution]. So, what that meant was that if somebody else wanted to try out this general approach, the place-based element of it required revision and customization.

To customize the curriculum, the designers began considering possible substitutions with respect to longitudinal data and stories to depict in the curriculum. A curriculum writer reviewed the original curricular content to identify specific data sets and readings about bird species related to the northeastern U.S. to be replaced with content relevant to the west coast. Further, information on ecosystems on the west coast was reviewed to understand better the climatic differences compared to the northeastern U.S. An ecologist consulted with science educators at research stations on the west coast about migration timing of common bird species in response to climate change. As noted in designers' email communication and drafts of the revised curriculum materials, new longitudinal data sets and stories reflecting local conditions were substituted into the in-class unit. In fact, during interviews, this is how an ecologist emphasized the importance of seeking input from local scientists to customize the curriculum for geographic relevance:

> When we go to an area that is different, we have to find out from the local scientists which would be good species to look at and feature, ideally something the students know. So we worked with the scientist educators in [a scientific research institution on the west coast] to find out some migratory species that were coming a short distance and were coming back earlier because of climate change. And as with [birds studied at their own scientific research institution], some very long distance migrants do not detect climate change, and therefore are not coming back earlier. And we contrasted one species that does that there and another species that is reacting to climate change. And that uses local data. And there's perhaps even a good chance of when the students go out and measure vegetation in the field there, they may see those birds, and the teachers will say to them, there's the bird that's in your curriculum.

Communicative connection: coordinating fieldwork

Understanding stakeholders

Designer work supported STSP stakeholders to *establish communicative connection* to coordinate their fieldwork through suitable data collection and exchange of relevant information. During interviews, the designers explained that they viewed fieldwork in STSPs as breaking barriers between science and the general public, empowering students to understand what was involved in collecting data and generating findings, and to recognize their role in contributing to climate science knowledge building. This was deemed critical to help students understand real-world effects and to nurture their personal interest in and concern for the real world through first-hand experiences in local, personally meaningful surroundings. An ecologist described the importance of fieldwork thus:

> Everyone, I think, is aware, especially in conservation biology and field biology, that fewer and fewer of the students even up to college level that you get … have had the experience of going out in the field. So, we thought an important aspect is really to put people back in touch with the real biology that is going on all around us. And unless everyone understands that these are real world effects, if they haven't experienced the real world, why would they care? So, a very important part of [the STSP] was to get students out of the classroom and get them into the field, even if it's only for two or three afternoons during the whole year, just for a period when they can collect some data, learn how to do this. And that gives them a personal interest in what's going on.

Curriculum supports

Participation. The vision for participation, as formulated in the grant proposal and as enacted subsequently, emphasized students' involvement in fieldwork that was framed (and motivated) by research projects introduced by partner scientists and other broader research programs. The designers also stressed that teachers would facilitate the fieldwork, and scientists would provide guidance on contributing student-gathered data towards appropriate scientific programs.

Tasks. During team meetings and in design documents there was evident a refined vision that students would collect and discuss observational and/or measurement data related to vegetation, birds, and insects near their school grounds. The designers also intended for students to contribute those data to research conducted by partner scientists and/or other national citizen science databases. The tasks for teachers included guiding students on the field and in class through questions and stepwise directions for planning and conducting different ecological investigations. The tasks for scientists were to identify suitable ecological programs for which student investigations could contribute meaningful data and to create or adapt as required specific protocols and materials to support school partners in conducting the investigations.

Materials. For the standardized vegetation fieldwork, early in the STSP, the designers provided school partners with hands-on kits, written protocols, data sheets for recording observations and measurements, and video tutorials demonstrating the ecologists' techniques to assist with collecting various vegetation data. Additionally, for supplementary fieldwork envisioned later in the STSP, there were science briefs and other background information. Finally, there were tips to help students analyze the data and report the findings to suitable scientific programs (see also the section on Research Approach for details about the fieldwork). Thus, through the written materials designed to enact the vision for fieldwork participation and tasks, the designers intended to provide school partners and scientists with effective means and procedures to cooperate around field activities and to exchange relevant information (e.g., research questions, data collection guidelines, data sets, etc.), thereby coordinating the flow of data across different sites. These materials have been reported in more detail in our previously published work (Bopardikar et al., 2021). The findings on design phases presented below show particularly how curriculum supports for supplementary fieldwork geared towards this boundary crossing process were generated by the designers.

Design phases

Evaluation. The designers observed pilot implementations of the standardized fieldwork to evaluate the extent to which teachers were comfortable with the content, prepared to lead the tasks, made any modifications, and faced logistical issues including time constraints. They also noted the extent to which students were engaged and seemed to understand the content. Additionally, the ecologists evaluated the extent to which relevant, accurate, and complete vegetation measurements were submitted by the school partners. They noted that school partners had difficulty in following the standardized protocols and data sheets, and that limited time was available to complete the standardized fieldwork, in part due to conflicts in the timing of spring vegetation development and standardized assessment schedules in schools. These challenges resulted in the schools' contributing vegetation data that were incomplete, contained errors, and had limited utility.

Development. In subsequent team meetings for redesigning the fieldwork, therefore, designers considered tailoring the fieldwork by providing a broad framework adaptable to the purposes, preferences, requirements, and constraints of schools and their partner science organizations in different regions to scale up the STSP. The result manifested in a menu of project options to help teachers plan fieldwork that would be both useful for science and within the means of the school partners. The options on the menu represented different "effort levels" according to the complexity of set up; estimated time required; number of variables under study; amount of data; extent of data management; time for teacher professional development; and the number of required class discussions. The low effort-level projects involved simpler protocols for feasibility from the teachers' point of view and reliability from the scientists' point of view. This was important to help students generate data that would be of value and avoid simply going through the motions of learning techniques. The more ambitious projects involved stricter protocols for reporting to different ecology programs. This was important to highlight the scientific value of the fieldwork and to enable students to not only explore their own data sets but also bigger data sets collected nationally. As an ecologist explained during interviews, although precise implementation, standardized data, and the scientific method were important to scientists, the emphasis of this STSP was on:

> This field now of citizen-science where people are contributing parts to a database. We realized if we can make this more relevant in terms of contributing not just to what [present scientific research institution] would do and what [they] would like, but to national databases that can be used by any scientists who are studying climate change.

Furthermore, a curriculum writer recalled during interviews that the projects could be implemented in a variety of spaces available to students, such as in their local surroundings or on transects set up specifically for the fieldwork. This was important to reduce dependence on proximity to natural environments, which was pertinent especially to urban areas. Additionally, the menu indicated alignment of the content with the standards in science curriculum frameworks in the United States to highlight the pedagogical value of the science embodied in the fieldwork projects.

Finally, given the interdisciplinary nature of the subject and informed by teacher feedback, designers stressed modularity in fieldwork to help teachers incorporate the projects in different grades or different content areas (e.g., earth science or life science). This was important because the climate science education standards were addressed in varied ways in different schools. The modular design, however, also meant thinking about how the fieldwork options would build towards a coherent structure to contribute towards both science education and scientific research. During interviews, a curriculum writer articulated the challenge thus:

> If you snap them all together, it should be a unit, but if you take it apart, each sub-unit should be able to stand on its own. And yet, call out to the others at some point. If we allow more pluralism in regard to field activities, then the [fieldwork] options have to make sense from the point of view of the scientific research program. So that meant clarifying the scientific research program to the point that the pieces that we offered to the schools actually could project onto this larger thing.

Guided by these specifications and rationales, input from the ecologists, and similar ideas in regional ecology research, the curriculum writers first reconceptualized the STSP's original scientific research program into a broader program on emerging regional cross-trophic level impacts of climate change, identifying hypotheses and species to address in the program. The revised program focused on a systemic context for climate change-related research, with connections among plants, insects, and bird arrival times and the ripple effects of temperature and precipitation changes on these organisms. This step was critical to explicate the relevance of students' fieldwork to citizen-science programs with strong scientific rationales and clear questions to answer. There was flexibility in choosing species to contribute a variety of rigorous long-term data, giving students and teachers opportunities to engage with science that was not only meaningful but also pedagogically valuable. For example, they could study a particular warbler, its favorite caterpillar, and the caterpillar's favorite food plant, or worm-eating warblers in general, or fruit-eating birds and the pests on the fruit.

Based on the scientific research program, several design principles emerged to guide the creation of different effort-level projects, as explained in a progress report to the funding agency. For example, one principle stated that at each "effort level", the field activities "will produce data of scientific interest — to the students as well as the scientists, and suitable for contribution to data sets being aggregated by other projects (e.g. the National Phenology Network, Audubon, or regional phenology research)." Another principle stated that effort-level activities "will be coordinated with each other, so that they form a mutually supportive suite of activities of educational and scientific interest."

Following this reconceptualization, the designers took various measures to develop the fieldwork projects. The interviews and planning documents indicated that they surveyed existing phenology and citizen-science programs, stressing projects involving stepwise protocols to reduce student error in measurement. The longitudinal nature of citizen-science databases was an important consideration, as recalled by an ecologist elaborated during the interviews:

> The first thing you do is you sort of cast around amongst all of your colleagues and try to find what databases are there, not just in my particular field of information, which might be birds in my case, but what is there on plant phenology and what is there on insect abundance. And so, you have to find some databases that are, first of all, prob-

Phenology calendar activity—Schools chose a set of phenophases that their students will monitor over the course of the school year. They will record and report the dates of each observed phenophase to scientists at <<scientific research institution>>. Although the timeframe is larger than with other protocols, the overall time requirement is considerably lower, as no measurement is required. These data will be entered into databases in the National Phenology Network. For distant schools we may suggest willing partners for advice on locally appropriate species.

Twigs activity—During the late winter, classes cut dormant twigs and force them to leaf out inside the classroom. This requires daily observation once indoor monitoring begins. Classes will record and report dates for a series of leaf out benchmarks to scientists at <<scientific research institution>>.

Arthropod sampling—Multiple times in the spring, students will sample for abundances of arthropods on a set number of trees within a circle on the school grounds. Five sampling events take place in at least four survey circles, 10m across. Abundance and herbivory scores should be reported via the "Caterpillars Count!" mobile app developed by UNC Chapel Hill. These data will be compiled and used by biologists that are part of the Caterpillars Count network. Required knowledge of arthropod families (identification guides are provided) and sample sizes are fairly large (50 leaves per/spot). Once trained, older students may be capable of collecting data unsupervised in small groups. Requires access to smartphone or tablet for digital data entry (written data entry on data sheets is an option as well). Also requires flagging

Vegetation Sampling—Original vegetation sampling both during early spring leaf out and later once leaves are fully grown. Schools must set up and/or maintain one or more transects in a green space near the school. These transects serve as reference points for annual fieldwork. This work requires a relatively large sample size for each variable measured. Also requires use of scientific measuring devices and knowledge of plant species identification. Three variables means that students must be trained (and supervised) in at least one field technique. Schools need measuring tapes, dial calipers, gps unit(?) flagging,

Fig. 4 Project document showing preliminary designer ideas for fieldwork menu.

> ably going to continue. And so, if we're talking about - wouldn't it be nice if we can look back ten years from now and see that data contributed, you have to know that the database is going to be there ten years from now. And then you have to look at the protocols, which… are designed for citizen scientists. Students are citizens. Students are very capable of doing more than you would think. And that's part of the learning. So, you have to adapt it to whatever would be appropriate for middle school.

projects, specifying the overall links to key science content and citizen-science contributions. The initial menu provided brief descriptions of the projects and proposed criteria to categorize the projects along a spectrum, namely time commitment, pre-requisite knowledge and equipment, and transferability to schools outside their immediate region (see Figs. 3 and 4 for project documentation showing preliminary designer ideas about fieldwork projects).

Accordingly, the curriculum writers elaborated drafts of fieldwork projects involving different effort levels, and these were informed by the nature of help sought by the partner teachers during previous evaluation of the STSP. For each project, the curriculum writers formed conjectures about its purpose and value to other scientific research programs; estimated time requirement; and protocols. Finally, they refined drafts of background materials for the projects based on clarification and elaboration of science content from the ecologists. During interviews, this is how a curriculum writer described their considerations behind the fieldwork menu:

> It's got to be meaningful science, but it's got to be pedagogically valuable science. It's got to be useful data, but the data collection has to be within the scope of means of the teacher that's doing it. So, [another curriculum writer] started putting out versions [to] give the teachers a sense [of] like, how demanding is this going to be? So, low, medium, and high effort. And there are some cases where the same thing could be done with low effort, it would be valuable to a certain extent, or high effort, but then what value? For each one, I've tried to identify what would be the purpose. So, what's the activity? How much time would it take? What's the protocol? Who cares about the data? And the more targets, the better. To give, from the students' point of view, a way for the data to matter. From the teacher's point of view, the data matter, and they can think about what the learning is, and so, they can look at documentation, the student materials. And is there background knowledge that needs to be conveyed? And so then, there has to be a link to our curriculum. And the final thing was that we keep saying that all these data could be valuable in various ways for learning and exploration. And it seems like there's so much of this going on across the country that in almost every case, there should be a way to say that we can link this to the National Phenology Network, Nature's Notebook.

Joint work: transforming institutional practices

Understanding stakeholders

Designer work supported STSP stakeholders to engage in *continuous joint work* via regular interactions around shared goals of the partnership. These interactions were conceptualized through a metaphor of "schools as satellite field stations," explained by the curriculum writers during interviews and in planning documents as a structure in which students and teachers would commit to "apprentice to research scientists by conducting a core set of data collection activities" linked to the research station's long-term study. Additionally, students and teachers would create their own research projects or join existing citizen-science projects. For the scientists, the metaphor was expected to "reify [their] responsibility for good communication," providing a clear basis to commit their time to the STSP. The designers thus hoped to foster mutual accountability because "there was a common purpose and a certain sense of give and get" in the STSP.

Curriculum supports

Participation. To realize this metaphor, the designers envisioned teacher and scientist participation in dialogue and negotiation of meaning to help them make adjustments in their respective work and attain fruitful outcomes for both science education and scientific research. The adjustments for teachers, for example, involved incorporating target climate science content (in the form of the project's in-class unit) and fieldwork practices into their existing science curriculum, while those for the scientists involved extending fieldwork and demonstrating their research methods in different formats to accommodate diverse student and teacher needs.

Tasks. To facilitate the joint work, as envisioned in the grant proposal and implemented subsequently, the tasks for teachers centered on attending professional development meetings and providing feedback on the content and implementation of the in-class unit and fieldwork. The tasks for scientists focused on assisting the fieldwork in-person and through electronic communication and providing tips and clarifications about the research agenda. The curriculum writers explained during interviews that the tasks were intended to make the science more familiar and understandable to students and teachers, who may have limited access to scientists. The in-person assistance from scientists would enable the school partners to see "naturalists in action", which would be both an affective sensory experience and a stimulating conceptual one. In the following excerpt, this is how a curriculum writer articulated the "educative power of personal contact" between scientists and school partners:

> One of the things that most teachers can't do, and that students almost never see, and that requires a little time, and there's a certain leisure, is seeing a naturalist in action, where trudging to your field site allows you to encounter other organisms, other habitats. You're seeing potential questions and physical juxtapositions. It's both an affective sort of sensory experience and a deeply conceptual one… And if you're doing it with a bunch of students, and you build the relationship enough, they're not going to be in awe of you. They're going to be asking you questions.

The personal assistance from scientists was expected to provide various benefits to students' engagement and learning of concepts and practices. The following excerpt from the grant proposal also portrays some of the envisaged benefits, inspired by the lead ecologist's personal presence on the field during prior work involving middle school students in gathering vegetation data to "bring science research closer to the classroom":

> The [present scientific research institution's] ecologists, especially [the lead ecologist], played several critical roles. They [i] provided personal stories and engaged the students personally, [ii] were a key source of science content, [iii] perhaps most important, articulated the driving research questions behind the [scientific research institution's] research program and its context within climate change research, and [iv] provided instruction in science practices designed to further the research program, instructing students in transect layout methods, helped with data collection, and discussed and analyzed findings.

Additionally, during interviews, an ecologist elaborated that interactions with scientists would "add weight to what [school partners] were doing" and help them see how gathering specific measurements was meaningful for scientific research. Indeed, surveys administered to teachers after the pilot evaluation confirmed the value of in-person training received from scientists. And an ecologist clarified during interviews that for scientists, the interactions with school partners would reveal what experiences were beneficial for students and teachers and how those experiences contributed to the shared goals of the STSP in service of science education and scientific research. Finally, scientists' in-person presence during fieldwork would provide them with insights into how well the fieldwork techniques and rationales were understood by the school partners. This contextual information, in turn, would help scientists to better interpret (and use) student-gathered data.

Materials. To bring this vision to life, the ecologists shared newsletters with teachers to communicate field news about their research, administer surveys to seek teacher input on enhancing their participation and share their experiences with in-class and fieldwork activities, provided (visualizations of) student-gathered vegetation data back to the schools to aid their data analyses activities, and included updates about project timelines and activities. In so doing, as observed during their team meetings, the designers aimed to convey the importance of teacher perspectives in the design process and to offer resources to "create a community" with "mutual give-and-take." There were professional development webinars to clarify the connections among the data sets in the in-class unit, the standardized vegetation fieldwork, and the ecologists' research on bird migration; to offer scientist-led demonstrations of fieldwork techniques; and to gather feedback from teachers. As explained by the curriculum writers during interviews, the webinars also served as a platform to extend the communication with a wider network of schools and nurture "relationship building" among the STSP stakeholders.

These designer attempts at "social engineering" were important because, as a curriculum writer reasoned during interviews, STSPs ran the risk of creating utilitarian relationships if partner scientists were interested in school-based citizen-science primarily for obtaining valid data for their research study. In the absence of carefully crafted supports, the school partners may not receive adequate help to "work their way into some experience about undertaking inquiry for themselves as well." Thus, through the newsletters and webinars designed to realize the vision for teacher and scientist participation and elicit their feedback to guide each other's work, the designers hoped to support the stakeholders in actual dialogue and collaboration around the shared goals of science education and scientific research on climate change. The findings on design phases presented below show how the curriculum supports geared towards this particular boundary crossing process were generated by the designers.

Design phases

Evaluation. Early in the STSP, upon conducting pilot trials of the standardized fieldwork, the designers noted the value of personal assistance from scientists, as described in the excerpt below in an annual report to the funding agency. Furthermore, to later generate topics and content for the PD webinars (the development of the webinars is elaborated in the next sub-section), designers also drew on their observations and surveys of teacher enactment of the in-class unit and fieldwork, written pre-and- post assessments of students' understanding of the content, and teacher feedback on specific needs and interests related to supplementary fieldwork and data analysis.

> In many cases the participating teachers didn't really know how to conduct field work, and weren't comfortable or knowledgeable about the natural history of their area.

> The presence of enthusiastic and knowledgeable naturalists as represented by [partner ecologists] meant that the routine of field work was enriched or enlivened by stories, spontaneous comments about other features noted, and interaction with the naturalist "habits of mind" that make field work stimulating and engaging. Moreover, [partner ecologists] provide a warrant for the authentic value of the field work, which was exciting and motivating for students and teachers alike.

Development. The designers considered the timing and sequencing of the webinar content, as observed in their team meetings and planning documents. The curriculum writers emphasized beginning with the in-class unit in a fall workshop to help teachers "overcome the barrier of unfamiliarity and feel like they have mastered the curriculum before implementing something new." This would also allow teachers ample time to try the curriculum "as though they were the students," which in turn would yield feedback for the designers. Field techniques would be discussed in a subsequent spring workshop, which would be closer in time to the actual fieldwork enactment.

Instead of a long web-based session, the curriculum writers stressed a series of shorter webinars to address various foci and challenges of the STSP, such as in-class tasks, fieldwork, and student engagement. The general approach was to "offer more than less but in unintimidating chunks." Hence, they proposed a sequence of discrete topics, which would include both canned and live components, all made available online to build towards distance learning and reduce the demands on partner scientists. As a next step, an outline of the webinar components was created. Additionally, teachers recommended including a broadcast from the ecologists to the students because the latter were motivated by "doing science of interest to real scientists." This resulted in a webinar in which the ecologists discussed their research on banding migratory birds and illustrated standardized vegetation fieldwork. The webinars were recorded and the recordings were made available to the teachers.

Discussion

This participant-observation case study set out to answer the question: *How do designers attend to stakeholders' (i.e., students', teachers', and scientists') needs, what curriculum supports do they create, and what methods do they employ during phases of the design process in designing for STSPs to integrate citizen science with school science?* In short, the designer work examined in this study aimed to help students, teachers, and scientists in the present STSP to engage in the processes of othering, communicative connection, and continuous joint work to cross boundaries between the cultures of science and schooling. In so doing, the designer decisions in creating various curriculum supports for the stakeholders align with recommendations from prior research specifically for promoting science learning via citizen science and more generally for effective environmental education and science education. The study extends current understandings in the literature by revealing empirical details of designer considerations and measures behind the curriculum supports to incorporate high-quality features. Furthermore, the study contributes to the literature by offering a practical guide that is derived from details of this designer work to aid others in designing for STSPs to integrate citizen science with school science, thereby serving to bridge formal science education with students' everyday lives and society. The guide is presented in

Table 4 and portrays curriculum supports and design methods to address specific designer considerations for serving the goals and needs of students, teachers, and scientists.

Reflections on Designing for STSPs

Boundary crossing to understand stakeholder goals and needs

The present STSP exemplifies designer attention simultaneously to multiple goals, needs, and constraints driving boundary crossing processes from the perspectives of the main stakeholders: the school partners and the scientists. Pedagogical goals stressed bringing current, place-based, and thus personally relevant science closer to the science classroom through scientist-designed and supplementary citizen-science fieldwork and analyses of authentic data sets. Broad curricular goals focused on the context of climate change for integrating core concepts and disciplinary practices to facilitate standards-aligned science instruction. And finally, there were scientific goals related to the research program(s) specified by partner ecologists and other citizen-science projects that motivated the standardized and optional fieldwork projects.

The designer work showed how diverse needs and constraints reflective of the practices of science and schooling were foregrounded in relation to one another to help stakeholders pursue these goals. Designers clarified connections between climate change theory and students' fieldwork via instructional tasks such as readings and discussions, thus tightly linking the fieldwork and in-class components of the STSP curriculum, as recommended in recent research on integrating citizen science with school science (Harlin et al., 2018). In so doing, they attended to local geographic relevance of in-class and fieldwork experiences to make climate change education personally meaningful to the students. Integrating environmental education with local ecosystems surrounding schools has been shown to deepen students' understanding of scientific concepts and processes and their connections to the real world and to promote students' interest in learning science (Lieberman & Hoody, 1998). Engaging with local phenomena was also intended to help understand more global, distant phenomena, both through first-hand experiences via standardized and supplementary fieldwork and second-hand experiences through in-class data analytic and discussion activities focused on students' own data as well as data from other scientific research. Prior research suggests that providing for rich experiences locally first and situating local investigations within a larger (internet-based) network of investigations can help students ultimately develop broader perspectives that integrate more complex scientific concepts (Feldman et al., 2000). The first entry in Table 4 is distilled from this designer work to foster connections between local and global phenomena for meaningful and productive student inquiry.

In helping stakeholders cross boundaries between the cultures of science and schooling, the designers also responded specifically to teachers' needs for understanding the background science to facilitate student engagement with data collection and analysis, in turn, and for interacting with partner scientists to help students contribute high-quality data towards scientific research. This attention to teacher needs is crucial because difficulties emerge when students (and teachers) have insufficient understanding of requisite concepts and skills to contribute to the partner scientists' research (Zoellick et al., 2012). The requisite background knowledge for understanding the scientific research program may be far too advanced compared to the school partners' current understandings of the science (Drayton & Falk, 1997, 2006). For instance, the practice of conducting (field) investigations is emphasized in science curricular standards, but it may not be familiar to many students and teachers. The rationales, techniques, and connections between local (school-based) fieldwork and the broader scientific research, while often implicit to scientists, may not be transparent to the school partners.

The designers also attended to stakeholder needs in establishing communicative connections for fieldwork. They considered curricular mandates, conflicting timing of ecological phenomena and school assessments, and limits on teachers' time, providing modular options to help teachers incorporate the in-class unit and fieldwork into different grade levels and subjects as specified by the school curricula. The considerations are crucial because the present science education frameworks emphasize integrating concepts and practices via student investigations involving planning and conduct of data collection, analyses, communication, and so forth (NRC, 2012). However, teachers are typically concerned with aligning the partnership with educational standards (Doubler, 1997), focusing on curricular topics relevant to standardized assessments (Moreno, 2005). Therefore, by attending carefully to these considerations, designers can align the scientific research agenda with the intended student learning outcomes through multiple projects and varied levels of engagement to strengthen the target concepts and skills specified in curriculum frameworks (Zoellick et al., 2012) and as emphasized in recent research (National Academies of Sciences, Engineering, and Medicine, 2018). The second entry in Table 4 is based on this designer work to support teachers in enacting citizen science projects within the expectations and constraints of their school settings.

In expanding the fieldwork, the designers also strove to balance scientists' needs for acquiring rigorous student-gathered data via standardized fieldwork experiences, while providing for flexible and varied fieldwork activities to enable teacher enactment and student engagement and learning, thus working towards harmony between the scientific and educational goals of the partnership (Zoellick et al., 2012). This was deemed important to motivate and facilitate students in making valuable contributions to broader citizen-science databases. As mentioned earlier, disruptions in collaboration may arise due to differences in the cultures of science and schooling, such as scientists' concerns with data quality and implementing fieldwork protocols and teachers' concerns with aligning the fieldwork with educational standards (Doubler, 1997). For instance, despite the provision of standardized protocols, school partners may contribute low-quality data due to inconsistent implementation stemming from curricular and time constraints (Means, 1998). Another difference is between the time scales of student investigations and scientific research (Barstow, 1997). Whereas the former is generally brief, the latter is often longitudinal to yield meaningful findings but more challenging to sustain student engagement. Additionally, a related challenge is that teachers are expected to not only orchestrate fieldwork within the requirements and limitations of their school settings but also to motivate students for the fieldwork. This is crucial because students' participation is school-based citizen science is non-voluntary, unlike broader citizen science projects in which the general public volunteers to contribute in various ways (Roche et al., 2020). The menu of optional fieldwork projects supplemented the original standardized vegetation fieldwork to yield more short-term findings and a greater variety of contributions focused on different species of potential interest and relevance to school partners, through protocols with different degrees of standardization, thereby aiming to maintain the interest of school partners in the partnership (see Means, 1998, for a similar point about supplementary data analytic activities to address curricular mandates and sustain partnerships).

Furthermore, in supporting stakeholder needs for continuous interactions and negotiations between teachers and scientists, the designers were sensitive to conveying more than simply action items to enact in-class and fieldwork activities. They strove towards a mutual exchange of information by providing teachers with access to scientific expertise and with opportunities to contribute ideas in developing and refining the partnership. These measures may validate the partnership for school partners, who may come to see their involvement as something of real value to science, other than just “doing school.” The second entry in Table 4 is also formulated through this designer work.

Finally, the study offers insights into how designers may tackle some of the challenges of school-based citizen science programs in promoting students’ interest. Specifically, current research shows that students may not feel a strong sense of ownership and contribution to scientific research, possibly because they may perceive their involvement with data collection and analyses simply as participating in curricular tasks (Dohn, 2021). Furthermore, students may feel low motivation if there are few opportunities to personalize the tasks based on their interests and prior experiences (Walkington & Bernacki, 2014). As a result, teachers are tasked with selecting among many possible citizen science initiatives that would enable them to align their educational pursuits (including the promotion of student engagement) with the scientific goals and requirements (Roche et al., 2020). The third entry in Table 4 draws on this designer work to nurture scientific and educational aspects of the STSP.

Curriculum supports for boundary crossing

These goals and needs were supported through various roles for participation and tasks envisioned for the stakeholders in crossing boundaries and through print and digital materials to bring designer vision to life in the classroom and on the field. Consistent with prior research in science education broadly and citizen science and STSPs specifically, the materials were targeted to the needs and wishes of the different partners. For example, informed by a place-based learning approach, the curricular content was customized to present students with local, familiar species examples through readings and discussions to appeal to their interests and affective engagement. The inclusion of local examples and discussions as part of the in-class tasks reflects current emphases in designing for effective environmental education (Monroe, Plate, Oxarart, Bowers, & Chaves, 2019). The in-class guides provided students and teachers with requisite background knowledge to contribute to scientific research, presenting learning objectives and desired student responses (Schwartz, 2006), educative notes about student conceptions (Roseman et al., 2017), rationales for specific scientific practices (McNeill et al., 2017), such as the target fieldwork techniques, and strategies to engage students in scientific practices (Bismack et al., 2015), such as analyses of authentic data sets. And to make standardized fieldwork accessible and engaging, the rationale and techniques were clarified through in-class guides, videos for instructional support, interactions with scientists in the field and through PD webinars, and structured data sheets and protocols to aid in data collection and reporting, consistent with recent recommendations in the literature specifically for school-based citizen science (Harlin et al., 2018) and more broadly for environmental education (Monroe et al., 2018). The work behind various curriculum supports

Table 4 Practical guide to design for STSPs

Designer Considerations	Sample Curriculum Supports	Design Methods
Blend local with more widely applicable explorations to provide for personally meaningful and academically productive student inquiry.	In-class analyses and discussions of readings and data sets focused on local environmental examples and some national or global examples. Design and conduct field investigations for stand-alone projects motivated by local partnerships and some to feed into broader citizen-science projects.	Survey relevant literature; input from scientists to incorporate suitable background information, data sets, and fieldwork to highlight local relevance of the STSP experiences.
Provide appropriate level of support tailored to teachers' knowledge; current practice and needs; and comfort with science content, inquiry, and in collaborating with scientists.	Multiple forms of support to provide complementary and ongoing guidance through in-person and electronic communication with stakeholders, print-based guides, and digital resources to enact in-class and fieldwork tasks.	Survey of teacher (and student) experiences, first-hand observations of implementations, and direct interactions with teachers. Data about student learning through pre-and-post assessments. Input from partner scientists to explain requisite background content.
Supplement core scientist-designed investigations with optional tasks to realize curricular, pedagogical, and scientific value of the partnership.	A toolkit of materials (protocols, data sheets, in-class guides, etc.) for school partners to conduct more and less standardized fieldwork for partner scientists; contribute data towards broader citizen-science endeavors; and analyze authentic data sets derived from students' own research and research conducted by partner scientists.	Input from partner scientists to specify the scientific research agenda. Survey existing citizen science programs to incorporate into the research agenda, and feed suitable data sets back to schools.

reported in this study shows how designers may respond to the cultural differences between scientific research and school practice in terms of the background content knowledge and access to resources that different partners bring to the partnership (Tanner et al., 2003), and also how they may address the need for direct interactions with scientists to sustain the interest of school partners, which is difficult due to the demands on scientists' time (Means, 1998).

For STSPs, the design of fieldwork protocols, data sheets, and authentic data sets merits special attention because these serve as standardized methods and boundary objects (Carlisle, 2002; Star & Griesemer, 1989); they are artifacts exchanged between collaborating sites, yet their purpose and significance may be interpreted differently by the partners. For instance, while teachers and students use fieldwork protocols and data sheets to record observations or measurements as part of specific instructional activities, scientists emphasize data quality and rigor in service of broader scientific endeavors, which may not always be apparent to the school partners. Similarly, whereas scientists may view student-gathered data sets as part of larger research programs, teachers may view these as narrower pedagogical tools for student learning and may need guidelines to make sense of specific data sets. The findings of this case study point to ways in which designers may plan towards supporting stakeholders to engage with such boundary objects for both scientific and science educational pursuits.

Design methods to create curriculum supports

Finally, the methods across design phases for building this partnership involved inputs (and outputs) from the stakeholders across phases of design, making it an iterative, collaborative process (Penuel et al., 2011). The partner ecologists contributed in multiple ways throughout development and evaluation, offering direct fieldwork assistance to school partners via in-person interactions and webinars and assessing the quality of student-gathered fieldwork data. They provided feedback on framing the scientific research agenda; supplied data sets from their own research; weighed in on suitable scientific content, local examples, and projects through surveys and consultation with other scientists, and on logistics and regional and broader applicability and scientific value of fieldwork tasks to shape curriculum supports. Specific materials created by them - fieldwork protocols and data sheets, instructional resources, and newsletters - also represented their perspective and expertise (Könings et al., 2014). The involvement of the ecologists thus served to provide school partners with access to current scientific knowledge via resources and dialogue, which may help structure and make citizen-science investigations attainable for students (Gray et al., 2012). Thus, as recommended in the literature, the ecologists contributed towards reinforcing the scientific authenticity of the envisioned participation and tasks through their feedback on using student-gathered data and towards providing access and supports for working with authentic data (National Academies of Sciences, Engineering, and Medicine, 2018). The teachers offered ideas for webinar topics and reflected on their experiences with implementation to help refine the curriculum supports. Through multiple activities and tools – in-person interactions, written surveys, webinars - they injected into the partnership both teaching and learning considerations, highlighting what was feasible for teachers and meaningful for students (Houseal et al., 2014).

Finally, core to the partnership was the involvement of curriculum writers, who mediated the school-scientist collaboration by drawing on their knowledge of school culture and their scientific training to translate the varied goals and needs into specific requirements and ideas for creating curriculum supports. In so doing, they blended their own insights with the contributions from scientists and teachers at specific points to yield a usable and acceptable intervention (Könings et al., 2007), deriving inspiration and information from various sources: literature; in-person observations and surveys of school implementations; pre-and post-assessments of student learning; interactions with teachers and scientists; and drafts of materials to elicit feedback from stakeholders. The work of the curriculum writers reflects recommendations in the research for cultivating school-scientist partnerships, such as to include a third-party liaison (Houseal et al., 2014; Zoellick et al., 2012); to value the contributions of all partners (Moreno, 2005); and to clarify curriculum-specific science content and practices to help teachers prepare for student inquiry and contribute student-gathered data to scientific research projects (Fishman et al., 2006).

Limitations of the study and recommendations for research

Despite several affordances of the approach used in this study, a few limitations also bear mention. First, as with all case studies, it is difficult to generalize the findings. Further research is needed to gain a broader understanding of designer thinking and action to tackle the challenges of STSPs for integrating citizen science with school science. Second, the present study did not gather data directly from the teachers or students who were also stakeholders in the STSP. In fact, the voices of these stakeholders were conveyed to the researchers only indirectly through the designers. However, including student input directly into the partnership is crucial (Roche et al., 2021) because student perceptions influence the effectiveness of educational interventions (Konings et al., 2014). Hence, future research could gather data directly from students and teachers to understand better how their perspectives and experiences shape the work behind STSPs. Third, while the study did have access to important data on students' learning outcomes, it lacked information on student motivation, teachers' enactment of scientific practices, and the usefulness of student-gathered data for scientific research. As such, the dimensions for which designer success can be claimed are rather limited. Subsequent studies could collect such data to understand better how designer choices shape the attainment of specific educational and scientific outcomes.

Final remarks

Designing for effective STSPs focused on citizen science is complex because these need to respond to the requirements and constraints of their stakeholders as they cross boundaries between the cultures of schooling and science. This study reveals the challenges and resolutions of designers in providing authentic, educative experiences in environmental education to students and teachers, whilst enabling them to contribute to scientific research. In so doing, the study elucidates key considerations and methods in designing for modular and customizable instructional experiences that can account for variations in geography, students' interests, teachers' preferences, and curricular requirements and constraints. Derived from in-depth empirical analyses and enriched by the broader literature, these detailed insights can inform the efforts of other educators who wish to extend STSPs to a wider spread of school and science partners. In revealing designer reasoning and methods behind scalable STSPs, the study makes the generally tacit designer knowledge visible to novice and experienced designers, yielding a much-needed precedent to inform similar pursuits in integrating citizen science with school science education.

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Data Availability The original data cannot be shared due to concerns related to confidentiality, as per TERC's Institutional Review Board.

Declarations

Conflict of interest The authors declare there is no conflict of interest.

The data collection and analysis procedures employed in this study were granted approval by the Institutional Review Board at TERC.

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