Citizen Science in Schools: Scientists' Perspectives on Promise and Pitfalls

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INTRODUCTION

Citizen science (CS) projects have become widespread in part because they expand the capacity of professional scientists, enabling research that would otherwise be impracticable or unaffordable. In addition to the research benefits, educators and scientists have seen educational value in CS because it can incorporate students into real-world science projects. As a result, CS is increasingly making its way into schools. Recent articles describe teachers integrating CS into their instruction, ranging from elementary students collecting pollinator population data to high school students mentoring younger students examining local watershed dynamics (Hayes, Smith, and Midden, in press; NSTA, 2018). Further, data from a major national survey of K–12 science teachers suggest that students would benefit from instruction that engages them in authentic science investigations. For example, in 2018, teachers reported that only about one-fourth of elementary science classes, and fewer than half of middle school and high school science classes, heavily emphasized how science is conducted (Banilower et al., 2018). In addition, many states have adopted the Next Generation Science Standards (NGSS; NGSS Lead States, 2013), which call for instruction that integrates disciplinary core ideas with crosscutting concepts and science and engineering practices. CS projects have the potential to engage students in these kinds of learning experiences.[1]

Although studies have identified factors that affect the success of public involvement in science projects (Elliott and Rosenberg, 2019; Golumbic, Orr, Baram-Tsabari, and Fishbarin, 2017; Riesch and Potter, 2014), the school context presents a distinct set of opportunities and challenges. Among them, school-based CS endeavors are influenced by education mandates and are subject to constraints on time and resources that differ from those of interested adults in the general public. School-based CS is likely to have student learning, rather than contribution to science, as the primary objective. Further, students typically lack the training and experience needed for substantial involvement that many adult volunteers bring to CS. Schools may be in a position to attract professional scientists to help guide CS efforts, but scientist roles can vary considerably, from occasional input (sometimes from a distance) to regular face-to-face leadership that is highly integrated into instruction.

The Committee on Designing Citizen Science to Support Science Learning from the National Academies of Sciences, Engineering, and Medicine (NASEM) reviewed the literature and reported findings that characterize CS and its potential impact. The committee reports: "As an emerging field, citizen science has opportunities to grow, to contribute to what we know about how people learn science, and to broaden participation in science" (NASEM, 2018: 10). The

[1] Throughout the paper, we use "CS project" to refer to an individual project (e.g., Bumble Bee Watch) and "CS program" to refer to a coordinated collection of CS projects.

report further concludes that much more evidence is needed to establish how CS can best design and implement authentic science experiences to produce desired learning outcomes (NASEM, 2018).

This paper offers experience-based insights that can help realize the promise of school-based CS. All of the authors are scientists who have been involved in such efforts. We discuss our views of what effective school-based CS might look like and achieve, as well as how to get there. We intend this contribution as a complement to studies conducted by science education researchers (for example, Steinke, Breton, Berzitis, and Hebert, 2017; Paige, Zeegers, Lloyd, and Roetman, 2016; Bonney et al. 2009). Although educators and education researchers also address methods and outcomes of CS programs, scientists are uniquely positioned to provide valuable input on what makes for effective CS in schools.

Context and Perspective

Recognizing the educational potential of CS, a team in the Midwest of the US designed and implemented "Citizen Science in Schools" (CSiS), a multi-year effort funded by the National Science Foundation, aimed at integrating CS into classroom instruction.[2] CSiS focused in part on a cohort of middle school (grades 6–8) teachers from two collaborating school districts.[3] About half of the participating teachers taught only science; the rest either taught all core subjects to one class of students or taught a single non-science subject (e.g., social studies). After one year of training on inquiry-based science instruction, the cohort was introduced to CS projects during a summer institute at the beginning of the second year. CSiS leaders recruited professional scientists, including five authors of this paper, to guide participating teachers and students in planning and conducting the CS projects over the following two years. Each CS project was intended to engage students in research that addressed questions of both scientific significance and local relevance. For example, 8th grade students collected and analyzed population data on bees and butterflies, while 7th graders assessed local water quality.

We recognize that school-based CS, and its leadership structure, can take many forms. The context we describe, which involved all science teachers in a school and considerable external support (both personnel and funding), may not be the norm. Regrettably, data on patterns of school-based CS are not available, but our experience suggests that a common scenario is one in which an interested teacher searches for an existing CS project and implements it essentially on their own. Such teachers deserve encouragement and recognition. However, for reasons we hope to make clear in this paper, we believe that a systematic and coordinated approach to

[2] The project name is a pseudonym.

[3] CSiS also included elementary teachers, but this paper focuses on the project's work with middle school teachers.

school-based CS that involves multiple stakeholders, including a team of program leaders, is more likely to be sustained and have the hoped-for educational benefits.

To collect the insights described here, the first author (himself a scientist) interviewed five of the co-authors, individually, twice after CSiS ended.[4] In the first round of interviews, scientists drew on their CSiS experiences to articulate important aspects of an ideal school-based CS program, taking into account what they had learned about students' and teachers' capabilities, as well as logistics and resources of a middle school context. The interviews specifically asked scientists to describe the kinds of outcomes expected if a CS program operating for several years had been very effective. After the first round of interviews, the authors reviewed each other's recommendations and reached consensus on eight central aspects of a vision for effective school-based CS. In the second round of interviews, the scientists described what should happen, and what should be avoided, to achieve the consensus vision.

The vision and corresponding recommendations we present here come only from the scientists who helped lead CSiS. We acknowledge that our perspective as scientists strongly influenced these views, and we recognize that other professionals (e.g., curriculum developers, teachers, administrators, science instruction coordinators) have essential experience and perspectives that can inform development of CS programs.

A Vision for Effective School-Based Citizen Science

As mentioned above, the initial round of interviews resulted in eight aspects that characterize our vision for effective school-based CS. We list each below, unpacking them to more fully describe our expectations for a well-developed school-based CS program. The first three aspects relate primarily to planning. The fourth spans planning and implementation, and the remaining aspects focus primarily on implementing projects.

(1) *Stakeholders (e.g., teachers, scientists, administrators) consider academic standards, district- and school-based curricular priorities, and existing instructional materials when designing and implementing CS.* Although other aspects of the vision have implications for CS program planning, this aspect is most explicitly focused on the planning stage. Stakeholder groups involved in planning will vary across school contexts and may include teachers, curriculum coordinators/developers, education researchers, or funders. In any case, we envision leaders identifying and empowering a team whose experiences position them to take contextual factors into account when designing the CS program.

[4] The last author, also a scientist, was the principal investigator of CSiS but did not provide project-specific support to teachers.

For efforts that span multiple grades, coordinating CS work across grade levels to address the progression of academic standards is especially important.

(2) *CS work has relevance to the local community and thus garners community support.* CS can provide opportunities for schools to interact with other community members in meaningful ways when projects are related to community resources, challenges, or priorities. By ensuring that CS projects address local issues, schools demonstrate an interest in community well-being and are more likely to generate cooperation from local organizations. We expect that students would present their CS experiences and findings to the community. Student recognition that their work can benefit their community would increase their interest and effort and contribute to improving their civic engagement (Billig, 2002; Bouillion and Gomez, 2001). We also expect that community members would actively support CS in schools as a response to the positive impacts they perceive it having on students and the community.

(3) *CS work is connected to broader science initiatives (e.g., GLOBE, Monarch Watch), which play meaningful and interactive roles with CS project participants.* In addition to being locally relevant, CS projects contribute to larger research programs established to use data from citizen scientists. We believe that students and the larger initiative benefit from interactions that develop a sense of partnership for a common purpose. We expect representatives from the broader initiative to provide feedback to students about their contributions so that communication flows in both directions.

(4) *Scientists are highly engaged with project work, providing guidance to teachers and students, and adjusting their emphases as teacher and student capabilities develop.* Because middle grades teachers typically have limited backgrounds in the practice of science (Craven, 2019; Plumley, 2019), we expect input from professional scientists to help establish a program in which students authentically contribute to science research. We expect scientists would play an important role from the planning stages through implementation, and we recognize that the needs for scientist leadership will evolve as the program matures and as teachers and students develop competency.

(5) *Teachers are highly motivated to integrate CS into their science instruction and routinely relate CS work to diverse topics across the established curriculum.* Our expectation is that leading students in investigating issues tied to the community and larger research programs, and recognizing the importance of authentic student experiences in science research will promote teacher enthusiasm for science instruction. We envision teachers looking to CS projects as instructional touchstones to connect diverse topics in middle school science courses, adding coherence to a curriculum that can otherwise be fragmented.

(6) *CS work is meaningful (not just procedural) to teachers and students. In particular, teachers and students understand how the data they collect are relevant in their investigations and therefore why the data collection methods are important.* When this aspect of the vision is achieved, teachers become more comfortable leading students in authentic science investigations. Teachers and students are able to describe the science question they are addressing and why the data they collect are important for building answers. Students can then appreciate what their observations mean and how they might fit with those of others into the missions of broader science initiatives. Such awareness motivates informed use of appropriate methodologies, such as random sampling, repeated observations, and experimental controls.

(7) *CS is a part of the culture of participating schools and is appreciated at the district level.* We envision CS reaching beyond science instruction in a particular class or grade and taking hold in the life of the school. CS projects influence and are supported by those whose primary role is teaching subjects other than science. Although we see CS work focusing primarily on science instruction and aligning primarily to science academic standards, acknowledging and leveraging connections to other subject areas produces a broader impact. Teachers and administrators cooperate school-wide to provide CS-related resources and overcome logistical challenges imposed by the nature of CS work (e.g., data collection events that disrupt typical class scheduling), and students have opportunities to present their CS work to others within and across grade levels.

(8) *The CS program improves student understanding of science content and practices.* This final aspect of the vision is particularly important in school settings. Curriculum development and pedagogical practices are critical to the success of integrating student participation in CS into mastery of the targeted science content. We expect that student learning will improve from substantial firsthand experience in science investigations that relate the subject of their science research to target concepts in myriad ways. Students emerge from the school's CS program with well-developed understandings of science ideas in the relevant standards. They also begin to recognize and appreciate important components of scientists' work and how those components combine to advance knowledge.

Recommendations for Establishing an Effective School-Based CS Program

In this section, we offer recommendations for achieving the vision of school-based CS described above. The recommendations grow out of our experience in CSiS. Specifically, we use successes and challenges of CSiS to highlight lessons we learned about what to do, and what to avoid, to achieve the vision. The recommendations are organized by the eight aspects above. In cases where potential pitfalls are not directly implied in the recommendations, we include particular cautions about circumstances that may undermine progress. We include direct quotes from the authors throughout to elaborate our recommendations or illustrate their foundations in the context of our CSiS experiences.

(1) Stakeholders should consider academic standards, district- and school-based curricular priorities, and existing instructional materials in designing and implementing school-based CS.

An effective CS program begins with frank, up-front, context-specific communication and planning to secure stakeholder buy-in. Planning should include curriculum coordinators or similar leaders who are used to taking on broader educational approaches or who understand how to implement inquiry-based science initiatives. Ideally, such a leader should serve as a champion for the CS project, helping to connect stakeholders and providing a broader perspective. This individual should also be sensitive to the difficulty of bringing about change when teaching practices and resources are engrained in the school culture.

> *[I suggest] working with school and district curriculum coordinators. Just in their training, [they] can easily have a broader vision for how to incorporate research projects like this into curriculum standards. [In] some of the experiences we had, this actually was challenging for some of the educators, for many of the educators who are highly focused in their area of teaching…. [Curriculum coordinators] had a much broader sense, not only of the curriculum for the science courses of each grade but also of other areas of study. And bringing them into the conversation quickly kind of opened up where our conversations were going into how different science projects can apply, not only to the science standards of that grade, but also into other classes. It made that conversation much more fruitful than without the curriculum coordinator.*

Being mindful of curriculum standards when designing a CS program is particularly important, especially when selecting specific projects for classes and grade levels to adopt. Selecting research projects should also factor in feasibility for teachers and students to adequately enact them.

> *I [suggest] having all interested parties, whoever that may be. For us, it was scientists and the teachers, even before this whole [program] development starts, go over the goals of their class. So whether it's their standards or whatever the teacher wants to get out of it. Some, I found, were more flexible with what they taught and could see kind of weaving it in throughout the year differently, and other teachers just had more kind of strict guidelines, "I'm sticking to the standards." I don't think one way is better or not, but just understanding that before you come up with a project on your own. Making sure that you're meeting the needs of that specific teacher's classroom [is important]…. That's kind of level one, but then to consider expectations of the school itself and the*

district, and the resources available when designing this with the teacher, because that can have a huge impact. Materials at the school—did they have this sort of equipment, or do they not? What's their school day look like? Can they bus? Do they have to eat lunch at school? What's the class size? There's so many things that go into consideration. But that's after, I think, the teacher and the scientist or whoever really understand the academic standards and come up with their [project] topics.

Those initiating a school-based CS program should also consult others who have had success, first being clear about what "success" means. Are contributions to science investigations a primary indicator of success, or is promoting student learning and interest in science the only major focus? In the planning stages, evidence of success from other projects can be important in building stakeholder support. In particular, stakeholders may need evidence (perhaps from test scores) that CS does not detract from student achievement. Of course, the best-case scenario is evidence that CS actually improves student achievement.

The pitfalls we identified around securing stakeholder buy-in include the following:

- Because CS often requires some change to the school culture, not having an influential advocate at the school or district level can be problematic. If this proponent is not the school principal, the principal should at least be supportive.
- Turnover in administration, whether at the school or district level, can erode the continuity needed to sustain a school-based CS program, both in terms of building teacher proficiency with CS and in terms of alignment with other school priorities (e.g., ongoing instructional initiatives, curriculum choices).
- Scientists typically have particular experience, knowledge, and interests. Without school-based perspectives to balance these, scientists may unduly influence CS topic choice, leading to misalignment with academic standards.

(2) CS work should be relevant to the local community in order to garner community support.

The purpose of linking school-based CS to local communities is twofold. First, teachers, students, and the school are generally more motivated to enact and complete research projects because they understand the context and feel it is important. Those planning and enacting projects would likely be familiar with either: (1) local aspects of particular issues being investigated or (2) the sites where data collection occurs. Second, schools reaching out to the community in this way can develop a sense of partnership that generates support. An invested community is likely to enhance the sustainability of the CS program. We also recommend that program leaders identify opportunities for students to present information about their research projects in the community, for example, at town council meetings and relevant local festivals.

This outreach can help generate community support for the CS projects and the schools, and it also provides an opportunity for the community to express their appreciation to the students. This support and appreciation can, in turn, increase student engagement in, and commitment to, learning.

> *Part of [building community support], again, is, I believe, communication—having parents and grandparents and students involved at the beginning, but also a way for [students] to share back with the community. So whether that's an open house that everyone is welcome to, whether that's the students going out in the community and talking to people about it, sharing with other schools…. Whether that is person to person, or whether that's via the Internet and some FaceTime, or Google Classroom, it's that sharing of information in schools and across the community.*

We advise prioritizing these community ties in the planning stage. As leaders consider project possibilities, they should identify local resources, including scientists and municipal authorities, they can consult about relevant community priorities.

> *When designing the project between the teacher and the scientist, this should be one of those questions: "What impacts does this have locally?" Contacting the county-level kind of entities, whether it's soil and water division, or natural resources, whoever has jurisdiction over the sorts of things that you want to study [is important]. I think discussions with those people who work heavily within that county, maybe your county's extension office or a 4H program, those sorts of folks who really have an understanding of what the issues are at that really small scale … is important.*

A challenge we experienced in CSiS points to a potential pitfall. Despite many successful efforts to connect CS activities to the community, community members did not always find the projects and their roles in learning compelling. Teachers and students sometimes struggled to communicate their findings at a level that the community could understand and "take home." For example, when students focus too much on procedural or technical components when presenting their work, they may not sufficiently explain the foundational questions or observations that connect their work to the local issue. Program leaders need to consider how to organize, where and when to hold, and how to publicize events to showcase the CS projects in ways that the community will appreciate and can attend.

(3) School-based CS work should connect to broader CS initiatives that interact meaningfully with students.

CS occurs on a wide variety of scales, from local to global. Larger programs typically have central organization, standard data collection protocols to guide citizen observers, and databases to compile their observations. For example, the GLOBE Observer Cloud project (https://observer.globe.gov/en/do-globe-observer/clouds) collects data from citizen scientists in over 100 countries. Other initiatives have a geographical focus imposed by the nature of the phenomenon being investigated. For example, Monarch Watch (https://monarchwatch.org/) monitors the North American monarch butterfly migration and its population dynamics.

Because these initiatives rely on data from novice observers, they typically provide orientation and guidance. Many of these initiatives also allow access to data collected by other citizen scientists, promoting connection to a large-scale science mission and opportunities for data analysis that would not be possible otherwise. The professional criteria often set and enforced by broader science initiatives can give students a stronger sense of the true nature of scientific inquiry, and discovery, and impress on them the roles of evidence and reason in advancing scientific knowledge. However, such initiatives vary in the extent to which they mesh with science instruction in school contexts and cater to students. We recommend that CS program leaders review an initiative's support materials to gauge their accessibility for teachers and students. Leaders should also investigate the extent to which scientists within the initiative are available to interact with teachers and students, whether in person or, more likely, through email, chat, or webinar.

> *Does the scientist who is running this [broader] project see the importance of connecting with those who are gathering their data? Basically, to sum it all up, do they view that interaction [to be] as important as the data that they gather from those volunteers doing the work? … [Choosing a receptive organization] might take a little bit of homework. You may have to investigate that quite a bit in order to get the answers to those questions. But I mean, there are certainly some citizen science programs that I know of that if you contacted the scientists in charge of the project, they would probably do a webinar with your class one-on-one. I'm convinced that there are others that just because of their sheer volume and size, it would be really hard.*

We think scientists recruited to help lead a school's CS program can be instrumental in connecting with broader CS initiatives. It is important to consult with these scientists or other experts about which initiatives are likely to yield fruitful connections with school-based CS participants. This preliminary research can also help scientists advise other program leaders about what specific projects within the initiative's scope are most relevant or might be adapted to align with curricular objectives.

A pitfall related to connections with broader science initiatives centers on teacher training. Relating class instruction and investigation results to any broader initiative will likely be new to teachers, so training should include a focus on how to effectively leverage these connections. In particular, as partnerships are established, teachers may benefit from training on technical aspects of systems that initiatives use for interfacing with contributors.

(4) Professional scientists should be highly engaged with project work.

As noted previously, the extent to which professional scientists help lead school-based CS varies considerably. As scientists, we view substantial involvement in school-based CS as beneficial for such programs. We acknowledge our bias, but we argue that some level of scientist input is valuable and perhaps even essential, especially for teachers who have little or no experience in science research. We discuss below some considerations for defining the scientist role and selecting appropriate scientist collaborators.

We recognize that involving scientists can present a peculiar "chicken and egg" challenge. A program could first identify scientists who have skill sets, experiences, and availability that make them strong candidates for interacting with teachers and students. This approach would allow substantial scientist input from the start in planning the CS projects. However, these scientists may steer projects away from alignment to academic standards in favor of science areas in which they are more comfortable or interested. Alternatively, leaders initiating the program, after considering the relevant academic standards and local concerns, could identify project topics and then locate scientists who are inclined to be involved *and* have expertise that fits the topics. In this case, finding strong candidates might be difficult, and scientists would come later to the planning process.

Ideally, CS projects are designed or selected to simultaneously address the curricular goals teachers have *and* the interests of scientist partners. In areas where access to scientists is limited, finding scientists may have to be the first step. In schools where academic standards, or their interpretation or implementation, are inflexible, identifying topics might have to come first.

In any case, because we believe scientists should have regular involvement with students and teachers, it is important that they are comfortable in the school setting (e.g., classroom dynamics, instructional scheduling, relatively limited resources) and sympathetic to teachers' responsibilities for addressing a particular set of academic standards. Program leaders can help by clearly communicating school and teacher priorities to scientists, but it is also important that scientists have the ability and inclination to communicate well with students and teachers.

> *Making sure that the scientist is a good candidate for a project like this [is important]—not that they need to be an expert in that specific grade science curriculum or anything like that, but a scientist that has some experience in communicating research to K–12 students as well as is familiar with talking with K–12 instructors. So having a scientist that is comfortable with those two groups of people is vital.*

In the CSiS program, one challenge was that scientists typically had many other demands on their time. We suspect the same is true of the vast majority of scientists who might become involved in school-based CS. Program leaders should define expectations for scientist commitment and make those clear to scientists considering involvement. Further, program leaders will need to recognize that the potential for CS work "going to the back burner" is ongoing for many scientists, and find ways to keep them engaged.

(5) Teachers should be motivated to integrate CS into their science instruction and routinely relate CS work to diverse topics across the science curriculum.

The teacher is, of course, the key to success of any school-based CS program. Because we see the investigative nature of CS as inherently appealing to most teachers and students (again, a bias we recognize others might not share), our advice focuses largely on how to empower teachers and build their ability and confidence to lead a school-based CS project.

First, ensuring that teachers are integrated into the planning process is important, as are opportunities for conversation between teachers and other experts, including scientists, instructional coaches, and curriculum coordinators. Teachers need deliberate efforts to help them understand how to make connections between CS work and the curriculum standards for which they are accountable.

> *The best way to have teachers really motivated and invested in the project is to have them involved early on. So I think if they feel as though they have some sort of stake in the projects or they helped develop them and create them, I think they will be more motivated to see them through because they were the ones who came up with them in coordination with the scientists. So if the development of [each] project is more of a dual effort, I would think they'd be more motivated and [would have] already discussed how it meshes well with their standards and the goals that they have for their course that year.*

We also recommend that program leaders describe examples of successful school-based CS projects, particularly those that resemble the projects being considered. Emphasizing to teachers that students being active in science investigations can increase their understanding of science practices may motivate teachers to integrate CS into their science teaching. Peer-to-peer testimonials from those in similar instructional contexts may be especially effective for many teachers.

> *Having these examples like CSiS and like other types of even smaller CS [programs] around the country [is helpful]. I know a lot of them have some sort of online presence, kind of showing their experiences and results. So [it's important] to go to a new group of educators that are considering this, I think, highlighting a lot of the success stories in CS and getting students not only doing these bits of research, but getting them just even outdoors and collecting real data, and understanding. And it helps also define for these students what a scientist is. But I really think to get an educator to that point of, I guess, excitement to take on something like this, thankfully now there are many examples and success stories.*

Teacher reluctance to enact new ways of teaching can be a pitfall, especially when the new approach is associated with giving up some control over instruction (e.g., sharing control with administrators, collaborating teachers, scientists or a broader science initiative; students assuming some control of investigative activities; conducting instruction outside the classroom). Modeling by teachers well versed in CS is a way to avoid the pitfall. Integrating CS gradually to build teacher confidence is another way to help teachers embrace the change. One approach is to start with a relatively straightforward project, one that teachers are likely to succeed with, then moving to more complex projects. An important component of this strategy is clearly communicating to teachers the plans for gradual transition early in the planning process, easing any anxiety associated with instructional change.

> *I think that you start out small. So you have maybe one or two citizen science projects that you start out with that have a high probability of success. So I think you start out and you get your feet wet. You find out that these projects—they're effective, they're fun, they're engaging. Students are more engaged in their own learning, taking more responsibility of their own learning, you know, all of the good aspects. What I think then happens is that there's maybe a natural tendency to then look at other possible CS projects that are available…. So I think it's just giving opportunities early that have a high probability of success.*

(6) CS work should be meaningful, not just procedural, to teachers and students.

In CSiS, we saw that a key to making CS work meaningful was science teachers becoming comfortable leading students in authentic science investigations. School-based CS programs should offer training to teachers before they implement CS projects in classrooms. The training should emphasize how science works, including how to develop realistic investigation questions and the importance of relating data back to these questions to make the endeavor meaningful. Ideally, teachers should engage in brief, small-scale investigations themselves before leading students in CS work. Teachers will benefit from facilitated firsthand experiences selecting focused research questions, identifying corresponding experimental approaches, methodically collecting data, and interpreting the meaning of the data relative to the research questions. Even though many CS projects linked to broader initiatives may have established research questions in place, student investigations may require narrowing these questions to fit curricular and logistical constraints. Further, participating in investigations will very likely help teachers lead students to identify the relevance of experimental results to underlying issues, even in instances where the research questions are predefined. Because scientists have experience planning and conducting research, we think they should have leadership roles in this training.

> *[I suggest] just engaging the teachers in what they [will] expect the students to do…. Teachers need the opportunity to engage with the data as well: know how to retrieve data, know how to communicate the data, [know how] to extrapolate meaning from the*

data. [Many] teachers don't have a lot of experience doing that. So I believe that they're going to require some extended professional development to give them [these] opportunities.

Of course, making CS projects meaningful to students requires further effort during instruction. Teachers need to consistently emphasize for students the relevance of data collected, highlighting how they can use the data to address the questions being investigated. However, strategies for leading students to meaningful connections can also leverage local issues, policies, and connections to students' everyday lives, as well as relationships to broader research initiatives.

A pitfall we experienced with some projects was attempting to lead teachers and students to meaningful connections only *after* much of the CS data-collecting work had been completed. Although having concrete data to interpret is important for encouraging students to consider the implications of their projects, we think it is a mistake to wait until data collection is well underway to have students think about how data can be used to address a project's questions.

I would like an earlier check back than what we did. So it's [regularly] going back and somehow assessing that the students really understand the "why." Because, for example, in the first year that our agency was involved, by the time we were asking the "why" and it became clear that the students didn't know the "why," it was toward the end of the school year…. I think some kind of early testing after the initial teaching is done, either by the teacher or the scientist [is helpful], some kind of assessment to see if the kids have got it, and if the teachers got it for that matter … to make sure that everybody's at a similar understanding.

(7) CS should be part of the school culture.

To instill CS in a school's culture, we recommend designing a program that connects with as many parts of the school as possible. We think of two dimensions primarily, one "horizontal" and one "vertical," when considering how to promote school-wide involvement. First, if a CS project spreads horizontally (i.e., in the same grade) beyond science lessons and relates to curricular objectives from other disciplines in substantial ways, it is more likely to take hold in a school. Exploration in other subject areas can expand students' understanding and appreciation of the broader context of science research topics and thus CS can enhance student learning across subject areas. A natural step on this path is designing CS projects to have obvious cross-curricular connections. Teachers can emphasize reading, writing, and mathematics while conducting CS projects, both in and beyond the science class itself. Students read critically to gather background information on the phenomenon or question to be investigated. Students write as they form and refine specific research questions, describe the contexts of their questions, and explain their interpretations and conclusions. Students apply mathematics as they make and record measurements, analyze data, and graph results. In social studies, local aspects of projects can pave the way to exploring municipal, and broader, government structures and issues that inform or expand lessons. More global aspects of projects may be fertile ground for ties to geography, foreign language, and study of diverse cultures. The visual arts come into play as students prepare to present their CS experiences to others. Of course, teachers who teach all core subjects are best positioned for such cross-curricular connections, but another strategy is to involve teachers of subjects other than science in the planning.

> *[Designing], like CSiS did, where involving not just the science teachers, even though it was science focused, but bringing in teachers from other areas of study [would be helpful]. I'm not [saying] that they need to be 100 percent as involved early on in training, maybe as the science teachers were, but having them at least somewhat involved in the project, I think, would help expand the culture more widely throughout a school program.*

Vertical connections *cross* grade levels, providing for ongoing skill development and a sense of continuity in what can otherwise be a fragmented curriculum. A program could simply identify different project foci that align with the science standards at each grade level and progressively build students' science practices. With additional strategizing, it may be feasible to find a series of project foci having some common thread that ties projects together across grades so that students readily build upon their previous findings and understandings. We suggest that CS program leaders integrate both horizontally and vertically to help secure a program's place in the school culture.

> *It's starting the CS very [early] and continuing it year upon year so that [students] kind of grow up understanding this is how it works, or [it's] part of the culture, rather than, for example, doing science one way for three years and then expecting to go totally outside of the box with CS and then go back into the box…. So it's kind of having that whole CS based on a long-term investment for the kids and integrated in many different ways, and possibly even followed throughout the years. So the first year maybe you're learning about native plants and what you planted. The second year, maybe you're learning about the soil and all [its] aspects. And then maybe the next year you're learning about the water chemistry and how it cleans the water from the parking lot. So it's not the same project year after year.*

We identified two related potential pitfalls in establishing CS in school culture. Horizontal and vertical integration of the CS program requires support from the administrative decision makers. Teachers and students likely need this support for logistical arrangements (for example, facilitating off-site data collection) but also to act confidently in implementing their CS plans. This support is also important for generating training opportunities for teachers. The leadership also needs to be consistent over time, not just at the outset. A possible threat to this consistency is continued introduction of new instructional initiatives. Administrators need to be wary of initiatives that might interfere with CS. Turnover in administration is also a threat. For this reason, although administrators are important for supporting CS, they probably should not be primary program leaders unless they are likely to remain in place for several years.

(8) The CS program should improve student understanding of science content and practices.

The ultimate accomplishment we envision for an effective CS program in a school is to advance learning. We see attention to the seven areas outlined above culminating in a CS program enabling this outcome. Like any good instructional program, formative assessment is essential for identifying concepts and practices where students are struggling. Scientists can be instrumental in helping to design these tasks. With the information gained, leaders can proactively identify and address learning difficulties that arise rather than rigidly adhering to an initial implementation agenda.

Another key to promoting student learning is designing investigation questions and methods to be sufficiently straightforward that students can collect data, interpret them, and relate them to a hypothesis. If methods are overly complex or resulting data are only tangentially relevant to the research questions, students may not have confidence in their investigations and be at a loss to draw even small conclusions.

Maintaining student enthusiasm is important for learning, but it can be a challenge with a year-long project, especially when data collection protocols are repetitive (as they typically are). Teachers and other school leaders need to display their own interest in and commitment to CS to ensure that students remain similarly motivated. Another factor in maintaining student enthusiasm is selecting and developing CS projects that allow sufficient flexibility for students to follow their particular interests within relevant topics. This freedom to explore based on curiosity reflects the excitement of science and can be an important student motivator.

A pitfall that touches on each of the above recommendations is unrealistic expectations. In the excitement of embarking on an investigation-centered approach to instruction, planners, perhaps especially scientists, can get carried away with potential contributions to scientific discovery. While this excitement can and should be a positive element of a CS program, expectations for student understanding and accomplishment need to take priority.

> *One of the pitfalls that I noted here, thinking through this, was…making sure the practice piece of this is appropriate for the age level you're working with…. Because that was something that we wrestled with a little bit at the beginning of the [CSiS] project. We had some ideas of what we could do and presented that to teachers and it took us a little while to adjust, and I asked that of the teachers a number of times: You work with [these students] every year or all the time. What level do we need to come in at to make sure we make it meaningful for the students?*

DISCUSSION

In the Context and Perspective section of this paper, we described the school-based CS initiative that drew us together, and we acknowledged that it may not be the norm in some important ways. Among them, the initiative benefitted from considerable funding, which made possible the substantial, long-term training teachers received. The funding also compensated us for some of our time, more than we suspect most CS initiatives can afford. That compensation also helped the initiative remain prominent among our many competing priorities. Apart from that funding, CSiS involved multiple schools, creating a robust network of peer support for all teachers involved. Finally, the initiative was led by a university scientist who is passionate about the student learning opportunities that school-based CS makes possible. We acknowledge that in these ways and others, we worked within a privileged context, but we do not believe this diminishes the validity of our recommendations. We were involved with CSiS for several years and worked with many teachers in diverse settings, affording us the opportunity to see what works and what does not work in school-based CS. Our recommendations are well considered and grounded in extensive firsthand experience. In concluding the paper, we highlight major lessons learned.

First, an approach in which a CS project is simply inserted in a school or classroom with little planning or training is unlikely to succeed. Most existing CS projects simply are not designed for seamless integration into schools. Considerable up-front planning is important to ensure that the projects: (a) align with the standards teachers are accountable for, (b) help students learn the science concepts in that curriculum, and (c) do not conflict with ongoing initiatives at the school. Schools are complex institutions with many agendas and functions. Attempts to integrate CS without acknowledging and planning for this complexity can actually have negative consequences, including teacher and school administrator resistance and ill-used instructional time.

Although science class is the natural home for school-based CS projects, meaningful connections to other subjects are important. In fact, CS projects can be a unifying theme across different disciplines, including the arts. Another dimension of up-front planning involves recognizing that schools are integral parts of their communities, and the more a CS initiative can connect with the community, the more support it is likely to garner. Such support can be essential for weathering the storms that school-based initiatives will inevitably face. Finally, choosing CS projects that are part of much larger CS initiatives has obvious advantages, among them the work that has already been done (e.g., developing data collection protocols and data warehousing infrastructure) and the opportunity to connect with other citizen scientists in distant and diverse locations.

The considerations above emphasize CS work being meaningful for students, which we see as critical for a successful school-based CS program. Students need to understand the “why” of their CS work, not just the "what." Without this deeper understanding, CS can devolve into rote data collection and reporting, and while some benefits from such an approach are possible, they pale in comparison to the potential for student learning. Connections within the science curriculum and with other subjects make the kind of learning we envision more likely.

As mentioned previously, all of the authors are professional scientists. While acknowledging our bias, we do believe that scientist involvement in school-based CS increases the likelihood of success. This view does not diminish the importance of the teacher. We have years of training as scientists, but would struggle to manage, much less teach, an elementary or middle grades class of students (the two groups that CSiS served). Teachers also have years of training in their profession, but they typically do not have training to conduct science investigations. A professional teacher paired with a professional scientist makes a formidable team. However, we recognize that scientist involvement is not always possible, and we think that in such situations, well-developed teacher support materials are especially important for CS program success.

Following all of the recommendations in this paper is unlikely, and doing so may not be essential for a successful school-based CS program. However, we do believe that following any of them will make a CS program better. As scientists, our years with CSiS have deepened our appreciation for the complexity of schools and the resulting challenges for establishing a CS program. If we had to choose one recommendation or group of recommendations to privilege, we would choose the up-front planning that takes into account the unique constraints and affordances of schools as settings for CS. We remain convinced of the educational potential of CS, and we believe the kind of planning we describe is key for realizing that potential.

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