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Agricultural Contexts as a Platform for Science and Technology: A Cross-Cultural Examination of Classroom, Community, and Modeling Dynamics

By

Rebecca L. Shareff

A dissertation submitted in partial satisfaction of the

requirements for the degree of

Doctor of Philosophy

in

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in the

Graduate Division

of the

University of California, Berkeley

Committee in charge:

Professor Michelle H. Wilkerson, Chair
Professor Erin Murphy-Graham
Professor Dor Abrahamson
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Abstract

Agricultural Contexts as a Platform for Science and Technology: A Cross-Cultural Examination of Classroom, Community, and Modeling Dynamics

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University of California Berkeley

Professor Michelle H. Wilkerson, Chair

The world faces imminent crises related to climate, science literacy, and environmental justice. Place-based education presents opportunities for students to develop environmental advocacy, leverage their prior knowledge, and broaden scientific practice to serve local communities. This dissertation examines place-based science education in two agricultural contexts that promote the incorporation of technology: rural Honduras and school-gardens in the USA.

Various qualitative methods were used to document and engineer successful place-based learning experiences. Field-based observational methods and interviews document SAT, a successful Honduran science curriculum that integrates learners' academic and community knowledge through agricultural experiences. Design-based methods engineer, and revise, curriculum and modeling technologies to create similarly integrative experiences in a school-based garden.

In both contexts, attending to the utilization of experiential and cultural knowledge across place, scientific content, and technology helps explain learners' tensions and successes. To design integrative experiences in school-based contexts using simulation models, a learning environment should align its stated *purpose*, the *instruments* used, and the *quantitative* opportunities of simulation.

Across three papers, this dissertation contributes (1) examples of successful place-based ecological education; (2) a framework for thinking about the role of technology in place-based ecological education across contexts; and (3) design principles for technology-mediated garden-based experiences in NGSS-aligned US classrooms.

Dedication

To the next generation of environmental leaders, who give this work meaning.

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Acknowledgements

I want to first acknowledge the commitment and support from my committee; to Erin for inviting me into the SAT project, bringing me to Honduras, and opening up the world for me, so that I could continue to engage in meaningful international work; to Dor for bringing me under your wing as an orphan advisee, pointing me towards modeling and a ‘feel’ for the organism, and always sharing articles and opportunities that you saw fit to my interests; and to Kimiko for your invaluable perspective on learning and technology design (and an emotional support bear!), thank you all for your dedication to my growth.

To my chair Michelle, thank you for the attentive, supportive, motivating, and consistent nudges to make it through all of this. Thank you for allowing me to be my most creative and authentic self as a scholar, and putting your faith in me by advising me so soon after your arrival to Cal. To all of my advisors who allowed and enabled me to spend time with your dogs, it truly bolstered my mental and emotional health, and for that I thank you endlessly.

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1 Introduction

1.1 Problem statement

This work aims to situate learning at the intersection of agriculture and scientific education to address problems both large and small in scale. Starting large, global climate change is affecting the environment and agricultural sectors at a rapid pace (Gowda et al., 2018). Soil erosion, access to clean water, and extreme weather conditions are just a few of the challenges facing the future of agriculture. Teaching kids to care for and about their natural landscapes is vital to human survival. Directing students' focus to the ecology and infrastructure of growing food is also important in considering the social application of scientific knowledge. This practice of thinking about and applying science and technology to social issues is also reflected through current educational initiatives like the Next Generation Science Standards (NGSS), as technology is expected to lend a hand in solving some of the biggest problems facing future generations.

More minutely, at the classroom level, science education and content are often objective and disconnected from students' lives. The positivist epistemology that has been enculturated into many practicing science communities, that all knowledge about our existence is generated through experimental procedure, excludes other epistemologies, such as those that consider more relational and interpersonal approaches to knowing about science (Bang & Medin, 2010; Turkle & Papert, 1992). Historically, women, students of color, Indigenous students, and students from rural communities have experienced barriers to feeling valued and successful when science is positioned in this way (Abrams et al., 2013; Calabrese Barton & Tan, 2009). Teaching through hands-on experiences invites more engagement from students (Bell et al., 2009), particularly those who have been systematically excluded, by drawing upon and positioning their life experience as meaningful and valuable in contributing to scientific knowledge (Ladson-Billings, 1995a). Place-based approaches to science teaching in particular, not only help students develop an awareness of the challenges facing their local communities, but also ground their thinking about larger scientific and social issues in a meaningful context that they have agency to impact (Ardoin, 2006; Chinn, 2015; McKim et al., 2019) One way to address these problems is through learning opportunities that bridge students' lived experiences in *school-based agricultural contexts* with *ecological science* and *technology* content. In particular, I explore the question, how do learners appropriate and apply technological tools to investigate ecosystem dynamics within a school-based agricultural context? In the next section I define these terms with respect to my dissertation topic and focus of study.

1.2 Overview of key concepts

In this context where technological tools are used to support students' learning of ecological science in school-based agriculture, the setting, motive, and tool are equally important factors, and are each imbued with historical significance. In the following subsections, I share a brief background of each term, followed by my specific orientation towards its role in my study context; I end with a description of two study environments thousands of miles apart, where these concepts are manifested in distinct yet related ways.

1.2.1 School-based agricultural contexts

Humans have manipulated and represented aspects of their identity in an environment since the earliest civilizations, intervening in their immediate environment to shape and create open-air surroundings for themselves and for a given society or culture (Hunt, 2000). One can reasonably assume that as long as there have been agrarian societies, there have been humans engaging in some form of education and transmission of knowledge about how to tend to the land and grow food. While often considered separate from formal 'schooling' activities (Scribner & Cole, 1973), this type of practice is greatly entwined in the livelihoods of many cultures around the world. As globalization and colonialism have shifted the social and economic structures of many people, the agricultural and schooling practices have shifted as well. At its most general form, a school-based agricultural context is a field plot or garden bed connected to schools where crops are grown and tended to by students and teachers, yet the cultural and political realm where these contexts are situated have changed in response to larger ideological principles.

In the United States, John Dewey proposed school gardens in the late 1800's as a way to integrate practical learning environments with school knowledge, inspired by European educational practices and theory that introduced science to public schools by stimulating curiosity and enthusiasm for the wilderness (Ralston, 2011). Kohlstedt's (2008) analysis of the history of school-based gardening practices revealed that this value of gardens as an exploratory and practical space for inquiry was not extended to all populations. The schools of Native American and African-American students incorporated garden work much more like vocational training, with tightly controlled sets of practices and the strict motivation to provide food for the schools and 'establish character'. Ultimately, the US government capitalized on the popularity of school gardens as a way to demonstrate support for troops in World War II, converting them into a "School Garden Army" for growing crops to support the troops. After the war, this practice, along with most school gardens, faded from popularity.

A resurgence of the original ethos of school gardens has enabled several offshoots of educational practices to reclaim and contextualize Dewey's original ideals. These include environmental education (Boyer & Roth, 2006), agricultural education (Arnold, Warner, & Osborne, 2006), outdoor experiential education (Ord & Leather, 2011), and place-based education (Woodhouse & Knapp, 2000). Garden based learning holds a role as an interdisciplinary setting distinct, yet related to, the fields of environmental education and agricultural education (Williams & Dixon, 2013). The distinction lies in the philosophical roots, desired outcomes, and proximity to school grounds– environmental education posits itself as linked to environmental action, conservation attitudes, and nature immersion, often experienced by school children on field trips. Agricultural education entails the particular procedures, techniques, and scientific knowledge involved in the production, maintenance, and harvest of food and livestock (Bell et al., 2009; Desmond et al., 2004; Hofstein & Rosenfeld, 1996; a more extensive review of North American agricultural education practices appears in the next chapter). These fields are intrinsically connected by the idea that interactions in outdoor spaces are powerful entry points to learning.

While different political motives have positioned garden-based education more or less in favor, the current ethos around school gardens in North America relies on both growing food to support nutritional habits and increased engagement in STEM content (DeMarco, 1997; Desmond et al., 2004; Dirks & Orvis, 2005; McArthur et al., 2010; Ralston, 2011; Rye et al., 2012; Thorp & Townsend, 2001). Many California gardens were installed with these two purposes (Agee et al., 2002; Graham et al., 2005), though research on their impacts has come largely from the field of public health and focused on behavioral outputs (eating more vegetables) and knowledge of the nutritional components of produce (Hazzard et al., 2011), or general behavioral changes like attention and enthusiasm for learning (Graham et al., 2005). While academic based instruction in school gardens is becoming increasingly more popular, there is still limited research detailing the potential for instruction with new content standards in science and technology (Blair, 2009), particularly with validated and well-aligned means for assessing student activity (Shareff, 2015).

Outside of the US, rural communities also incorporate agriculture in school-based activities as a means to connect instruction to meaningful application and vocational preparation. In Latin America, for example, formal secondary schooling is primarily located in urban centers where content is decontextualized and taught in lecture-style (Urquiola & Calderón, 2004). Many students from rural communities do not complete school (One Country, 1996), as it would require leaving their families alone to tend to their plots, and engaging in an entirely different practice from what would be relevant to their lives (Murphy-Graham, 2012). I examine one innovative curriculum that seeks to re-incorporate agricultural practices and academic curriculum in rural communities in Latin America (Arbab, Correa, & de Valcarcel, 1988), to be elaborated further in this dissertation.

I focus on school-based agricultural environments as a setting to address the problems above as they involve the interaction of experiential and cultural knowledge within a school context. In particular, I bring into focus the role of community and the social application of this knowledge as powerful potential resources for students to feel connected to school, and more specifically, science. The next subsection explores how a particular scientific topic (ecology) is well-suited as a motivation of study within this setting.

1.2.2 Ecological science

Ecological science is generally understood as the behaviors and cycles that comprise the interactions between soil, plants, animals, water, weather, and humans. This topic of inquiry invites investigation into the complex systems and behaviors that make up many social and scientific problems in the post-industrial world. In particular, the inclusion of human intervention to otherwise sustainable cycles of nutrients, weather, and animal and plant behavior have impacted global climate change, migration, soil degradation, and other public health concerns. While often classified as similar to environmental science, ecology specifically refers to the study of environments and the entities within them: relationships between living things that share a 'home' (Mason, 2018). These environments can be small or large in scale (within a single creature's digestive system, or the whole Earth), so their study similarly involves the ability to think about systems, dynamics, and behaviors of the creatures within them. The NGSS incorporates the study of ecosystems from grades 3–12, particularly about properties of independent relationships between organisms, cycles of matter and energy within an ecosystem, and disruption and resilience caused by shifts in natural resources (NGSS Lead States, 2013). For the purpose of this dissertation, I define *ecology* as the study and associated practices that cultural communities engage with to integrate both natural and human systems.

While clearly a realm of scientific and social importance, ecology tends to be ranked lower in prestige (National Opinion Resource Center, 1989) than other science fields, and compared to chemists, biologists, and physicists, ecologists in the United States earn less annually (Occupational Information Network, 2018). One could speculate about the reasons for this; in particular, physics and chemists rely on highly specialized equipment, often developed in research laboratories that have become prestigious as features of Western (European) scientific approaches. Ecology, on the other hand, has been practiced by Indigenous people for centuries, though imperialism has distanced native communities from the lands that they know and understand intimately (Macfarlane et al., 2019). The cultural knowledge systems developed through deep interaction with and reliance on local ecosystems have been a topic of science research in recent years, especially with attempts to understand how cultural groups differ in their understanding of the relationships in ecosystems. Specifically, Medin & Bang (2014) argue that Native Americans tend to see humans as part of natural ecosystems, while European Americans see humans as removed from them. These cultural differences also emerge in how students classify scientific entities (Unsworth et al., 2012), reason about features of an ecosystem (Bang, 2015) and define interdependent relationships between animal species (ojalehto et al., 2015).

Instead of warranting less prestige or financial reward, these features of ecology make it more likely to be a realm of science that people have intuitive and contextual knowledge for, especially locally, as they spend time outside, see how their environment changes from season to season, the animals that come and go, and how humans continue to develop, extract from, (or maybe, preserve) that land. We should value this, rather than condemn it in the academic world. Despite this distinction in the realm of science, I propose that ecology, in its explicit incorporation of both natural and human systems, is an appropriate topic to pursue in school-based agricultural environments, as they too are a blend between a 'natural' ecosystem and one generated through human activity.

1.2.3 Technological tools

Broadly, I adopt Pickering's (2010) definition of technology: materials developed by humans to enact on their environment things they could not do on their own, and a recursive evolution from learning the limits of those technologies, and designing new ones. This definition is wide enough to include the technological products developed in communities outside of the urbanized United States, which will also be included as part of this research. However, as a researcher situated and trained within a Western, computer-based society, I have the most exposure to cultural artifacts and innovations reflecting this stance (Papert, 1980). While I review these technologies below, I am aware that their use in instruction is a positioning of those epistemologies and values, and may not be in alignment with agricultural education in other communities.

The scope of scientific content that one could teach in an agricultural environment (plant biology, agroecology, ecosystems dynamics, plate tectonics/ geology, nutrient cycling, and weather systems, to name a few) range from the microscopic to large and multi-variate. To better understand these concepts, particular technological tools such as virtual models and simulated dynamic systems are valuable for isolating particular components of the physical landscape and allowing students to examine their interactions and emergent properties repeatedly, and at varying speeds (Kamarainen et al., 2015; Wilensky & Reisman, 2006).

Two particular technological innovations encourage interaction with these components of the environment that might otherwise make them hard to see: computer-based simulation, and augmented reality. These have been utilized in a variety of ways, including entirely virtual immersive environments (Dede et al., 2017); outdoor environments where augmented reality technology accompanies physical exploration (McClain & Zimmerman, 2016; Ryokai & Agogino, 2013), and modeling systems that combine physical and virtual elements (Blikstein et al., 2012). These technological tools are conjectured to support learning for their inclusion of scaffolded use of authentic scientific tools and practices, multiple varied forms of representation, collaboration with peers, personalized learning, and application to outside learning contexts; I offer a more extensive review of computer-based simulation models as a technological tool used in scientific education in Chapter 4.

As mediating artifacts used to investigate and demonstrate particular facets of the world, I believe the technological tools that students and teachers use to investigate an ecosystem are an important resource towards addressing the problem of broadening scientific participation toward addressing global environmental issues: they carry cultural values and assumptions that are important to surface when attempting to understand the way learning is structured and enacted. In particular, when students are invited to construct the technological tools themselves, they can apply their own values and interests towards their learning. For one phase of this project, I have developed a NetLogo (Wilensky, 1999) simulation model of an agricultural ecosystem that offers users a space to experiment with ecosystem dynamics, edit its features to reflect their individual interests, and evaluate based on their own experiences in the school garden. The evolving design of this tool is documented in Chapter 3.

1.2.4 Exploring these key concepts across contexts

In sum, I focus my research on *the use of technological tools as a resource for investigating ecosystem dynamics within a school-based agricultural environment*. These concepts can be operationalized in many different ways, though in this dissertation I explore two instatiations. In one, the setting is a rural community where agriculture is a primary occupation and practice; the learning environment incorporates agricultural technology (fertilization, pest-reduction, irrigation, and bed-building methods) as students learn about soil composition, nutrient cycles, and plant resilience in practice with their school peers and community members. In another setting, the scientific content under investigation is similar, though the technology and community resources that shape the formal learning environment are remarkably different. Here, the school garden is a feature of a school community with high use of computer-based technologies, and without much explicit agricultural practice: a natural space adjacent to many concrete structures. Within this setting, a simulated garden model is used to support inquiry of the garden, for students to reason about the relationships between abiotic and biotic components of the garden, and the role of humans to tend to them. Comparing the two settings illustrates the roles of communal knowledge and practice, cultural connections to differing forms of technology, and how agriculture can incorporate formal school science activities in a meaningful, experiential way. The next section will demonstrate the particular questions I seek to answer within this realm, followed by more detail on the particular cases of study.

1.3 Research questions

At the highest level, the question driving my investigation is:

When students learn about ecosystem science and technology through interactions with agricultural space(s), what shapes their relationship to:

a) The garden or agricultural environment;
b) The scientific content; and
c) The technologies they interact with?

Composing the question in this way specifies the three important concepts of the learning environments I investigate, with an awareness that the answers likely involve interactions between the three. I also speculate these answers to vary depending on the cultural context and technological tool used in each space.

To answer this question, I consider how these three components interact with students' lived experiences, the values they ascribe to each, and how they make decisions within this context. In this dissertation, I explore the design and implementation of technology in agricultural-based science education spaces with a three-paper structure to cover the breadth of contexts of study. Like many design-based researchers (Brown, 1992; Collins, 1992; diSessa & Cobb, 1994), I contribute both theoretical and practical applications from this work. In particular, I contribute to the theory and epistemology of cultural science instruction by analyzing distinct educational contexts described below, and how they each shape learning of similar scientific content (namely, plant science and agricultural ecosystems). The practical contributions include the design of an instructional tool (a simulated garden model) as well as a framework to support the integration of such tools into an inquiry-based science environment. A full breakdown of the research questions and the investigative approach for each paper is seen in Section 1.6.

1.4 Case contexts and researcher positionality

Central to this investigation is the distinction between two cultural contexts with school-based agricultural environments: rural Latin America and suburban Northern California. Within each of these regions, students are learning science via explorations and projects in agricultural spaces, and in the past decade I have been a witness to this learning while holding roles as an instructor, curriculum designer, research partner, and evaluator. These experiences have shaped the particular language resources, familiarity, and personal affinity I have for education in this context.

Particular to this dissertation, I focus on three spaces. The first is a series of communities using the SAT (Sistema de Aprendizaje Tutorial, or Tutorial Learning System) secondary curriculum in rural Honduras, specifically science and technology units, with several project-based workbooks that explore themes in agriculture and local ecosystems (Kwauk & Perlman Robinson, 2016). While this context is well-aligned with my professional background and interests, I ultimately was a White foreigner operating within a research environment that did not reflect my cultural orientation. As such, what I was able to see depended on the development of trust between me and my research subjects; this was heavily influenced by Dr. Erin Murphy-Graham's research presence and personal relationships with administrators and community members that has been cultivated for decades. At the training facility, my sustained presence in the classroom slowly shifted into a participatory-observer role, which allowed for more candid conversations with tutors attending the training, who then volunteered to be interviewed individually. When I returned to the training facility two years later, the tutor-trainers could also vouch for me and help create a dynamic of trust and inclusion earlier on in the data-collection, based on our previous visit. Similarly, during the field visits to communities, an administrator within the program helped facilitate the trust we relied upon for access to authentic educational experiences. I believe that the time I spent in rural Latin America before these visits minimized the cultural acclimation that I needed to be able to both understand the research context and communicate authentically with the participants within it. Chapter 2 focuses exclusively on this case study of science learning with the SAT communities in Honduras.

The next two spaces are public schools within suburban school districts in Northern California. One is a middle-school within a district with explicit directives and resources to facilitate school garden instruction at its elementary and middle schools. Before studying this school as a researcher, I worked as a contractor for the school district to design curriculum and support instruction at this particular middle school, and evaluate and refine their curriculum for the elementary schools. This type of access meant I was already familiar with the school culture, the type of garden experiences students were regularly having, and how particular teachers utilized the garden in their domain contexts. This information was integral in the design of the first two iterations of research studies articulated in Chapter 3. In both the middle school and the high-school where I implemented studies with the NetLogo model, I co-taught with the instructor so that I was the primary facilitator of model activities. This choice was meant to minimize the cognitive load required for the partner teachers, and best support students as they learned about the tool. As a result, my role in the classroom was more than an impartial observer, and possibly influenced the way students behaved or related to the lessons.

The shift from the middle-school to a high-school was primarily a result of the partner teachers leaving the middle school, though the shift also enabled more breadth and flexibility within the science curriculum. This high-school is in a more affluent suburban district, with less of an infiltration of researchers from surrounding universities; this likely influenced the number of students whose parents consented to their participation in the study. The classroom teacher who agreed to participate in the research study is also the current manager of the school garden, so they had sustained access and interest in incorporating the space with their students. They are also a friend and former colleague of mine, as we share experience leading garden education programs with high schoolers in rural Latin America. As such, our investment in and ability to co-design activities in the garden was driven by a prolonged history in doing so, which also was expressed in our dynamic as co-instructors. This relationship was likely a factor in some spontaneous decisions about the length of activities that impacted the implementation of the design, as responding to student behavior in the moment was a part of our repartee and there was mutual trust in making decisions to do so. The study enacted in this context is described fully in Chapter 4.

1.5 Ontological and theoretical stance

1.5.1 Epistemology and ontology statement

Ontologically, I believe that realities are shaped by individual experiences, cultural artifacts, social scripts, and the tools of language, per the relativism camp. As I am greatly interested in the ways that technological tools are utilized towards personal meaning and understanding, the epistemological approach of constructionism is most aligned with my views. In the interactive spaces I am drawn to, I believe any learner's experience will rest on social-constructivist claims that meaning is co-constructed in activities, with the guiding hand of instructors. As a constructivist, I believe the answers to questions of how learning happens in a particular environment rely on the individuality of a student's perspective and their ability to extract meaning from a particular situation, rather than an objective truth to what that learning environment, such as a garden, either provides or does not provide. Operating from this perspective, I will incorporate individual viewpoints and reflections on school-based agricultural environments as valid ways of knowing what types of learning are occurring, that when linked together will illustrate the wider constructs at hand.

1.5.2 Theoretical orientation

I orient myself within a range of theorists that emphasize how social interactions between humans direct the use of tools and natural resources within a learning environment. Across this scope, I ground the focus of my work in contemporary Activity

Theory (Engeström, 1987). The model of activity theory allows for a deeper examination of the interplay between culture and human actions, or as Leontiev defines it, the processes in a person's actual life in the objective world that incorporate their social being in all its variety of forms (Leontiev, 1977). This framework expands on Vygotsky's initial triangulation between subject, object, and mediating artifact (here labeled 'instrument' in the blue triangle in Figure 1), to include layers for the collective activity and its general motives and objectives, the actions and their associated goals, and the operations that serve as a means for the achievement of those goals. This interplay can also be examined through six related elements, as illustrated in the combination of the orange and blue triangles: Instrument, Subject, Object, Rules, Community, and Division of Labor. The model has been used to analyze a great variety of networks of social activity, but as a tool to study the development of children it has primarily been used to examine play, labor, and learning (Engeström, Miettinen, & Punamäki, 1999). Insomuch as garden-based education in its ideal form is an amalgamation of all three of these components, and has much cultural and historical context to draw on, it seems productive to analyze that context through this model.

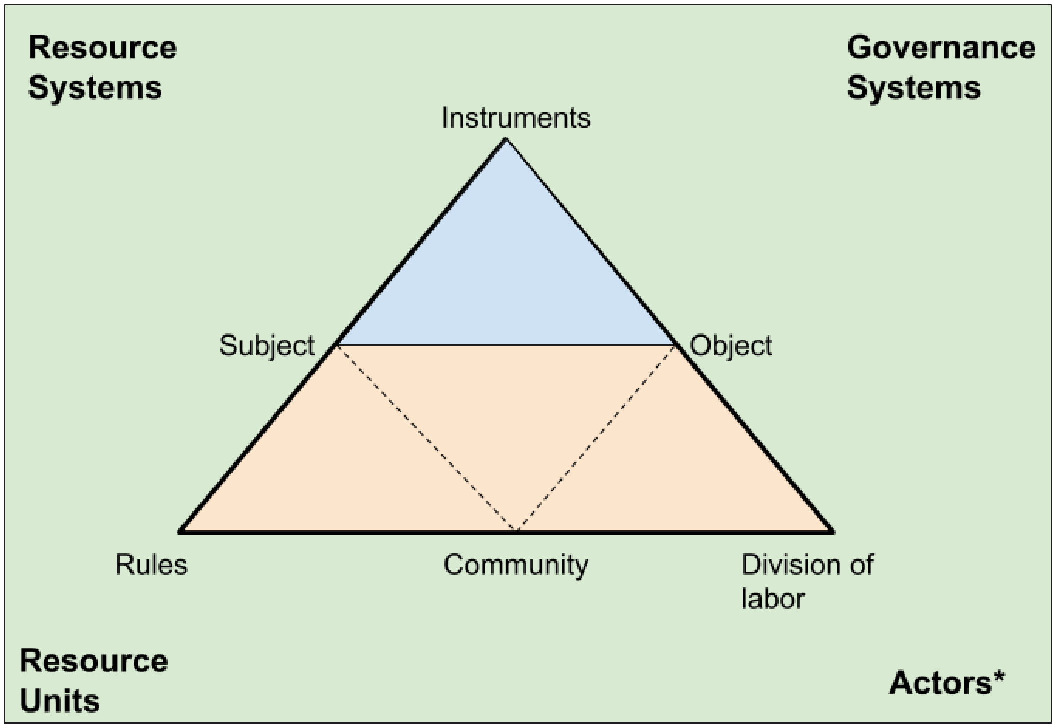

Figure 1. Conceptual framework.

Note. Instrumental genesis focus (blue) is located within the classic Activity theory triangle (orange + blue), which is then further contextualized within the large-scale social, ecological, and governance factors of SES (green). I scale back and forth accordingly to address my research questions across the contexts of Honduras and the US, to incorporate the role of the larger community and land-based resources (Honduras) and particularly focus on individuals learning about and utilizing technological instruments (US).

Activity theory (AT) is the primary theoretical framework I use to support my investigations in education, as I am most interested in questions of how the context of gardens, and the different types of activity they afford as an informal oasis to a formal school structure, can support scientific learning. This theory takes into account many factors of the environment, embodied action, and tools. Additionally, I believe the cultural context of such spaces is a large influence on the way learning happens, and therefore consider shades of activity theory that attend to the cultural and historic influences. I think this framing will further drive insights into the domain of model-based reasoning, as it invites for interpretation not just the modeled environment and classroom social environment, but also the lived associations with the model context itself (gardens). While this framework centers the predominant theoretical perspective of my work, as my work spans two distinct contexts, I broaden and narrow the theory accordingly to examine the systems of learning at a macro and micro level.

1.5.2.1 Social-ecological systems + Activity theory

As a nationalized curricular system is the focus of one component of my research (Sistema de Aprendizaje Tutorial, or SAT in Honduras), I take a larger-scale interpretation of activity systems to account for more than just the local networks of activity. The curriculum draws explicitly on local natural resources; therefore, to think about the forces affecting learning, I am also incorporating the environmental and economic systems that shape the regions, as in Krasny & Roth's (2010) hybridized framework. In particular, embedding the Activity network within a Social-ecological systems model (Figure 1, Triangle within the green rectangle) provides context for the political, environmental, and economic systems present in the examination of learning. Yet this relationship is bi-direction; while collective activity, mediated by tools, rules, community, and division of labor, can produce change and learning in humans, so too can the humans change their environment.

Hybridizing the frameworks in this way adds layers of environmental, social, economic, and political settings that bound the activity. These settings are comprised of resource and governance systems that structure the nature of activity; natural resources are quantified in units that are used within the learning environment The Social-ecological Systems (SES) framework was developed as an organizational tool to help communicate and disseminate political and scientific knowledge around natural resource use (Ostrom, 2009). Its motivation is to enhance resource-users' abilities to self-organize to preserve and sustain their local environments, sometimes in opposition to governmental policies. The context in study (Honduras) is highly vulnerable to climate-related hazards like hurricanes, floods, droughts, and landslides; in 1998 around 70% of the country's infrastructure and crops were destroyed by Hurricane Mitch, and global climate change is expected to impact access to water and agricultural stability (USAID, 2017). Additionally, government disruption continues to impact educational and environmental systems, by delaying salary disbursement to teachers or restricting access to watersheds (Altschuler, 2010).

As the SAT curriculum was founded to support sustainable development through education, and operated through a partnership between an NGO and the Honduran national government, an examination of the curriculum in practice is widely influenced by these systems. This will include reference to local business involvement, access to natural resources such as water, corporations that could be land proprietors, and the sale and production of goods that arise from the curricular units. While my research will still mostly focus on the perspective of the learners, I will frame the objectives and activities that shape STEM agriculture projects with respect to these external components.

1.5.2.2 Activity theory + Instrumental genesis

For the Northern California classroom contexts, I narrow in on the activity-network triangle to focus particularly on the nodes of Subject, Instrument, and Object, (Vygotsky origin, shown as the blue triangle within the orange triangle in Figure 1). Within this system, I am particularly interested in two phases of learning; students' adaptation to (1) and use of (2) an ecological garden model in activities with their school garden. In the framework of Instrumental Genesis (IG), this is referred to as instrumentation and instrumentalization (Verillon & Rabardel, 1995). These phases are particularly important to me as I seek to understand the unique affordances of grounding model-based learning and fluency within a familiar and accessible context. I believe the context has an important role both in how students come to understand the model, and in their application of the modeling principles to caring for the physical garden space, so these particular features in the activity system will be emphasized.

As a contribution to the model-based learning community, I also hope to construct evidence of the particular design features that were useful in supporting students' connections to context, and the changes to the code or new model elements that were inspired by the situated nature of the model within the adjacent ecosystem. While this analysis will be informed by students' outputs of instrumented activity and applications of the model, the emphasis will be on the particular design features that support learning in these activity systems in CA and Honduras[1]. However, there are still implications for learning, in particular a better understanding of the role of situated knowledge in deciding the design features that are helpful or need to be changed in order for a computer-based model to be successfully used as an instructional tool.

Towards this end, an emergent design framework that I call PIQ draws on AT and IG to specify key features for analysis within this learning environment. PIQ provides structure to build and evaluate learning experiences that situate learners within an environment with an instrument: their knowledge of the environment supports the use and evolution of the instrument, which also has specific features that support reasoning about the environment. While specified to this particular design (of a garden model and a school garden), the abstracted version of this framework is a valuable contribution to the discourse of how students come to develop fluency with epistemic tools in science classrooms.

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[1] While the model was not used formally in instruction or as part of a research study in Honduras, it was shown to SAT administrators, who commented on the particular features they saw connected to the values, instructional goals, and agricultural activities that make up the SAT curriculum.

1.5.2.3 PIQ elaborates knowledge integration from situated and instrumented activities for reasoning about a communal space with a novel tool

PIQ contains three nested features of a designed environment for utilizing novel technology towards localized scientific investigation: Purposeful application (P); Instrumented + situated negotiation (I); and Quantitative reasoning (Q) (Figure 2). A full break-down of the motivation and emergence of this framework is detailed in Chapter 2. Working from the top-most layer, the purposeful application of learning is generated by elements from the activity network surrounding the learning environment, namely the community, rules/ history, and tools available. This network also supplies the background for the situated knowledge about the community space (here, garden) that the instrument (here, garden model) is centered in, and ultimately is invoked when students decide a change to make towards the community space. In the next nested layer, learners negotiate this situated knowledge against instrumented knowledge developed through working with the instrument.

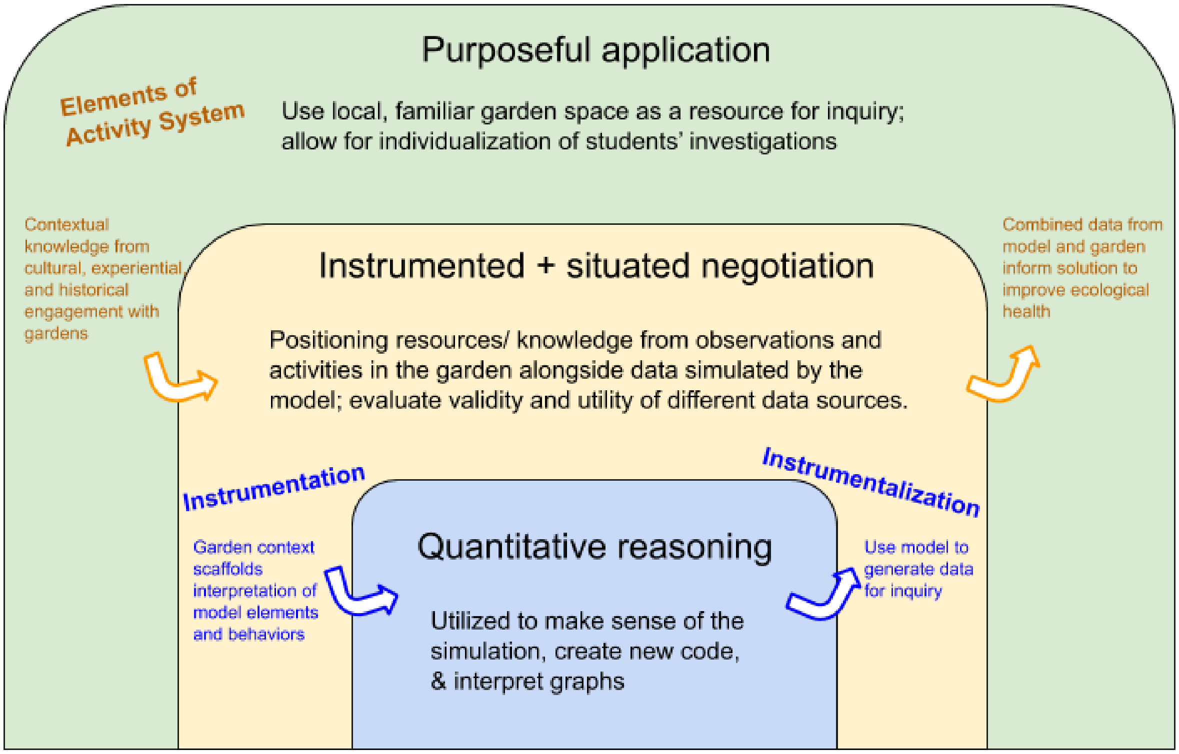


Figure 2. PIQ, a nested design framework.

Note. The three embedded layers interact through designed classroom activities. The orange + blue text and arrows show the final iteration where the model was used to support inquiry of the garden ecosystem and the promotion of an activity to improve its health.

During instrumentation (the first phase of instrumental genesis), when learners come to understand the affordances and features of a tool, their situated knowledge helps inform how they make sense of what is going on in the tool; one example of this is represented by the blue arrow crossing from layer "I" to "Q" in Figure 2. Then by the next phase of the activity, instrumentalization (the arrow that crosses from Q to I), they either run the model with a certain purpose or actually change the code so that it helps facilitate their research topic. To apply their knowledge, students negotiate their instrumented knowledge along with situated knowledge to state a claim about what is happening in the garden ecosystem, and what to do about it (arrow from I to P layer). Quantitative reasoning is nested at the bottom, as it gets invoked in both phases of instrumental genesis as students engage in multiple ways of reasoning about the numerical, logical, and representational features of the model: in instrumentation, this includes learning to read the code and interpret graphs; and in instrumentalization, this could include changing the model code, exporting data, and creating novel graphs.

All of these theoretical frameworks highlight different features of the learning contexts that I value and posit contribute to the unique opportunities afforded to reasoning about a local space, from the larger political and environmental systems surrounding it, to the intricacies of developing fluency with a new technological tool to better understand it. The specific research questions and approaches I take with these frameworks in each of the three papers are described in the next section.

1.6 Research questions in each chapter

To revisit, at a high level, the core research questions my dissertation seeks to address are:

> When students learn about ecosystem science and technology through interactions with agricultural space(s), what shapes their relationship to:
>
> a) The garden or agricultural environment;
> b) The scientific content;
> c) And the technologies they interact with?

These questions advance knowledge about place-based science education as a method across global agricultural contexts, and in particular how students develop technological fluency for new instruments as a part of their science experience. This high-level question is operationalized through both observational and design studies across three papers that look more specifically into these contexts:

Ch. 2) Conceptualizing culturally sustaining science pedagogy in rural developing contexts: An immersive field study of teaching and training in the Honduran SAT program

> 2.1) How are environmental and community-specific resources shaping and shaped by the (Science and Technology) learning experience in a rural agricultural education context?
>
> 2.2) How are knowledge systems incorporated and taken up by community actors in this learning environment?

Question 2.1 focuses on the larger communities and resource systems that impact the learning environment; for example, agribusinesses, waterways, local production and economies; the paper will show the way these are explicitly connected to the scientific content through curriculum design of science and technology units in SAT, and shape how students operate their own school garden plot.

Question 2.2 examines the scientific and agricultural knowledge systems created between groups of students, parents, tutors, and tutor trainers, in particular around the technological practices to be used in school garden plots, but also addressing their implementation in the wider agricultural community.

Ch. 3) Grounding science in virtual models: A DBR study on school garden ecology

> 3.1) Which features of the comprehensive learning environment optimize students' opportunities to critically juxtapose knowledge from the physical and simulated gardens?
>
> 3.2) How does the iterative development of activity design support theoretical development on mediated artifact use in situated scientific inquiry?

Chapter 3 foregrounds the technological instrument as a feature of study, with respect to how it corresponds with student activity conducted in the school garden (3.1) and its use more generally within scientific investigation (3.2); data across several iterations show shifts in opportunities for students to incorporate knowledge developed about the garden with knowledge developed about the model, while also showing the changes to the model and instructional environment that enabled them. The development of an analytical framework (PIQ) is then applied in the next chapter.

Ch. 4) Contextualizing evidence from physical environments and agent-based models towards environmental solutions

> 4.1) In what ways do students select and apply evidence collected during an investigation about the garden towards a scientific claim and ecological solution?
>
> 4.2) How is the model, in its representation of the garden and production of simulated data, viewed as an instrument?

In Chapter 4, the garden and the modeling technology are positioned as resources that contain evidence for the scientific task of ecological sensemaking. Question 4.1 looks at the ways that students apply evidence from both sources towards their goals, while 4.2 investigates model-based epistemologies that can be gleaned from their actions. These questions drive theoretical development around the situation of instrumental genesis within an activity system, and use the PIQ framing to elevate areas of student activity where they directly interface one another. They also support theoretical development on how students' epistemological stances towards computational models shape the way they approach models as a resource for scientific evidence.

1.7 Methodological approaches

Each paper uses slightly different methods to develop insight towards answering these research questions. In Chapter 2, I designed a case study of the SAT program in rural Honduras to illuminate the complex interactions between community knowledge and resources, and science and technology content. In this context agriculture is a main economic provider, though communities vary in the particular ecological resources and crops that are meaningful and valuable. For this study, I include interview and observational data from two main phases; the first is a regional teacher-training institute, where teachers and administrators prepare to implement science and technology units to their cohorts of secondary students; I also analyzed workbooks used during instruction of these trainings. Secondly, I traveled to several SAT communities to visit the school farm plots and talk with teachers, students, and their families about the garden projects they had worked on. In this case study, I use Culturally-sustaining science education (Ladson-Billings, 2014; Paris, 2012) as an analytical lens to organize the data around key principles guiding the design and policy of science education. This paper will speak to the ways communities around the world utilize local spaces as a grounding resource for learning about science and technology content, and how that knowledge in turn shapes the development of the communities; it will also highlight the particular curricular guidelines that best invoke the connections to local spaces and community alongside the content knowledge. This paper also serves to broaden theory by exploring how science instruction is implemented in agricultural spaces outside of the US.

In Chapter 3, I use a Design-based research structure to describe the multi-year design process of the computational garden model and accompanying activities to support its use in secondary schools with active school gardens. The retrospective analysis of the design led to an emergent framework (PIQ) that is then used as a structure to demonstrate how both the model and learning environment evolved across iterations. The initial conjectures and design features are tracked across iterations, and data from a series of design conversations (iteration 1) and a classroom pilot study (iteration 2) demonstrate how the nested features of PIQ were indicative of the learning opportunities afforded by the overall design. The study also demonstrates how PIQ as a structural framework can support the use of epistemic tools such as models in the science classroom. This procedural overview previews the set-up of the third iteration, a multi-week classroom intervention to utilize the model and school garden as resources for scientific investigation.

Chapter 4 details the aforementioned multi-week classroom intervention where the model was introduced as a tool to support investigation of the local school garden. Activities were designed to allow students to first explore the garden and model, before selecting a research question to then pursue in the next stage. In groups of 3-4, students gathered a variety of evidence in both environments related to their question. Then they were tasked to generate a claim about the garden ecosystem, followed by a proposal for an action project that would best support the health of the environment. Multiple sources of data were collected for this project: students' worksheets and final project presentations, video data of their time in the garden and classroom, audio recordings of group conversations as they generated research questions and claims, screen recordings of selected students as they worked with the model, and html files of code changes generated by students during the study. Analyses focus on groups of students as they enact the particular layers of the PIQ framework, particularly to understand how attempts to scaffold quantitative reasoning might have provided another resource for students' instrumented knowledge, as well as trends in their negotiation of situated and instrumented knowledge sources. The connection back to the communal garden space is explored through the ways students envisioned purposefully applying the results of their investigation to support the ecosystem. In this paper, PIQ enables a focused perspective on the specific roles of situated and instrumented activity as opportunities to gather evidence, justify decision-making, and advocate for local action in the science classroom.

1.8 Objectives and intended contributions

This collection of studies offers a cross-contextual examination of learning environments that combine garden ecology and technological science. I take both a wide and deep approach to this study, first exploring the interplay of cultural and community resources in rural Honduras, then examining how students negotiate situated and instrumented knowledge about their local garden in classroom inquiry tasks. Within an expandable activity system that included both a wider social-ecological-system or more narrow instrumental genesis focus, applying the same theoretical approach to both learning environments offers an appreciation for the influence of context and content in the implementation of place-based science curricula.

While distinct in study design, these studies support a more expansive understanding of situated STEM pedagogy; in particular how students negotiate their situated knowledge of a local ecosystem with the knowledge generated through new technologies. While using different tools and from distinct cultural backgrounds, these studies provide rich qualitative descriptions of the means through which students reason about their cultural and historical traditions, advocate for new methods of caretaking for the land, and develop new, and potentially more meaningful, applications of science and technology in their lives. Understanding how this situated knowledge can both shape and be shaped by the design of technology provides more leverage and access for students to be included in scientific conversations, as promoters of knowledge and sustainers of local environments. Comparing these cases using a similar theoretical grounding can expand awareness of the environmental, cultural, and cognitive resources that make learning possible in these spaces.

From a design perspective, this work offers an example of a technological tool that supports rich quantitative reasoning alongside the opportunities to incorporate situated knowledge, and apply instrumented knowledge in a purposeful way. The design of the computational model anticipated learning goals in many kinds of school-based agricultural environments, and the structure supports students in reasoning and tinkering with code in meaningful ways. This dissertation also proposes a framework (PIQ) for thinking about the design contours of this genre, to support facilitation of technologically-enhanced situated STEM education. Beyond its use in this dissertation as a retro-spective design frame and analytical lens, PIQ could serve as a conceptual tool for teachers to plan interdisciplinary activities that invite protracted tool use in a common space with diverse pedagogical goals.

The number of similar environments that could benefit from this type of investigation are vast, and span content disciplines; the design work initiated by this study provides a foundation to understand how this tool may be interpreted and utilized differently across contexts. Specific to the realm of agent-based models, this work shows how the context of modeling can be utilized to support students' computational thinking and reasoning with code, which can be especially helpful to those who feel disenfranchised by the field of computer science. At a more global level, this work offers examples of meaningful science education that position students to develop knowledge that empowers them to invest in their local environments. This dissertation shows there are multiple ways to do this type of work, and it is worth doing; while yet to be seen, one can hope that this type of learning experience motivates individuals to continue learning and feel connected to caring for their surroundings.

2 Conceptualizing culturally sustaining science pedagogy in rural developing contexts: An immersive field study of teaching and training in the Honduran SAT program

2.1 Culturally sustaining science pedagogy in rural Honduras

Expanding culturally relevant science pedagogy to rural and developing regions is challenged by imminent climate and economic issues, as well as minimal pedagogical resources. Place-based approaches that integrate natural resources and local problem-solving have the potential to overcome these challenges. To further develop these learning experiences, it is important to understand how natural resources intersect with community practices to co-create educational structures and developmental outcomes. This paper examines the training and teaching practices of the Sistema de Aprendizaje Tutorial (SAT, or Tutorial Learning System) curriculum, nationally implemented in Honduras, in an attempt to broaden theoretical understanding of culturally relevant science instruction in rural regions of developing countries. Interview and observational data were collected in two domains: a SAT regional training center, and field visits to six rural communities in Northwest Honduras. A hybridized Activity Theory and Social-Ecological Systems framework (Krasny & Roth, 2010) was used to analyze how the learning environments in SAT are simultaneously shaping and responding to a network of natural resources, knowledge systems, and governing bodies.

Using textual analysis, observational field notes, and interviews, this paper provides a detailed qualitative description of the community-based resources and their roles in the teaching and learning of three curricular units: Raising Chickens, Planting Crops, and Ecosystems. Findings show that academic success for students is framed in their increasing capacity to serve their communities. This is manifested as developing inquisitive approaches to local ecology, and inviting community members as resources, through both materials and knowledge. Per the tenets of culturally sustaining pedagogy, students develop sociopolitical consciousness through moderated dialogue around alternative agricultural practices, and learning about global examples of structural injustice. This analysis paints a richer understanding of how culturally sustaining science education in rural and developing contexts can operationalize through a rich interplay of actors, tools, dialogue, and the natural resources that support life in those communities.

2.2 Introduction

Driven by global standards for educational equality and growing recognition about the disconnect between education and students' lived experiences, policy and research have focused on expanding culturally relevant education, in particular in former colonies and communities with marginalized learners (Singh, 2011). Students in poverty, racial minorities, and those not being taught in their home language are particularly at risk for not connecting to their classroom culture and content (Gray, 1999; Waldrip & Taylor, 1999). This risk is magnified if the teacher is from outside of their community, and holds stereotypes or biases against their potential for success. These cultural mismatches further perpetuate education inequalities and completion/achievement rates for those students, and have been challenging to rectify in the context of standard educational reform (Aronson & Laughter, 2016).

For science education in particular, cultural relevance often incorporates place-based or localized education structures (Aikenhead, Barton Calabrese, & Chinn, 2006), as this ties students' scientific investigations to their surroundings, traditions, and lived experiences. However, teaching in this way involves challenging shifts such as new practices, extra resources, teacher training, different assessments, time commitments, and more (Chinn, 2006; Ogunniyi, 2007; Ramnarain, 2014; Thair & Treagust, 1999; World Bank, 2007). Because these shifts are effortful, most students learn science "traditionally", using standard curricula often produced in a Western context or distributed through large philanthropic organizations. Some policy makers think that utilizing these predominantly Western scientific curricula can equalize the global economic playing field (Laughter & Adams, 2012; Westbrook et al., 2013). Yet what emerges from institutionalizing curriculum in this way is a perpetuation of cultural dominance: who does science, how science is taught, and what counts as science are infused with the viewpoints of the dominant cultural context, in this case, the Western curricular developers.

Implicit in many of these curricula is an epistemological orientation that frames science as objective, universal, and practiced by European men in laboratories (Aikenhead, 1996; Bang & Medin, 2010). In teaching science from the objective Western perspective, the traditions of local communities are not reflected in school practices. Furthermore, the culture of formalized schooling, with laboratory equipment, scripted experiments, and standardized tests to prepare for a 'global scientific workforce', do not reflect the job opportunities and meaningful application of scientific content most likely available in non-Western countries (Brayboy & Castagno, 2008). This contrast is especially poignant in rural areas, where schools and teachers are more spread out, and children are often splitting their time between school and family farm work. In rural communities, agriculture education is often informally taught by parents, rather than an integrated part of the science and technology curriculum. Welcoming these experiences into the classroom could be a valuable stepping stone for the enactment of meaningful investigations of science and technology.

Using the local context as a learning laboratory for understanding content, connecting community, and developing skills for sustainable development and cultural maintenance not only engages students and their families, but supports their ways of life and draws deeper connections to content than these students would otherwise get from an imported curriculum with disconnected units of study. However, an important consideration of using local contexts is the degree to which the local natural resources are interconnected with the learning opportunities, in both enriching and limiting ways. These resources can include the physical surroundings (air, water, soil), economic structures (local businesses, market supply/demand, governance structures), and community elements (neighbors, local knowledge). This consideration shows promising importance, but is not well established for how it could work.

To continue to develop these types of integrated learning experiences in rural communities, it is important to understand how the natural resources intersect with local knowledge and community practices to co-create the educational structures and developmental outcomes. Notably, there are few published research studies investigating these sorts of programs, let alone culturally relevant science education from Central and South America. This paper aims to contribute to this dearth in the research by providing observational data of a robust curricular model and implementation of culturally relevant community-based science education in a rural developing context. The main research question driving this inquiry is:

How are environmental and community-specific resources shaping and shaped by the (Science and Technology) learning experience in a rural agricultural education context?

A secondary question is:

How are knowledge systems incorporated and taken up by community actors in this learning environment?

With these questions, I aim to consider both the micro and macro components of community-based learning. Specifically, I will use a novel application of a hybridized Activity theory + Social-ecological systems model (Krasny & Roth, 2010) to understand the bi-directional influence of large-scale environmental and economic resources on the local activity structure, as communities of learners enact science and technology units from a national culturally-relevant curriculum. The application of this framework to three curricular units can uncover the role of and reaction to large-scale resource constraints, as well as the influence of local knowledge in the teaching and learning activities. Illuminating this interaction of resources, learners, and curricular tools is valuable towards theorizing the structures and limitations of enacting culturally relevant science pedagogy, specifically in under-studied contexts and under-resourced such as rural school environments and developing countries. This work is also particularly rich in that it investigates a (multi-)national curricular program, with relatively consistent teacher-training and implementation.

2.2.1 Study context

The SAT curriculum, developed in Colombia and implemented in countries throughout Latin America, contextualizes secondary disciplinary content into project based units that incorporate local ecology, agriculture, and community practices. This paper will examine the training and teaching practices of three units in the curriculum as they are nationally implemented in Honduras, in an attempt to broaden theoretical understanding of culturally relevant science instruction in rural regions of developing countries. Using textual analysis, observational field notes, interviews with teachers, students, administrators across several SAT communities, and participation in a regional training session, this paper provides a detailed qualitative description of the community-based resources (both environmental, and knowledge-based) and analysis of their role in the implementation of the curricula as seen in the teaching and learning of units on Raising Chickens, Planting Crops, and Ecosystems (hereafter referred to by their Spanish titles *Cría de Pollos*, *Sembrando Cultivos,* and *Ecosistemas*, respectively). Through this analysis, I argue the curricular units offer ample opportunities for rich content and culturally relevant instruction by elevating different key resources from the social-ecological system, and in particular balance immediate success and support with a slow shift of cultural norms. Additionally, findings indicate knowledge development is distributed, involving careful facilitation with family and community members through reflective practices, perspective taking, and a reframing of student success.

2.3 Literature review

To situate this investigation, this review first establishes the current state of global science education, in particular in developing countries. This paper seeks to theorize how localized curricula in SAT are enacted in this context, therefore I present a brief review of the origins and progression of culturally relevant pedagogy, framed in particular around science and place-based pedagogies. Next, as the curricular content of study is explicitly contextualized to the agricultural domain, a brief review of the agricultural education literature from the US is conducted to frame the way SAT practices relate and contrast to that field. The review concludes with an overview of the design of SAT and the existing research on its implementation and effectiveness.

2.3.1 Science teaching and learning in developing contexts

Political, environmental, and social forces have shaped the educational resources in developing countries, such that inequities persist and dominant cultures prevail. To better understand the backdrop that this paper explores (rural Honduras), as well as preface the analysis of a macro + micro lens of educational contexts and curriculum, I examine the context of science instruction in developing countries. Note that due to a dearth of published research (in English), findings from large-scale studies of developing regions outside of Latin America are included to speculate about issues in schools, training, and curricular resources.

Systemic resource inequity limits educational opportunities for many children, in particular those in rural communities and those experiencing poverty. Specifically, malnutrition, hunger, having to work, and living far from school are some of the barriers these students face (de la Garza, 2016; UNESCO, 2014). While more children are enrolling in school worldwide, the disparity between rich and poor, rural and urban, and male and female completion rates are still quite stark (UNESCO, 2015). In some Latin American countries, the achievement gaps between rural and urban students in reading and mathematics is greater than fifteen percentage points (UNESCO, 2014, p. 19); in Honduras in 2011, 84% of the richest but only 10% of the poorest children completed lower secondary school (Honduras Ministry of Health et al., 2013; UNESCO, 2014, p. 96). Countrywide, only 65% of Honduran secondary aged students are enrolled in school (UNDP, 2019). These issues compound; as fewer students graduate and are trained at the university level, there are fewer teachers that are ethnically, linguistically, and socially representative of their rural students, meaning teachers need to be incentivized to relocate from urban areas. These teacher shortages lead to large class sizes, or posts filled by those without secondary training.

On top of having fewer teachers, students in lower-income and rural areas have their educational experiences affected by weak infrastructure and the impacts of climate change. In Honduras, 62% of the country lives below the established definition of poverty (World Bank, 2018), and 45% live in rural agricultural communities, where much of the poverty is concentrated (European Commission, 2020; UNDP, 2019). As one of the ten most at-risk countries for climate related events (UNESCO, 2016), shifting weather frequently threatens rural infrastructure and the agricultural industry. Most recently, a four-year long drought exacerbated food insecurity and decimated more than half of the country's crops (World Food Program, 2019), while deforestation rates are some of the highest in the world (UNDP, 2019). As these issues affect the livelihood of rural communities, they additionally impact students' abilities to attend and thrive in school.

In light of these issues, a tension arises towards the purpose of science education in developing countries. Historically, it has been seen as a means to establish economic development on a global playing field, where colonialism has entrenched the privileging of Western thought and practices (vis a vis curriculum, epistemologies, teaching practices, and assessments) (Aikens et al., 2016). However, critical scholars, large stakeholders (UNESCO, etc.), and reform initiatives are calling for shifts towards pedagogies, curricular tools, and practices that honor indigenous thought, local contexts, and a goal of sustaining ecological balance to adapt to and mitigate the threats of climate change (Fahey et al., 2016; Lee, 2018; UNESCO, 2016). When considering certain standards of achievement such as PISA scores, doctoral dissertations, and patents, developing countries are regarded as having "poor" science and math potential (Seo et al., 2016). However, the low availability of employment that directly relates to typical science instruction, let alone the irrelevance of many imported curricula to students' lives, suggest that science education as-is *cannot* be successful, as it is not relevant to students' vocations or applicable to their lifestyles (Dzama & Osborne, 1999; Waldrip & Taylor, 1999).

Regardless of the curriculum being used, "reform" teaching strategies such as inquiry-based and student-centered are hard to achieve in rural developing contexts given the lack of training on these methods, large class sizes, minimal exposure to these practices in action, and an internalized sense that science classes should be objective, isolated courses. As a result, many teachers in rural schools believe didactic approaches and scripted laboratory experiments are more effective for their students, as inquiry projects might lead students to become "easily distracted by the apparatus and chemicals" (Ramnarain, 2014, p.71) Even schools that do have integrated science courses have issues implementing them, as teachers do not feel comfortable or prepared to do so (Gray, 1999, World Bank, 2007). Traditional authoritarian practices can also contribute to this issue, where teachers prefer to lecture and students are ingrained to not question the objectivity of scientific 'facts' (Shumba, 1999).

2.3.2 Culturally relevant & Place-based pedagogies for rural communities

To support the livelihood and agency of students in rural and developing contexts, science instruction should involve an overhaul of curricula, teacher training, and context. The Culturally Relevant Pedagogy (CRP) movement (Gay, 2000; Ladson-Billings, 1995b) is a well-known framework of such a shift in thought and practice. To understand its potential theoretical application in rural developing contexts, I discuss the origins and the development of the field as it has gained international awareness.

2.3.2.1 Culturally relevant pedagogy

CRP emerged as a powerful presentation of the possibilities of education for minority students in the US, and has expanded in its uptake as a theoretical framework to understand and analyze classroom practices. A product of the multiculturalism movement in the 1970's and 80's in the United States, its founders aimed to shift the narrative away from a deficit mindset of African American students in predominantly white teachers' classes, and towards a reframing of instructional texts and pedagogical moves visible in spaces where African American students were thriving. Ladson-Billings and Gay are credited with establishing the core tenets of the field: *academic success*, *cultural competence,* and *sociopolitical consciousness.* As this pedagogical orientation has become more mainstream, the tenet of sociopolitical consciousness has become a bit diluted, to the point where CRP no longer exclusively refers to an overhaul of teaching practices and curricula, but rather a conceptual buzzword that can mean a single day of teacher professional development, or stand-alone curricular units that are marginally inclusive (Brown-Jeffy & Cooper, 2011; Singh, 2011; Sleeter, 2011). Although initially conceptualized as context-specific, CRP is now conceived as a theoretical framework in educational research internationally (Gay, 2015; Peña-Sandoval, 2019).

With this expansion has come some challenges in practice, leading the premier scholars in the field to re-establish the norms and intentions of CRP. Aware of the distillation of the core principles, Ladson-Billings and other scholars have posited a remix of the initial concept, from culturally relevant to Culturally *Sustaining* Pedagogy (CSP), where the impetus is to actively work to maintain and increase the cultural influence of the non-dominant student population (Ladson-Billings, 2014; Paris, 2012). This affirmation to support the empowered learning of diverse students challenges the existing social order, so advocates of the movement are confronted with persistent affronts to simplify its meaning, and backlash from political establishments (Sleeter, 2011). This resistance to incorporate CSP has been experienced in communities particularly with few minority teachers, curricular resources, or professional trainings (Emekauwa, 2004; Leonard et al., 2018; Nganga, 2015; Wortham & Contreras, 2002). Despite the pushback, the movement has expanded beyond the United States, with global promotion of culturally responsive teaching, especially regarding the language of instruction in rural and developing communities (UNESCO, 2014, 2015, 2016).

2.3.2.2 Culturally sustaining science education & Place-based education

For science education, culturally sustaining pedagogy must upend the globalization of Western epistemologies, the outcome goal of competitive global workforce development, and the rigid boundaries of curricular content with pre-scripted experiments. This structure of science education, in emphasizing generalizable scientific conclusions, de-values the importance of localized knowledge and Indigenous traditions (Sutherland & Swayze, 2012). The push towards global economic competition does not question who benefits from current science practice, de-prioritizing the needs of underserved students (Laughter & Adams, 2012; Tate, 2001). Framing science as a tool for economic development has not been especially helpful in rural developing contexts; in particular, not everyone wants a science job or further education, as some folks will likely stay in their communities, where school science and village life are not obviously connected (Fahey et al., 2016; World Bank, 2007). School science that prepares students to agentively solve problems in their local contexts increases the likelihood that science education will be relevant and meaningful. *Place-based education*, while not explicitly the same movement as CSP, mirrors some of the core tenets by moving the context of study from the classroom to students' local environments, invoking their lived experiences, community members, themes of cultural importance, and in some cases inviting them to create actionable change to improve environmental conditions (Aikenhead, Barton Calabrese, & Chinn, 2006). Utilizing principles from place-based education, culturally sustaining science education should include local knowledge, increase student empowerment and agency, and integrate practices across content areas while investigating local spaces.

To enact these changes, while acknowledging the social capital that Western science instruction has predominantly provided, involves adjustment on three fronts: teacher preparation, instructional materials, and contexts for classroom study. Research has documented teacher trainings that support culturally sustaining science education by addressing teacher mindset, classroom practices, community partnerships, and curricular development. Ogunniyi (2007) describes a training that focused on shifting instructors' worldviews to motivate their teaching of indigenous values, with the result of increasing knowledge of Indigenous scientific knowledge and seeing it as more complementary and compatible to Western scientific knowledge. Another series of trainings (Aikenhead, 2001; Aikenhead & Jegede, 1999) positions teachers to understand their roles as "scientific culture brokers", and to consider the types of students they may encounter and how they will need different teaching tactics to help these students approach and integrate content from within and outside of their cultural traditions. Specific to place-based science education, Pauline Chinn's line of research has developed a series of professional trainings situated within the contexts of the intended science instruction. Key components of these trainings are immersion in the cultural context, constructing a community of practice around new pedagogical strategies, trying out new curricular activities together, sharing in feedback, and direct scientific inquiry towards sustainability efforts (Chinn, 2006, 2007, 2015; Sylva, Chinn, & Kinoshita, 2010). In all of these examples, ongoing professional support or mentoring is considered critical to achieving long-term implementation of culturally sustaining science pedagogy.

2.3.2.3 Culturally sustaining instructional materials

While research has improved our understanding of how to support teachers enacting CSP, the development of instructional materials to support teaching students of diverse backgrounds is still in progress. Some successful curricula include activity designs that bootstrap all students' lived experiences into target scientific content (Calabrese Barton & Tan, 2009; Rivet & Krajcik, 2008), as well as problem-based learning, which aligns with many Native cultural practices of students as equal partners in the learning process (Quartaroli & Sherman, 2011). Indigenous scholars in particular have highlighted some key components of a framework for indigenous learning (Sutherland & Swayze, 2012), which should include Elders, experiential learning, social and ecological justice, and cross-cultural pedagogy. These framings have been useful in illustrating and attending to the varying epistemologies that students navigate from their home communities to science classrooms (Bang & Medin, 2010), especially on biological classification and teleology. However, there are criticisms that directing these initiatives towards "informal" science education promotes a false binary that scientific practices of indigenous communities are incongruous with 'formal' teaching (Brayboy & Castagno, 2008).

Fewer studies infuse CSP in the explicit design of classroom curricular units within secondary STEM education. Technology has been used as an anchor in one cross-cultural science education unit that connects Chinese Indigenous technologies to their modern scientific instantiations (Lee, 2018). Some scholars that have described such initiatives have found that other norms of the classroom environment impeded the success of their designs for CSP. In particular, one study where the teacher included Native cultural symbols in a coding exercise didn't realize he had made students uncomfortable by tokenizing their culture, as they still wanted to succeed and please their teacher (Leonard et al., 2018). Other work by Enyedy & Mukhopadhyay (2007) demonstrates how the norms of math pedagogy and statistical reasoning came into tension with the designed goal to leverage students' local knowledge of their communities through GIS technology; in this case, the two knowledge systems were not incorporated in a way that could facilitate higher order mathematical reasoning, but rather to confirm existing hypotheses. These studies help illustrate challenges in the design of curriculum that meaningfully incorporate CSP while also attending to persistent norms of instruction that impact its success, particularly if the instructor is not of the same cultural background as the students. An approach by Sánchez Tapia et al. (2018) to minimize these tensions has been to adapt an existing curricular unit on natural selection based on empirically derived curricular contextualization principles, through a series of studies with an indigenous community in Mexico. The outcome of this work is a framework that can be applied to any existing curriculum, and encourages students to negotiate, advocate, and incorporate practices of both Western and Indigenous scientific knowledge into their applied work.

2.3.2.4 CSP in rural and developing contexts

CSP in science has been harder to achieve in developing countries and rural contexts, in particular because education has been driven by centralized political efforts (World Bank, 2007), and students from these areas are often overlooked for their perceived limited capacity or unwillingness to engage in political matters (Eppley, 2017). In describing some barriers to implement this type of instruction internationally, Westbrook et al. (2013) report:

> More equivocal findings come from: Bhutan, where teachers were concerned that localisation meant that students missed out on international perspectives (Childs et al., 2012); Malawi, where efforts to localise the curriculum failed either to overcome the strictures of the national curriculum or to integrate local knowledge successfully (MacJessie-Mbewe, 2004); India, where it has been questioned whether indigenous knowledge can in fact survive incorporation into the educational system (Sarangapani et al., 2013); and Zimbabwe, where teachers were reported to dismiss indigenous knowledge and privilege only knowledge that came from textbooks (Shizha 2007). Thus the evidence on successful innovations in localising curriculum is at best mixed. (p. 28)

These barriers mirror some challenges that are occurring for students in rural communities in the US, though research about science education in rural settings are relatively scant and focus primarily on resource deficits or outcome differences from urban communities (Harmon, Henderson, & Royster, 2003; Panizzon, 2011). Major issues in rural education appear to be similar in the US and globally: teacher quality via recruitment, preparation, and retention, along with subtle stereotypes against those communities. Approaches to address these issues similarly include specific training for rural contexts, making curricular choices that are culturally relevant, and mentoring teachers through the transition to new styles of teaching that build on unique school and community resources (Gallo & Beckman, 2016; Oliver, 2007). By adopting a place-based approach along with relevant curricular materials, rural communities can incorporate their values, resources, and take sustainable action to advocate for their means to thrive (Eppley, 2017; Jennings et al., 2005; McKim et al., 2019). In doing so, this practice can create learning communities that span outside of the classroom to include parents, businesses, and educators collaborating to build healthy and sustainable social-ecological systems (Chinn, 2012; Emekauwa, 2004) Some strategies to connect rural science with people's experiences include critical reflection of place— thinking 'like a bioregion' or 'like a watershed', and also the extent to which economic development is interconnected with ecological management that might be more subtle (Kingsolver, 2017). In particular, the context of farming and gardening is a common approach to teaching content in this way, as it invites students to connect their experiences and knowledge from their familial and cultural domains to scientific knowledge about health, economics, and ecology (Upadhyay, Maruyama, & Albrecht, 2017).

2.3.3 Secondary agriculture education in the US

While motivated to incorporate STEM and support rural areas, secondary agriculture education in the United States is not currently a predominant context of culturally responsive science teaching. To better understand the distinctions between agriculture as a context for education in Latin American SAT communities and in the United States, this section of the review considers the structural and ideological principles that have shaped formal agriculture instruction as examined by educational researchers in the US.

As a formal institution, secondary agriculture instruction has been incorporated into American schooling for just over a century. The official structure includes three parts (or "circles"): classroom instruction, supervised agriculture experience (SAE), and leadership development through extra-curricular organizations such as Future Farmers of America (FFA, the largest organization has 700,000+ members) (National FFA Organization). By definition, it is a career preparatory/ vocational program, so workforce readiness is an integral feature of its identity. This framing, along with the founding values of the organization within the Southern Agrarianism movement, have shaped who the program serves and how the framework perpetuates Western ideologies mirrored in the policy initiatives in global science education discussed previously. In particular, Southern Agrarianism is trenched in the ideas of self-dependence and a dedication to preserving American traditions (Martin & Kitchel, 2013). With such a stronghold on "tradition", it is of little surprise that FFA membership is predominantly white even within more racially diverse communities, and majority of instructors are white men (Lawrence et al., 2013; Luft, 1996); women have only been allowed to join in the past 50 years. Rural students are the primary participants and beneficiaries of these programs; one study of LatinX agricultural students across California indicates that there is a dynamic of 'rural privilege' that urban students experience when trying to join FFA, gain access to SAE projects, or develop their leadership skills (Elliott & Lambert, 2018).

2.3.3.1 Internationalization of US agriculture education

However, as the country increasingly urbanizes and becomes more diverse, as well as the globalization of the agriculture industry that increasingly relies on immigrant labor (Rodriguez & Lamm, 2016), there have been calls to diversify the make-up as well as the content taught in these programs (Roberts et al., 2016). Specifically, calls for multicultural education (O'Malley et al., 2019), recruiting diverse students (Lawrence et al., 2013), and content about immigration labor (Qu et al., 2018) and international agricultural practices (Ibezim & McCracken, 1994; Wright et al., 2019) aim to direct the evolution of the field. Yet while these issues have been acknowledged as imperatives by the American Association for Agricultural Education (Roberts et al., 2016), a definitive approach to implement them has not been organized or instituted (McKim et al., 2019; Stewart et al., 2004); without major initiatives in training and curricular development, and so long as teacher educators are primarily white, their ability and tendency to speak to multi-cultural practices in agriculture is limited. A review of the research of international agriculture education from 1975 to present day revealed that the most common instances of globalizing American agriculture education are described through study abroad experiences, and none of the included articles evaluated the presence of global competencies in any agriculture education setting, or the effectiveness of globalizing American agriculture curriculum (Wright et al., 2019). Even as study abroad trips appear to elevate intellectual dissonance, enabling students to envision local knowledge and problem-solving agricultural practices of different cultural groups, the primary reason students choose to engage in international opportunities is not for this cultural awareness, but rather the perception that it will advance their employability (O'Malley et al., 2019), indicating that this framing has been prioritized above a multi-cultural one.

Alongside an awareness of international issues, the focus on workforce readiness has also shaped initiatives in the agricultural education field to promote better critical thinking (Edwards, 2004; Hendrix & Morrison, 2018) and integration of STEM content (Scherer et al., 2019). Challenges to implement these changes start at the top of the pipeline, where there is a shortage of agriculture education instructors (Graham & Edwards, 2018) and the predominant training method is lecture-based (King et al., 2019; Myers & Dyer, 2004). As a result, many teachers do not feel confident using experiential teaching styles (Arnold, Warner, & Osborne, 2006) even though active teaching methods have been found to be more effective and engaging for their students (Colclasure & Thoron, 2018; King et al., 2019). Additional promising techniques to increase critical thinking include utilizing case studies (Akins et al., 2019) and socio-scientific issues (Cross & Kahn, 2018) as these both involve making the content more relevant to students' daily lives.

2.3.3.2 STEM-based initiatives in agriculture education

STEM integration has also arisen in the past decade as a means to address workforce readiness, critical thinking, and the relevance of agricultural contexts as a viable industry for growth, though as with other initiatives, a lack of coherent framing for training, implementation, and curricular guidelines have led to mixed results (Colclasure & Thoron, 2018). In particular, the position of agriculture as a *context* for learning STEM content, or a *content* area that integrates quantitative reasoning is a point of tension in the field (Roberts & Ball, 2009; Robinson et al., 2018). A synthesis of STEM in agriculture education efforts indicates that though the acronym is used broadly in these directives, the bulk of the research focuses on science and mathematics content, with engineering rarely incorporated (Scherer et al., 2019). The use of technology in agriculture education is growing, though also relatively broad. Some examples include using mobile phone apps in agroforestry units (Smith et al., 2019), and sensor data from global farms connected to curricular activities (Trotter et al., 2017). In one study addressing teachers' perceptions of the top 15 emerging technologies of the field, while most of the technologies were included in their curricula (most frequently precision sensors, genetic modification, and value added processes), teachers felt they needed much more support on computer-based technologies, and predominantly taught these using lecture methods (King et al., 2019). Though still evolving, it is clear that integrating STEM and agriculture is seen as a means to increase the relevance, complexity, and applicability of these knowledge systems).

Tying back to the 3-circle model of US agriculture education, STEM-literacy has been posited as integral to one growing pillar of the FFA tradition that has gained prominence for its ability to incorporate active learning and promote the viability of agriculture careers: entrepreneurship as an SAE project (Heinert & Roberts, 2016, 2018; Scherer et al., 2019). By giving students practice in experiential learning through addressing community needs and providing a meaningful service, this component has the potential to increase connection to local businesses and social systems. Despite low representation within the formal system of US Agriculture education, Native American leaders in the Osage nation have generated a theoretical framework to expand agriculture education to serve the needs of their communities, in particular, "By emphasizing ecological consciousness through Osage-specific place-based agricultural education, it becomes possible to foster stronger Osage identities and cultural knowledge while contributing to community development through improved land stewardship and Indigenous leader development" (Hayman, RedCorn, & Zacharakis, 2018, p. 7). This reframing through the lens of place-based education is echoed in a recent white paper by McKim et al. (2019), claiming problem-based learning experiences that develop students' capacities to address complex socio-economic problems have been missing from the dialogue and practice of agriculture educators and are needed for the viability of sustainable systems. This is a transformational directive, as scholars within the field argue that the Southern Agrarian values of the FFA have perpetuated, noting, "The FFA has not shifted its traditions to be more aligned with or more accepting of neo-agrarian ideology, which includes concepts like environmentalism and/or sustainability" (Berry, 1977; Major, 2011; Thompson, 2010; Wizba, 2003, as cited in Martin & Kitchel, 2013, p. 35). However McKim et al. (2019) insist that this reliance on tradition will persist when innovation is urgently required, unless the focus on integrating agricultural education with the STEM content domains instead considers integrating the interdisciplinary learning of local environmental, economic, and social systems.

2.3.4 The design and implementation of SAT

The structure of the SAT program embodies elements of the educational fields reviewed previously. With regards to global and rural science education, SAT communities have similar resource needs, have to recruit teachers unconventionally, and are not representative of those currently employed in Western science fields. Like the tenets of culturally sustaining and place-based pedagogy, SAT prepares students to question the status quo by developing sociopoiltical consciousness to advance the resilience of their communities, and incorporate their local spaces and community knowledge. SAT resembles US Agriculture education in that it utilizes vocational content and context as a means for future employment and models some supervised projects; however rather than the 'global workforce', SAT promotes self-employment and assessment of community needs as opportunities for students to be self-sustaining within their home environments. Rather than the similarities, it is SAT's distinctions from these fields that warrant a nuanced investigation of the implementation of the curricular model and its impact on communities.

SAT is an innovative educational program throughout Latin America created to develop rural communities in a holistic way. This approach on enhancing students' capabilities integrates curricular domains into a series of workbooks with emphases on community service, ecology, and basic moral values, applied to local projects rooted in agriculture (Arbab, Correa, & de Valcarcel, 1988). With recruitment of tutors from local communities, whose backgrounds and cultural knowledge complement the assignments, the SAT program has been successfully implemented in several countries in Latin America. Additionally, other educational organizations have adapted the curriculum for implementation in rural regions in Africa, Southeast Asia, and the Pacific (Kwauk & Perlman Robinson, 2016).

The units in SAT have a specific design to focus on service to the community at the heart of all lessons. This is multi-faceted; one component of service is developed through moral and spiritual reflections, connection to living things, and perspective-taking (Kwauk & Perlman Robinson, 2016). Another realm of service to the community is by building collective capacity at the social, environmental, and economic levels. This is accomplished through sharing knowledge, conserving natural resources, and improving economic opportunities. By structuring these activities into the curriculum, the SAT program seeks for its graduates to develop the skills to become agents of change in their communities. This model mirrors the concept of 'critical consciousness' Freire (2000) describes in emancipatory education systems for students in other Latin American communities: students serve their environments by generating meaningful discussion on local issues and innovating on existing practices to promote a new reality. This critical practice is the strand of development that this paper will examine in the SAT curriculum.

In Honduras, SAT is recognized as a national secondary curricular option, and the recruitment and training of teachers is administered by the non-profit organization *Bayan* (Bayanhn.org) Longitudinal work suggests that SAT schools (as compared to traditional secondary schools) in Honduras are highly effective in increasing test scores (McEwan et al., 2015), and evidence also suggests that SAT is helping to promote civic responsibility, and empower girls (UNESCO, 2015). Lample (2015) provides a detailed account of scientific agency and local knowledge development in the SAT-affiliate extracurricular program called Preparation for Social Action (PSA) in Zambia; through the workbook activities and opportunities to engage in scientific practices, learners were able to increase their abilities to act upon and change their life conditions. These studies suggest the SAT program is positively impacting educational outcomes, yet there are few case studies that investigate the complex interaction between rural schools and their adjacent communities through the lens of resource availability. This gap in the literature drives the motivation for an exposition of the processes of learning involved in the enactment of SAT units, with a particular focus on the social-ecological systems the schools are situated within.

2.4 Theoretical framework

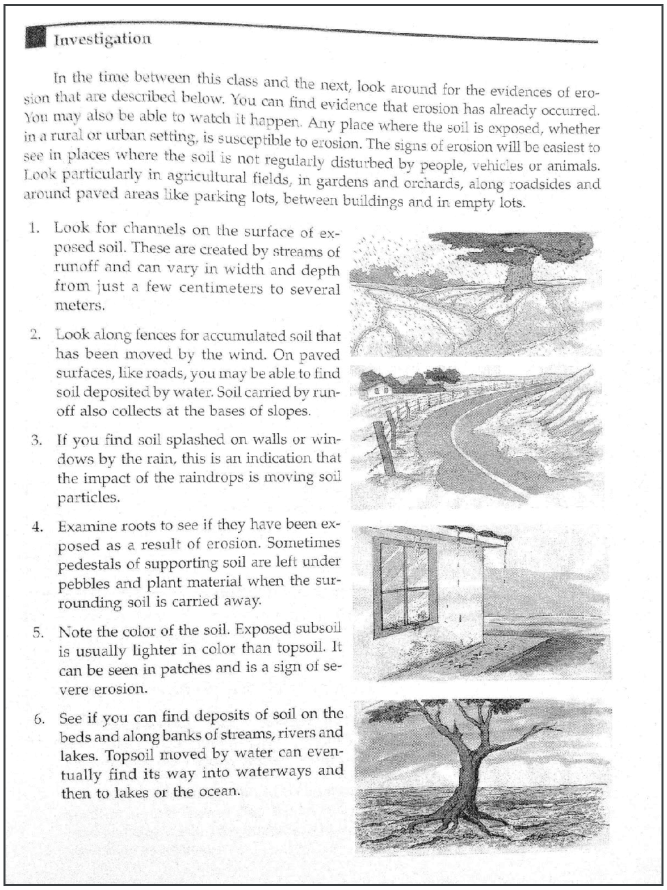
I use a framework that hybridizes Activity Theory (AT) and Social-Ecological Systems (SES) (Krasny & Roth, 2010) to analyze in particular the way that the learning environments in the SAT program are simultaneously shaping and responding to a network of natural resources, knowledge systems, and governing bodies. I argue that utilizing this framework helps illustrate the interactions within place-based, interdisciplinary science instruction in rural communities, as a means to understand how a local educational system can operationalize the tenets of culturally sustaining science education with respect to these local resources.

Krasny & Roth (2010) propose the hybrid model to analyze the learning processes at play in an environmental education program that contributes to adaptive capacity and resilience at an individual and systems level in a local watershed (p. 546). At the individual capacity building level, the authors argue that activity theory (Engeström, 1987) captures the essential processes, resources, rules and outcomes that motivate a particular educational practice. On a greater scale, a social-ecological system (Ostrom, 2009) tracks the long-range impact on the communities and ecosystems within the activity network. Together these two frameworks help support the analysis of SAT as an activity system, linking design and curricular features and how their enactment contributes towards individual and systems-wide capacity building. Combining the two frameworks allows for a detailed description of both the communal practice of learning, and the biological and physical changes enacted on the learning environment.

In the context of SAT, a hybridization helps contextualize the individual and classroom based activities within the curricular units taught throughout rural Honduras to the governing forces and environmental resources that shape them. Compared to the previous analysis with this framework, this study presents a remarkable change in scale; rather than examining one learning community through time, the focus is on a national educational intervention, through the enactment of curricular units across many communities. While there are likely to be small variances in implementation, the design of the units and local resources are similar, and the examination of a program of this size has implementations for other reform efforts in rural education, particularly in place-based science education.

By utilizing this combined framework as a lens to conceptualize culturally responsive science education within the SAT program, distinct design features are brought to light as they contribute to different aspects of community development. The variety in these features helps highlight challenges in creating and implementing meaningful education specific to rural and developing contexts. They also demonstrate how particular design choices in curricular projects are linked to, and can support the growth of, an extended network of community-based and environmental resources. In sum, utilizing solely a SES framing would focus on how SAT objectively utilizes and influences the resources around it. Yet the treatment of knowledge and interaction with those resources delicately rest on its integration of community within the learning process. To understand that nuance, in turn, the activity theory framing helps illuminate *how* the community actors are participating in the educational process to shape collective capacity, both at the tutor and student levels. For these reasons, this analysis can help to develop a richer understanding of how culturally sustaining science education in rural and developing contexts can operationalize through a rich interplay of actors, tools, dialogue, and the natural resources that support life in those communities.

As a means to examine the data, this framework was used to conduct a first pass at thematic qualitative coding (Attride-Stirling, 2001; Braun & Clarke, 2006). With respect to the SES framing, for example, a textbook activity included below (Figure 3) prompts students to look for examples of erosion in their community evokes analysis of soil structure, roads, buildings, roots of trees, and waterways; the natural resource elements being soil, trees and water, while the buildings and roads are resource units developed through a combination of community actors and governance. With respect to activity theory, this task invites students to leave their classroom and observe the content topic (erosion) with respect to how it impacts their community. There are explicit instructions for where and how to look for erosion, and illustrated examples. The tools required are minimal (just the text), though a mindset of investigation is cultivated. This task utilizes a local perspective on the topic, and precedes further exploration that will ultimately connect to an agricultural practice (terraced planting) that minimizes erosion and runoff. With this framing, it becomes clear that to engage with the resources, students first need to develop an understanding of what exists in their community, how it is impacted by the topic of inquiry, and the many ways a single phenomenon may appear. Throughout the data analysis (explained in further detail below), particular attention was dedicated to how structures of activity (as seen through different curricular texts/projects and tutor training) relied upon and influenced the resource network they were situated within.



Investigation

In the time between this class and the next, look around for the evidences of erosion that are described below. You can find evidence that erosion has already occurred. You may also be able to watch it happen. Any place where the soil is exposed, whether in a rural or urban setting, is susceptible to erosion. The signs of erosion will be easiest to see in places where the soil is not regularly disturbed by people, vehicles or animals. Look particularly in agricultural fields, in gardens and orchards, along roadsides and around paved areas like parking lots, between buildings and in empty lots.

1. Look for channels on the surface of exposed soil. These are created by streams of runoff and can vary in width and depth from just a few centimeters to several meters.
2. Look along fences for accumulated soil that has been moved by the wind. On paved surfaces, like roads, you may be able to find soil deposited by water. Soil carried by runoff also collects at the bases of slopes.
3. If you find soil splashed on walls or windows by the rain, this is an indication that the impact of the raindrops is moving soil particles.
4. Examine roots to see if they have been exposed as a result of erosion. Sometimes pedestals of supporting soil are left under pebbles and plant material when the surrounding soil is carried away.
5. Note the color of the soil. Exposed subsoil is usually lighter in color than topsoil. It can be seen in patches and is a sign of severe erosion.
6. See if you can find deposits of soil on the beds and along banks of streams, rivers and lakes. Topsoil moved by water can eventually find its way into waterways and then to lakes or the ocean.

Figure 3. Activity excerpt from the *Ecosistemas* textbook.

2.5 Methodology + methods

To examine the previous research questions, I designed a qualitative case study (Yin, 2003) that explores how environmental and community resources interact with science teaching in a rural context. This case in particular is of the training and teaching of STEM courses within a community-development focused secondary curriculum (SAT), enacted throughout rural Honduras; it is bounded temporally by the extent of two sessions of data collection, and geographically by the communities within driving proximity to the researchers.

2.5.1 Data collection

Given this methodology, a diverse array of data were collected to encompass the breadth and depth of the program, spanning the content materials, how the training institution prepared tutors to teach it, and how it was implemented and received by students and their families. For this study, interview and observational data were collected over four weeks in 2016 and two weeks in 2018, coordinated with the thrice/yearly training program. Research was concentrated in two main areas: a SAT regional training for tutors in a central region of Honduras, and field visits to six rural communities in the Northwest region of Honduras; these communities were selected for their ease of access (road conditions and terrain-appropriate vehicle access were variable) as well as their inclusion as follow-up data sites within a larger longitudinal study pairing 47 SAT communities with comparable non-SAT secondary education centers (McEwan et al., 2015). A few days of each trip were also spent in discussion with the staff of the NGO that supports the training and hiring of tutors at their administrative office on the North coast to understand the administrative perspective and coordinate the field visits.

At the training site, over 30 hours of STEM trainings were observed and video recorded; to understand the scope and progression of an instructor's approach during training, full courses were observed (roughly three full days), which meant some courses were not observed. While initially just an observer, the researcher became included as a participant team member of the classroom by the second week of the trainings, as the instructors and students encouraged this perspective. In 2016, interviews were conducted and audio recorded with four tutors attending the training as well as one instructional coach. In 2018, follow-up observations and interviews were conducted with two tutor-trainers initially observed and interviewed in 2016, whose sessions were observed over two days. The visit was not previously announced to tutors or trainers. Workbooks (student texts that contain content and activity descriptions for the unit) were collected from the trainings and annotated during the observations to encompass how the trainer utilized and referred to specific elements of the course material. Workbooks for STEM units beyond those covered at the training were also obtained and analyzed to assess the roles of community knowledge, engagement with local spaces, Western STEM practices, and social justice themes present. Most workbooks received were in Spanish, though a select few had also been translated into English.

After the trainings, field visits were conducted at six SAT communities in the

Northwest region of Honduras. With a local tutor or administrator, the school site and communal agriculture plots were visited. Informal (unplanned, and predominantly unstructured) garden talks were conducted with students and their parents at their homes, as well as with students at one school. In these conversations, students were asked to share what they had been learning in school with respect to the class plots / home gardens. Formal semi-structured interviews were conducted and audio recorded with four tutors and eight students in these communities (interview protocols in Appendix A). Classroom observations were also conducted and video-recorded of any STEM courses taking place on the days of the site visits; in one community the students were joined by family members as they completed the unit. All participants gave verbal consent for their participation in the research study. Finally, photos and video still frames were taken from the field studies as supporting evidence of the infrastructure, instructional tools, and local surroundings used in instruction.

2.5.2 Data analysis

Interview recordings were transcribed by Honduran research partners, and video footage was reviewed and categorized by date and the curricular units covered. Footage from the trainings was mapped to the relevant pages in each workbook, and data were tagged based on their inclusion of pedagogical practices, STEM content, and community involvement. From this arrangement, the three curricular units emerged as consistent themes within interviews and site visits, and therefore the data were organized with respect to these lessons. With these initial groupings, the frameworks of SES/AT were employed to identify the activity systems (social and material resources utilized in the learning environment) and the natural and economic resource systems (waterways, terrestrial and atmospheric elements, local businesses, government initiatives, industrial practices) elevated and addressed by each of the three units.

Using this lens to analyze the training and implementation of SAT revealed relationships between learners in an activity network and their social-ecological systems unique to each of the three units but with overlapping thematic elements. While illustrative in their own right, to support theoretical developments in rural science education, these relationships between actor-networks and the surrounding Social-ecological systems were then interpreted through the tenets of Culturally Relevant Pedagogy (CRP; later Culturally Sustaining Pedagogy or CSP) to add contextual detail to the operationalization of CRP. These findings help surface what supports and structures might be useful for others in implementing CRP in rural areas, and understanding how learning encompasses daily life and extended surroundings in these contexts.

2.6 Findings: CRP through SAT

The findings presented below offer an interpretation of how SAT instruction and training practices operationalize CSP, with an explicit focus on the treatment of knowledge systems and natural resources within the process. They are presented with examples from three focal units, though should not be seen as exclusive to any one unit or as uniformly present in the entirety of the curriculum. Given the thousands of students and tutors that participate in the program, it is unlikely that the curricular projects are implemented in identical fashion in every community, so these findings should be seen as approximations of what is possible given adherence to the texts and adequate resources. That being said, the illustrations made here consist of evidence gathered from students and teachers across the country and indicate consistent patterns in implementation of projects and interpretation of the ideology and impact of the program.

Gloria Ladson-Billings (1995b; 2014) indicates three core tenets of CRP: Academic success, cultural competence, and sociopolitical consciousness. In her words:

> "By *academic success* I refer to the intellectual growth that students experience as a result of classroom instruction and learning experiences. *Cultural competence* refers to the ability to help students appreciate and celebrate their cultures of origin while gaining knowledge of and fluency in at least one other culture. *Sociopolitical consciousness* is the ability to take learning beyond the confines of the classroom using school knowledge and skills to identify, analyze, and solve real-world problems." (p. 75)

When referring to the often muted sociopolitical consciousness that led to the 'remix' from culturally relevant to culturally sustaining pedagogy, she continues, "However, they [educators] rarely pushed students to consider critical perspectives on policies and practices that may have direct impact on their lives and communities" (Ladson-Billings 2014, p. 79). As these tenets are primarily understood within the context of Black and LatinX minority students within a dominant White culture of classrooms in the US, a re-reading of the tenets through a different contextual lens can expand upon these principles. Examples from the three curricular units (*Cría de Pollos, Sembrando Cultivos,* and *Ecosistemas)* are used to illustrate these principles in action.

2.6.1 Academic success

Ladson-Billings (2014) describes this as the "intellectual growth that students experience as a result of classroom instruction and learning experiences" (p.75). This growth is established through particular networks of individuals and materials that incorporate and impact the surrounding ecosystem and account for the political and economic structure of the country. The following points indicate how SAT operationalizes academic success, through attentiveness to the relationships between components in the activity networks (*actors, rules, community, division of labor, instruments, objects,* and *outcomes*) and components of the social-ecological systems (*resource systems, resource units, governance systems*).

2.6.1.1 Access and ownership over integrated, relevant content resources

SAT students and teachers have prolonged access to engage with content matter in a way that increases their ownership of knowledge, allows it to build on itself, and evolves through group discussion and community projects. Regardless of the challenges in finding university-graduated subject-area experts, SAT provides curricular content with an increasingly complex development of knowledge, in particular in STEM content. This is orchestrated by providing interdisciplinary framings of concepts that build on each other throughout and across units; one example of this in the *Cría de Pollos* text involves student calculations of the unit cost for supplies, caloric conversion as the birds eat, and energy transfer once they are weighed for consumption. Within a new context, students are reinforcing math, economics, and physics concepts from previous lessons. By administering affordable and interactive workbooks, SAT considers the *governance structures* that have led to economic challenges that limit educational resources in Honduran rural communities; these workbooks serve as a reliable *instrument* that allow students to have consistent access to and engagement with academic content, which they can refer back to as they progress through the program.

Rather than essays or tests, students are evaluated through practice-based activities that rely on group discussions and collective responsibility for promoting knowledge; this principle extends to the tutor-training as well. In *Cría de Pollos*, one such activity has groups of students use their recent knowledge of the engineering principles involved in building a chicken coop to assess and assist a neighbor in evaluating their own animal enclosures. In addition to the relationship-building within the community, this activity allows students to apply their knowledge while collaborating with peers. This activity is one of several in the workbooks that provide a structured rubric that outlines the *rules* for these interactions, and distribute the *division of labor* to students as they actively address routines, infrastructure, and health of their *community*.

Additionally, access and ownership is generated by SAT tutors acting as a facilitator or guide rather than a lecturer, prompting students to generate and discuss many possible answers. Through this stance, students are positioned as contributing to knowledge, rather than recipients of it. This was observed consistently across the tutor training as a guiding principle, carried out in real-time lessons with students, and also expressed as an asset to their learning by students from several communities. In the following quote, a tutor trainer mentions that in the training when this behavior is *not* carried out by a tutor, they will receive feedback on how to improve their methodology.

> *Tutor Trainer:* In fact the lesson will be read completely, point by point, and if you noticed, there are questions in the text that the student has to answer. Many times if the tutor does not, is not guided very well, they answer the questions themselves. I do not know if you noticed [in the training] many times that some tutors...a tutor I think was reading and he answered [the questions] himself. So these are things that, we would want to say 'No, the student should participate more,' to help him a little in his methodology, you know?

A ninth grade student notes that their tutor guides them in re-stating the main ideas of the text in their own words, as well as having them generate their own answers.

> *Researcher*[2]*:* Ok, what else does your tutor do with the texts?

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[2] In all interview segments, "Researcher" refers to the author of this dissertation.

> *Student 1:* He sometimes gets us to read things that are really important and to get a guide from, a guide, he asks us the questions and we give the answers that we think about the text but, with our own words expressing ourselves.

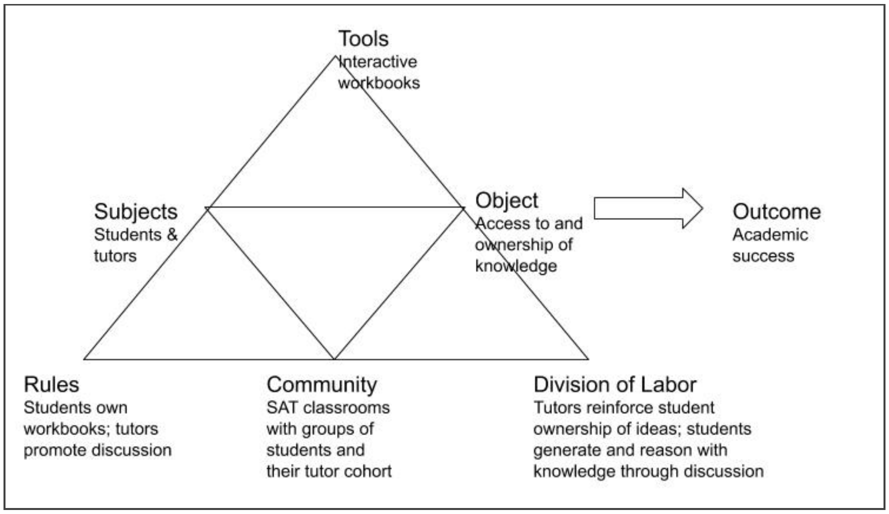


Figure 4. Example of how Activity theory was used to analyze SAT's operationalization of academic success.

As seen in Figure 4, Activity theory in particular helps identify that the network between the students, tutors, and texts relies upon students having access to their workbooks, tutor practices that reinforce student ownership of ideas, and activities where collaboration and discussion are relied upon to progress knowledge.

2.6.1.2 Resourceful tutor training and cohort structure

In order for students to have this level of agency and ownership with the content, the training and community-building amongst tutors is an integral step. SAT tutors attend regional trainings three times per year across all content areas; in these trainings, after initial content review the tutors will practice teaching the lessons of their upcoming units. Following each lesson, it was observed throughout the training sessions that tutors will evaluate both their peers and the facilitator; through this activity, everyone is held responsible for the betterment of each others' knowledge and practice, across content areas that they may initially not feel confident in.

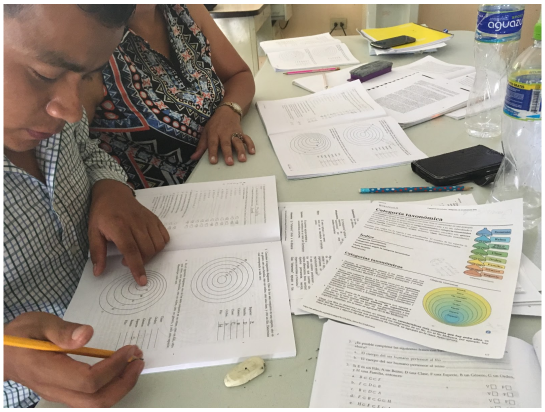


Figure 5. Tutors receive supplemental training materials in one of their mathematics sessions.

In the trainings, tutors are also exposed to content area experts (tutor-trainers) and supplemental information via the internet, videos, and extra workbooks (Figure 5), that allow them to maintain their own development once they return to their home communities. Tutors were observed filming and taking photographs on their smartphones to preserve and re-create their experiences. As one tutor remarks, the trainings are essential for addressing their doubts about content, noting that, "I am always asking [questions], this and that and the other, because I say if I perform well in training, and I learn, I won't have problems when I go to teach."

Once in their communities, tutors are also able to use each other as resources, as they all ultimately teach the same texts. One group of tutors remark on how they use each other, and the internet, as resources for texts they may not feel as prepared in, stating "Looking for help maybe on the internet or with other co-workers who have already been through the same thing, we believe we can find better solutions." Another tutor from the same community adds that this is especially pertinent in the upper secondary texts; the difficulty in implementing more advanced content matter arises given that ,"As a single teacher we impart the five [subjects], though I feel that one's strength may be in just one or maybe two subjects," so he relies upon those other resources. Tutors progress through all of the texts with the same group of students, building a rapport that often allows for closeness and supporting students to continue their studies and work through challenges they may have. This structure contributes to academic success in that the tutors come to know their students as people, what motivates them, and how they learn.

The structure of the tutor program counteracts the *governance systems* that make recruiting university-graduate single-subject experts an impossibility, by providing a wider *community* for tutors both among each other in their placements, and in training sessions alongside peers from across the country. In these regular trainings, they have extended access to *instruments* such as extra content resources (printouts and internet); for many tutors this is not an accessible *resource unit* once they return to their community. The *rules* governing these interactions mean tutors are responsible for all content areas, progressing alongside their students; while an intense undertaking, this also establishes a *division of labor* where tutors are continuously providing feedback to each other, and hold each other responsible to develop their practice.

2.6.1.3 Flexible/ localized definition of 'academic success' that relates to quality of life

On top of the 'Intellectual growth' that Ladson-Billings mentions, success in the SAT program also has a localized definition with both a personal and communal meaning beyond just knowing the content. Several administrators and tutors across multiple communities remarked that the intent for the program is to have students come to understand the tools necessary to build a life and generate work within the community that enriches it, supports others, and uses awareness of the natural system of resources. In one tutor's words:

> *Tutor:* From the beginning, it creates within them a mentality of community development, of not leaving and going anywhere else, looking at the need, helping their communities, making micro-businesses that can help to do that.

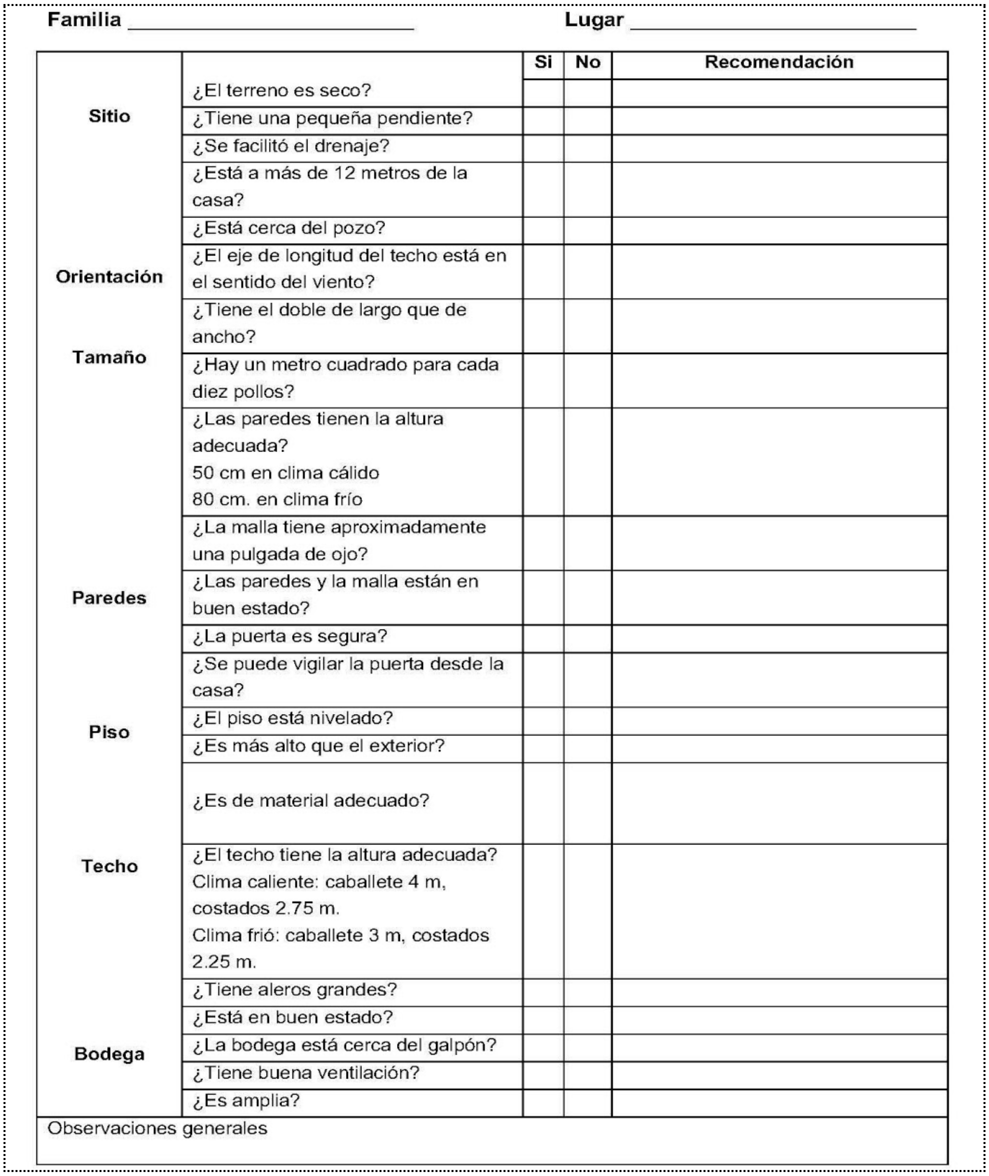
Examples of this type of development abounded in the communities visited and were recounted by several tutors (including making tamales, mondongo soup, starting farms with nurseries, etc.). In one community, a SAT graduate had developed their knowledge from the *Cría de Pollos* text to create a micro-business of raising pigs. This allowed her to support her own financial wellbeing as well as create an economic resource for her community (Figure 6).

Figure 6. Pigs of various sizes and ages being raised in a large concrete structure, monitored by a SAT graduate.

On the personal level, students are taught to embody and practice a set of values that support their ability to develop their communities, and approach decision-making, promoting sociopolitical consciousness, and the treatment of others with this moral integrity. The values are integrated into many texts throughout the program, though the Ecosystems curriculum begins with a unit just on the values, stating in the introduction:

> To start thinking about the multiple services that you can provide to this community, you can analyze your physical environment and how it can be improved. The two units of this text, "Ecosystems" and "Relevant Environmental Issues," are intended to help you promote a healthy physical environment. To develop the necessary skills, you will have to acquire knowledge, skills, attitudes and qualities in a process that combines study with action. The spiritual qualities you possess will have an enormous influence on the outcome of your acts of service. For this reason, this first lesson is devoted to briefly analyzing some of these qualities. (Ecosystems text, p. 3)

These qualities include love, faith, kindness, sensitivity, respect, patience, reliability, honesty, humility, and diligence, and are seen as indispensable parts of completing their practice-based activities. In the aforementioned activity in *Cría de Pollos* where students assess their neighbors' chicken coops, they are pressed to consider the distinction between telling people facts and inviting them to question, participate, and co-facilitate the knowledge sharing, and to question the appropriateness of delivering knowledge as an authority without a source or explanation. These skills are modeled through the story of a character, Rafael, who takes this role within his community. Along the way, students are asked to assess Rafael not just on the basis of the information he provides, but his means of interacting and methods of including community input.



Familia ________________________ **Lugar** ________________________

		Si	**No**	**Recomendación**
Sitio	¿El terreno es seco?			
	¿Tiene una pequeña pendiente?			
	¿Se facilitó el drenaje?			
	¿Está a más de 12 metros de la casa?			
	¿Está cerca del pozo?			
Orientación	¿El eje de longitud del techo está en el sentido del viento?			
Tamaño	¿Tiene el doble de largo que de ancho?			
	¿Hay un metro cuadrado para cada diez pollos?			
Paredes	¿Las paredes tienen la altura adecuada? 50 cm en clima cálido 80 cm. en clima frío			
	¿La malla tiene aproximadamente una pulgada de ojo?			
	¿Las paredes y la malla están en buen estado?			
	¿La puerta es segura?			
	¿Se puede vigilar la puerta desde la casa?			
Piso	¿El piso está nivelado?			
	¿Es más alto que el exterior?			
Techo	¿Es de material adecuado?			
	¿El techo tiene la altura adecuada? Clima caliente: caballete 4 m, costados 2.75 m. Clima frió: caballete 3 m, costados 2.25 m.			
Bodega	¿Tiene aleros grandes?			
	¿Está en buen estado?			
	¿La bodega está cerca del galpón?			
	¿Tiene buena ventilación?			
	¿Es amplia?			
Observaciones generales				

Figure 7. Checklist students use to assess chicken coops.

In particular, the text emphasizes personality traits and capacity building (the time spent in preparation, technical experience, motives) for being able to offer this kind of information and help to one's neighbors. In their own practice, students are encouraged to assess and advise the families on their infrastructure (using the checklist in Figure 7), with care not to overwhelm them with information or induce shame. Students take this message to heart, as one 7th grader indicates that responsibility to the community and respect for others are intertwined in her definition of 'educated':

> *Student*: My responsibility has developed quite a lot with the community, because we must be responsible not to mistreat the community and respect all the people who are older and younger than us, so that we can show that we are educated students.

Academic success in the SAT program is operationalized through content resources that are integrated, practice-based, and accessible to students, who express ownership of their knowledge through collective activities and the guidance of their tutors. This is made possible through the structure of recruiting and preparing tutors who may not have traditional backgrounds in education or be content area experts, but support each other through regular training, communities of practice, and establishing rapport by progressing through all content areas with their students. Finally, the definition of success has added components outside of content knowledge: finding and filling economic and environmental needs in their community, and developing values deemed essential to service, which support including community members' input and knowledge. In this context, academic success incorporates a wide actor-network between students, tutors, and community members, utilizing practices and attitudes that bridge content knowledge with the economic and environmental prosperity of students' home regions. This mindset centers students' academic success as thoughtfully evaluating and supporting the communities in which they were raised, reinforcing the resilience of local social-ecological systems.

2.6.2 Cultural competence

CRP in urban classrooms often foreground Western European/White traditions as a baseline 'norm', challenging a system where diverse learners are often enculturated in traditions that are not from their own histories. To develop *cultural competence*, Ladson-Billings posits that education should "help students appreciate and celebrate their cultures of origin while gaining knowledge of and fluency in at least one other culture" (2014, p.75). Given that SAT communities are relatively homogenous, and the framing of success mentioned above that explicitly directs students' educational experiences in their own communities, this context operationalizes the tenet of cultural competency differently than it might be seen in US classrooms.

2.6.2.1 Gaining knowledge of Western scientific traditions as 'other' culture

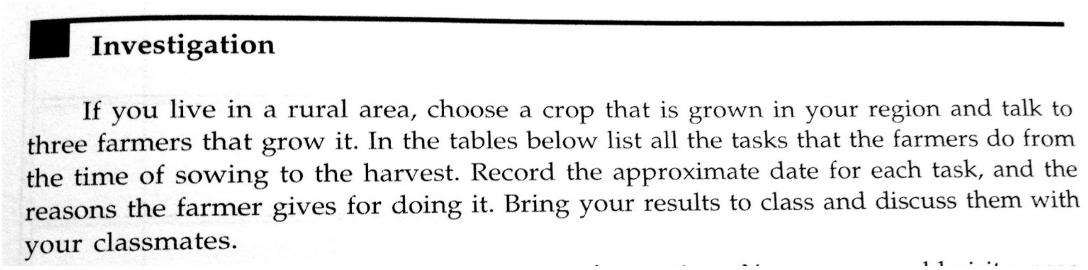
The STEM books in the SAT program don't frequently use the contexts of other cultures, though the Ecosystems text introduces ecological principles through the contexts of bio-regions around the world. While not explicitly stated so, one could interpret that the 'other culture' invoked in these science and technology texts are the practices informed by western science traditions and technologies (data charts, microscopic images, soil testing, etc.). It is uncommon that these materials are stocked in any one community, so groups go on trips to visit the equipment in nearby towns, or the materials travel with advisors in a science cart. Although students are practicing the scientific method frequently in their hands-on investigations in their community, one tutor mentions that, "Though one of the objectives of science is that the student acts or thinks like a scientist", his students hold perceptions that, "being a scientist is only going to be in the laboratory" and not when they are making observations. A group of tutors mention that scientific content principles are challenging for their students, in particular because, "We did not have enough resources, we did not have a laboratory or the substances indicated by the book to do they experiments"; this was mitigated by a field trip to a nearby community to complete the experiments. As some concepts are nearly impossible to grasp without this equipment (one tutor mentions properties of matter, for example), these field trips offer an opportunity into a different realm of science culture than is regularly present in SAT communities.

Figure 8. Tutors get a chance to interact with a microscope and chemical reactions during the training for a chemistry unit.

While this is perhaps not what CRP scholars might have in mind as an 'other' culture, it is important to consider how these laboratory based practices are not the dominant science practice SAT students engage with. Given that many rural communities may not have the *resource units* to support science laboratories (electricity, in particular), SAT creates extended networks for students to engage with Western science practices. Students have the opportunity to learn the cultural practice of Western science, though its value to their livelihoods is through applying the embedded concepts to *community* practices; this mentality is supported through tutor actions to help students recognize that Western science is not inherently more valued than their own local investigations.

2.6.2.2 Investigate community structures as primary context for knowledge

The SAT technology units offer a variety of ways for students to connect their school learning with their cultural background; the projects engage students as investigators of their communities, elevating information about what their neighbors know and do, considering the meaning for their actions, and ultimately adding and adapting existing structural elements (chicken coops, composting bins) or environmental features (cleaning waterways, planting trees, terracing land) in collaboration with those who will continue to use them. In one exercise in the *Sembrando Cultivos* unit (p. 13), students reflect on the forces that drive decision-making by farming families through a personal interview task outlined below:



Investigation

If you live in a rural area, choose a crop that is grown in your region and talk to three farmers that grow it. In the tables below list all the tasks that the farmers do from the time of sowing to the harvest. Record the approximate date for each task, and the reasons the farmer gives for doing it. Bring your results to class and discuss them with your classmates.

Figure 9. Investigation activity prompting students to record the tasks and purposes for farmers' activities.

Once they've completed this exercise, the text prompts students to reflect on how certain economic, cultural, and social situations might impact the particular choices that farmers have made, as well as their outcomes (p. 19). This task inherently drives home the message that knowledge lives within the community, and that there are many ways to consider or investigate their surroundings and cultural practices that relate to the content they are learning.

The *Ecosistemas* unit takes this approach in every chapter as they narrate people confronted with a complex ecological problem created by humans and their environment; the narratives encourage students to use patience and a lens of inquiry to collaborate with human partners to better understand the reasoning behind actions they've taken. After evaluating the range of environmental, political, or economic factors that led to the state of the ecosystem, only then can collaborative work begin towards improvement. Each chapter ends with sections for Extension (added content knowledge), Reflection (value-based questions), and *Trabajo en campo* (Field work), where students apply the concepts that have been elaborated through a diverse array of ecosystems back to their own communities and practices— during the training, these activities were emphasized by the tutor-trainer as vital for tutors to spend ample time on with their students. In one chapter on carbon sequestration, this sequence involves first demonstrating the many purposes of natural resource management (improving agriculture yield, soil fertility), how carbon sequestration can be achieved by planting a mixture of tree types, and then tasking students to organize a group to plant trees in their community, conferring on what types and where they should be located. For many communities, this activity coincides with *El dia del árbol*, a national holiday for trees. Several students mentioned this as a memorable activity in their interviews; one ninth grader notes:

> *Student:* On the Day of the Trees, we always go to the micro basin to plant trees there in the high forest, because the water flows down from there for us to drink, so always, every year we have gone and we carry trees, two or three for each student, and we go to plant them there at the spring, from here in the community.

This practice involves assessing the interaction between tree planting and water use, and becomes a ritual that celebrates the national holiday. By utilizing local spaces (in particular the environmental *resource systems* such as waterways and forests) and cultural traditions as an application of their content knowledge, students come to draw connections between scientific principles and the local management of their own environments, contributing to their sense of cultural competence.

2.6.2.3 Parent/ communal engagement in projects

Establishing value and awareness of how their own cultural practices interact with the science and technology content is amplified when SAT students and tutors include family members directly in their projects. The *resource units* available become amplified; some community members donate land so each grade can have a plot to grow crops, in other communities parents had donated wood to build the chicken enclosure for the main project in *Cría de Pollos.* In one site observation, many mothers were involved in preparing for the end-of-unit celebration (Figure 10).

Figure 10. Mothers assist students in the cleaning and processing of chickens.

They offered their stoves, cookware, and guidance in preparing the tools needed to slaughter, clean, and prepare the birds before cooking them. In this community in particular, they had timed the culmination of this lesson with a larger festival for the anniversary of the community’s founding.

In addition to providing resources, parents and community members share in the development of knowledge through formal presentations from students, being a ‘part’ of the data that students collect (such as in the chicken structure evaluation), or having the tutor facilitate conversations with parent and child around projects that take place in the home. A common task for *Sembrando Cultivos* is to practice organic fertilizer techniques in a garden bed in front of students’ homes; this was seen in multiple communities. In one community, students and parents talked together about the benefits of their small raised bed, and learned to apply fertilizer and construct protective barriers to keep neighboring dogs from eating their seeds (Figure 11a-c). Parents appeared engaged and excited by the projects, as a tutor prompted students to share the processes that they were practicing.

Figure 11. Parents participate in home-garden activities.

Note. (**a**). Daughter (left) and mother describe the seedlings in their home garden; (**b**). Home garden with erosion barriers; (**c**). A father describes adapting his daughter's project with poles to protect it from a dog.

Through these exercises, the social-ecological system is widened in that students' families are included in the process, thereby adding additional resources (land, wood, etc.) to what is otherwise possible to be investigated in school, and also acclimating parents to practices they may not otherwise be familiar with like organic fertilizer and pest management.

In short, cultural competence is unique in relatively homogenous communities where by design the curricular projects are framed around their daily lives. The 'other culture' brought in is Western science, though because of resource constraints students often have to travel to have these experiences; nevertheless, they are seen as important features of the curriculum that tie in to content that is otherwise hard to imagine. The other way cultural competency is established is by using the community contexts (local landmarks, businesses, practices) as the means to apply students' science and technical knowledge. This helps frame that knowledge lives and exists in the community and can connect to the otherwise abstract and isolated principles explored through science experiments in laboratories. This connection is further amplified by extending the network of who participates in these school activities to students' family members: observations included community members 'being' the data (in the farmer interview & chicken coop activities), 'sponsoring' certain projects with gifts of land and materials (chicken structures), overseeing their students' home garden plots, and leading the culminating activity of a unit by helping student slaughter and prepare chickens for feasts. With the help of the tutor, students' practice-based applications of their knowledge is shared with their families so that it can disseminate into the community. This *distribution of labor* utilizes more *actors* and their available *resource units* into the knowledge-sharing practices developed through school, allowing the units to both incorporate and impact resources at a larger scale.

2.6.3 Sociopolitical consciousness

While Ladson-Billings initially phrases this concept as "the ability to take learning beyond the confines of the classroom using school knowledge and skills to identify, analyze, and solve real-world problems" (2014, p. 75), it is later emphasized that a more critical framing that was often missing from CRP initiatives was a push for students to "consider critical perspectives on policies and practices that may have direct impact on their lives and communities" (p. 78). This approach has the potential to upend power structures, revolutionize communities, and change outcomes for students who are regularly underserved by wealth inequality. In SAT, this is a core value that is developed through textbook directives, interpersonal connections, and initiatives that target large-scale social-ecological systems. In one tutor-trainer's words, "SAT looks like a hopeful alternative for rural areas. That is, because the educational authorities are not thinking about people from rural areas, somehow there is a kind of discrimination." How the workbooks, community activities, and relationships developed between tutors, students, and families confront and challenge this discrimination by empowering critical shifts in thought and practice is the focus of this section.

2.6.3.1 SAT frames education as capacity building for individuals and communities, through critical reflection as a means of justice

Primarily, SAT cultivates a sense that everyone can continuously improve upon themselves for the sake of their community; this message incorporates the historical and political actions that have shaped rural communities, not establishing blame or helplessness, but invoking reflection towards growth. For one tutor, Lucia, she motivates her students with education as a defense against being taken advantage of by discriminating forces:

> *Tutor:* Generally, one way to motivate them is, seeing that in our country education is something constant, I tell them, my knowledge is only a drop of an entire ocean, so what happens if we do not study, anyone can come to deceive us, as we do not know the reality.

Understanding that the capacity for growth is limitless and extends beyond students, SAT staff model this principle through their own continuing desire for knowledge; tutors learn alongside their students and at trainings, while feedback between the tutors and trainers is also revered as an important part of the system. Tutor-trainer Alberto reflects on this aspect, regarding the impact one person can bring to the world through the continuous development of their abilities:

> *Tutor-trainer:* I see the student as a person with many possibilities, many abilities, but who needs to advance in developing them, so my job as a trainer, in this case with the tutors, is to help them move forward, but I also learn a lot when I am helping them, then to feel one that is moving forward and that they themselves are assuming this responsibility to continue learning for themselves, because they have so much to learn and give to society.

Rather than simply echoing what is being taught in the texts, for SAT communities to engage in continuous learning, the curriculum cultivates a practice of generating new types of knowledge systems by analyzing and critiquing dominant power structures, the justifications for actions, and conditions of human rights. In one example, the introduction to the *Sembrando Cultivos* textbook frames a questioning mindset towards both traditional and modern agricultural technology, where complacently accepting one over the other, or even both, is less valuable than generating new knowledge by positioning them in interaction with each other towards solving local issues:

> Most students will already be cognizant of the traditional and modern approaches to agriculture production in their region; it is in this context that the lessons seek to raise the discussion above the formula of 'either-or' or even the harmonious co-existence of both. The unit attempts to show students that in every region, including their own, a learning process can be set in motion by which new knowledge is generated from the interaction between the traditional knowledge system and modern science and technology, which can then be applied to the problems of everyday life and used to promote the sound progress of the region. (p. ix)

In addition to a critical lens on technology, a Reflection section in the *Ecosistemas* text book extends this critical mindset towards the decision-making process, especially by those with fewer economic resources, with respect to the environment. While this is initially done through an examination of the actions of shepherds in the African savannah, it has implications for the agricultural practices in students' own ecosystems:

> After a brief investigation, the members of the conservation club learned that the shepherds did not have many options: they had been expelled from their ancestral land and forced to find any grazing land in another part of the country. Then, we could be right in making the following statement: "When people operate under a limiting reality, such as extreme poverty or lack of land, they are 'forced' to make short-term decisions that they otherwise would not take." At first glance it seems that this was a fairer statement. After all, we recognize that the poor are rational and that they would make better decisions under less difficult circumstances. However, even if the statement is more subtle, the poorest are being blamed again for environmental problems. As in the first statement, it focuses on how the actions of the poor— in this case, pastoral communities— are causing damage to the ecosystem, even attaching the warning that they are done "with many reservations."
>
> The question that remains to be answered and examined is who must be blamed for subjecting the poor to such difficult conditions. How did these communities lose their ancestral lands in the first place? Is it not that the fundamental cause of the deterioration of the grazing lands are the deliberate decisions of the cattlemen to use their money and power and knowledge of the legal system to become the most productive lands? This is the kind of question that we must continually ask ourselves. We hope that you have already begun to understand that the establishment of justice is an indispensable prerequisite for maintaining and improving the quality of the environment. (pp. 46–47)

Most rural regions in Honduras are also the most impoverished; this reality is not one that SAT tries to paint over, yet instead organize into action-based projects in its curriculum. For students to confront environmental problems in their community successfully, they must understand the wider social-ecological system of governing systems, large corporations, and economic power. In particular, they must also understand how these systems have created the conditions under which people in their community have been led to take actions that may have health consequences, and to consider accountability through this critical lens before placing blame on their neighbors and family members.

2.6.3.2 Students confront their community members to make informed changes to ecological practices as they impact health and agricultural outcomes

As the physical and financial health of the community are the means to sustaining life, they are a pivotal focus for developing sociopolitical consciousness through student projects. Primarily these are directed towards shifting agricultural practices; the most frequently mentioned in data seem to be using chemical fertilizers and improper trash disposal (burning it or leaving it scattered near buildings/ waterways); importantly, these practices emerged through global economic activity that reshaped the economies of rural communities to supply cash crops, rather than subsistence farming, and rely on imported plastic goods. The practice of confronting and changing behavior is grounded in an involved, shared investigative process with many group discussions and possible actions considered. However this process is prolonged and delicate, as students are accustomed to the traditions they learned from their parents, and must negotiate with what they are learning in school to be different. As one tutor explains:

> *Tutor:* What I think is that, more than anything in these communities, the students, from an early age, the parents already take them to the field to sow corn, beans and all that, they already have, how do you say? other techniques, burn before sowing, fumigate, even now we are in technology project *Lotes Diversificadeo de Alta Eficiencia* [Diversified high-efficiency plots] and they tell me 'Teacher, isn't it better to use Gramoxone [herbicide] which is faster?' as they find it difficult to adapt to the SAT methodology, but over time they are acquiring and applying the technology that SAT teaches us there.

While this tutor describes their students wavering between their parents' practice and a new one, another tutor, Nathaniel, speaks with a bit stronger conviction of students' abilities to correct their parents in the err of their ways, by including parents in the modern technological practices demonstrated through the SAT curriculum:

> *Tutor:* Students bring [to the lesson], let's say, things that their ancestors did, such as burning, things that do not go well with agriculture and soil health, practices that are not appropriate. Then, knowing that, the student tries to raise the awareness of his dad and his neighbor, that this practice is not correct, and to instead do what the texts suggest to them. As the students accompany them, they try to make their parents aware that they [the students] will not continue doing that, and put into practice what they are learning. We look for lots of land, so that parents will practice with them, and they can realize that, [crops] can be produced both ways, but that in the other way, they are damaging the environment, and in what we are doing, we are conserving the environment for future generations.

In this excerpt, Nathaniel indicates that students will acknowledge that their parents' practices, particularly burning, are not appropriate, and guide them in learning and carrying out new practices with inter-generational farming— the impact of this being improved environmental conditions for the community. In one site visit, it was clear that students as young as 7th grade (their first year of SAT) understood the biological advantages of conservation practices taught in the workbooks. In particular, they discussed the benefits of tree planting for increasing the soil humidity and creating a compost source (worms), regarding that organic compost replenishes both macro and micro-nutrients in the soil (Figure 12), which would support their economic viability as farmers in the future as well as improve the environmental systems in their community.

Figure 12. Students lead a trip to a mango grove, remove leaf litter to reveal rich soil, and dig up red wiggler worms.

Additionally, these students described the distinction between their preferred method of fertilizer (organic) and the actual buying-habits of the farmers where they lived. They were able to see the perspective of one who would buy chemical fertilizer, and the change in conception needed to switch to the organic method (spending 'time' vs. money):

> *Researcher:* Are there people in your community using that organic fertilizer method?
> *Claudia:* Almost none, almost none.
> *Diana:* They only buy urea cans.
> *Claudia:* Sacks of urea to fertilize, but not, almost no organic fertilizer.
> *Researcher:* So, what do you think is the effect of using that [conventional] way, more than another way?
> *Claudia:* Maybe they think that the organic fertilizer is slower, and fertilizer than–
> *Diana:* Buying it is easier.
> *Claudia:* Buying from the agro-farm store is easier, just take it out and it is all ready to go, and they know that their crops are going to grow better ... So they prefer the one they buy.
> *Researcher:* In your opinion, which method is better for the environmental and social factors in your community and economic?
> *Claudia:* The organic compost is better.
> *Researcher:* And why?
> *Diana:* Because it has more fertilizer.
> *Claudia:* Because it has more fertilizer, and the other fertilizer, the one they buy, that one costs money, and in this one, you don't spend anything, only time.
> *Diana:* And using organic compost does not cost anything, you just have to prepare, to prepare it to put it on the plants.

In this moment, students are able to understand the cultural history driving community members' decisions to buy non-organic fertilizer, and also incorporate the knowledge from the unit around how organic soil over time would be a less expensive and more effective method. They recognize that the step of preparing the compost is not common or fully understood, and therefore is bypassed for quicker solutions. While awareness of the differing decision-making processes students may hold from their parents is an important first step, to confront and change behavior appears to be more challenging. Another group of slightly older students (9th grade) from a different community describe how they are variably successful with sharing knowledge around the negative impacts of chemical fertilizer:

> *Juan:* Well when you irrigate the crops, you are putting on chemicals and because it is, sometimes you apply, this, as they say, poison and that poison falls to the ground and consumes the plant
>
> *Yandi:* The plant absorbs it.
>
> *Juan:* And then turns into food.
>
> *Yandi:* And we consume the food, so that could possibly affect us.
>
> *Researcher:* And do you feel that you can teach what your parents are learning? If they can listen, or how do they feel about this?
>
> *Juan:* Well yes, one can, though only half of the times they want to hear it.
>
> *Researcher:* And what do you think?
>
> *Yandi:* If they don't want to listen to us, then we can't.

To elaborate, the ways that students develop sociopolitical consciousness are through engagement with rich scientific knowledge about soil structure and the development of new practices to share with their families about how to incorporate those practices into large-scale agriculture. The larger connection to the Social-ecological system includes specific investigations of the soil, air, and water quality in their entire region. Access to these resources is limited by overarching governance systems, climate change, and decades of globalization that changed the nature of fertilization technology. As a result, the emphasis through the *Sembrando Cultivos* unit in particular is on improving the sustainability of natural resources, and by proxy, the health of the community members. For this process, students and tutors are in constant conversation with family members about their practices and the environmental implications of them, though the ingrained 'ease of use' of chemical fertilizers, among other reasons, make this transition challenging for students to accomplish.

2.6.3.3 Friction in developing sociopolitical consciousness within the AT/SES network

While SAT initiates shifts in practice and participants in the data collection were proud to share this progress, there was also evidence of friction in this process that incorporated interactions between economic and natural resources, students, tutors, and their families. One example continues with the seventh grade students previously mentioned who discussed the fertilizer use within their communities. The clarity students demonstrated in the workbook content is entangled with the cultural practices that they have become accustomed to, particularly around burning garbage. In the following segment, students conflate the knowledge that "black soil means compost," with their awareness that scorched terrain is also the outcome of burning garbage; they try to reconcile the observation of soil color with the recognition that, should there be a simplified way of making compost [such as burning], it would have likely been in the textbook.

Researcher: Are there places near your house where the soil is better for sowing than others?

Claudia: Yes, for example where you burn garbage there is fertilizer

Diana: There is compost

Claudia: Black soil is compost

Diana: In my house, there is a place, because the book says that the soil goes in a scale, there is a soil that has organic fertilizer, some that have pebbles…there are some that are black, then there is compost.

Researcher: But you tell me where it has been burned, there is compost?

Claudia: Yes, where the garbage is burned.

Researcher: Do they talk about the practice of burning in that text?

Claudia: It hardly mentions it.

Researcher: Then what do you think?

Diana: But here it said that we should not burn the forests, because there will be no fertilizer, there will be no shade, then the water is going to run out too.

Claudia: Maybe the leaf litter that falls from the trees can be burned too and then it may be organic fertilizer.

With this interaction, students do not see the same concretized 'good vs. bad' when it comes to the practice of burning trash that Nathaniel indicates. Rather, they understand, via the science in the workbook and their parents' historical knowledge, that burning does result in darker color, which is evidence of a rich carbon source that can be used as fertilizer in soil. However, they don't incorporate air pollution or the other nutrients from slow-compost making into this explanation, and yet recall the textbook's warning against depleting shade and water. This array of discussion around the practice of burning leaf-litter is one poignant example of an existing tension between the text as it was designed (to instruct in the process of building healthy organic compost), a tutor's interpretation (that students will help in correcting their parents' practice of burning), and the ambiguity of students' interpretations of it (that burning can be both good and bad); this interaction is made visible through analysis of the activity system between the parents, students, and tutor, where students take the middle ground between learning from their tutor and appeasing their parents' traditions. Yet the implication of this interaction is intensified by the impact it has on the surrounding Social-ecological system, where the resilience of natural resources (water, air, soil) depend on shifts in agricultural practices, though the governance systems (especially globalized agricultural industries that promote chemical fertilizers and provide economic incentives for fast production of single crops) motivate the status quo.

This 'middle space' where the educational context intends to incorporate and impact the local resources of rural communities is continuously evaluated when considering immediate vs. long-term needs and resource availability. A tutor-trainer describes this tension in the following quote, noting how the resource of timber may be cautiously consumed to preserve a family's ability to feed themselves, though when a logging company offers money for the same resource, it requires a different interpretation of the same action:

> *Tutor-trainer:* Well, there is also the issue of family sustainability, because there is a pressure…you have seen it, in each house there must be a stove and that is fed with, with firewood. So where does he get the firewood? He has to go to the mountain and cut, that is, and although the son or we can tell him, you cannot do it, Dad, that is something that must be done. Perhaps we have not reached the other side of saying, as we go, it is time that we have some banks of firewood of certain species, we are not thinking about that. The issue of burning is always very strong, still in that because there will always be a pressure on resources, but as long as it is to support the family, it will be justified. But another extreme comes, where we say, people have come to the communities and here there are precious woods, right? So here we are going to dedicate ourselves to cutting trees and there is a lot of pressure on that.

While the student may want to confront their family member's choice to log local timber, a parent's decision in the moment to support their family's immediate needs can take priority. If this one action becomes accepted over time, it leaves the community vulnerable when outsiders come to harvest the timber to a larger extent. This balance between a family unit's consumption and knowledge of their role in preserving their social- ecological system ties into the strength of the community at large's resilience and sustainability over time.

By design, SAT incorporates the daily practices of many students' families, and seeks to modify future practices through ecological knowledge. While this makes learning inherently relevant, the shift in knowledge has to incorporate more than content knowledge— the framing of critical questioning offers students the opportunity to develop both conversational and scientific skills that are immediately relevant to their surroundings, and include their families and local farmers in the process. As such, it represents capacity building with a long-range focus on environmental outcomes; students must continue to confront existing ideas about soil fertilizer with their increasingly specific ecological knowledge. The negotiations around changing practices will take place gradually and only with a nuanced understanding from all parties that the economic trade-offs are slow to reveal themselves. This is one facet of developing sociopolitical consciousness that is an important resource for SAT community members, though it is not without friction towards its implementation.

2.7 Discussion

This investigation of a national curricular program revealed how culturally sustaining science pedagogy is operationalized in communities in rural Latin America. The use of a hybridized Activity theory + Social-ecological systems framework highlights the complex interplay of resources (both environmental and economic) that are influencing the educational environment between students, tutors, tutor-trainers, and local communities. Through this analysis, the three tenets of Culturally Relevant Pedagogy: Academic success, cultural competence, and sociopolitical consciousness were expanded to incorporate the practices of implementing the localized curriculum developed by the founders of SAT. In particular, academic success relies on the access and ownership of knowledge by both students and tutors, where students are evaluated not only on their application of science and technology content to community projects, but in the spiritual values and dedication to their community members they establish alongside the content. In rural regions that often experience brain-drain or are seen as having few viable career opportunities for graduates, SAT establishes cultural competence by incorporating local landmarks, community members as data, and family participation in students' projects. Additionally, Western scientific culture is made accessible through regional microcenters, though the mentality that students are constantly practicing science through their local observations (and not only in the moments they are in a laboratory) is emphasized as well.

Students in the SAT program develop sociopolitical consciousness through practices dictated by the text, as well as alongside their family members and in their local communities. The workbooks establish a critical mindset towards existing structures of power, especially as they shape the conditions that force people to make decisions that might be seen as detrimental to their environment. Students are also taught to develop patience and camaraderie around decision making, careful not to induce shame when introducing a new idea or practice to those in their community. Tutors and tutor-trainers are valuable resources in this process as they support students' growing awareness of the ecological benefits of organic fertilizer and reforestation, and mediate complex decisions around how students' families justify the means to support themselves. Within this educational space is a balance of rules, division of labor, and awareness of the impact both short and long-term on the environmental resource systems that are used in practice; students are constantly fluctuating between their increasing knowledge of scientific content and the relational practice of being change-makers in their community without alienating their loved ones.

This operalization of CRP offers new insight into how curricular implementation can extend beyond the classroom to support relevant action-based projects that establish community members as a vital part of the academic experience, both as data sources and as a participant. Utilizing land-based resources is an asset to rural communities in particular, where science can be meaningfully enacted through conservation activities that combine tradition and critical thinking to sustain local resource units such as water, soil, trees and air quality. Additionally, the way SAT positions academic success as cultivating students' contributions to their community builds the resource of knowledge and opportunities, where graduates can analyze the needs and issues among their neighbors and develop their own initiatives to remain close and also create their own livelihoods. Based on these findings, I argue that proponents of culturally sustaining pedagogy, particularly those working in rural communities, consider how their classroom work engages and supports a network of knowledge between teachers, students, and families; utilize the local resource systems both for investigation and application of knowledge; and develop critical mindsets where students examine the role of power structures and environmental justice, engage in cooperative decision-making within their own communities, and work with their teachers and families to model sustainable industry practices.

With respect to other agricultural educational movements seeking to incorporate STEM content and practices, trainings that develop teacher cohorts with shared experiences, where resources can be distributed across communities and teachers and trainers are continually reevaluated on their practice are of utmost importance. Using applied projects where students utilize content knowledge towards industry activities that their community members are already engaging in can contextualize their knowledge and demonstrate the growth potential of the field. Additionally, rather than introducing emerging technologies as isolated components of the agriculture industry, having students evaluate them in concert with more traditional practices, alongside their community members who can also share valuable opinions, can promote the 'critical thinking' practice that the field is calling for. Towards diversifying the students served, shifting away from Southern agrarianism towards a multicultural model that explores the efficiency and scientific rationale of agricultural practices developed all over the world, is a promising start that also can expand cultural competence for students of cultural minorities in these classrooms.

Above else, the place-based model of investigating one's surroundings is seen here not only as an opportunity to establish relevant science education, but also expand the network of knowledge within a community, while building resilience in the face of climate change (via conservation of water, soil, and forestry) and minimizing reliance on global industry. How students come to understand the power structures that have shaped the existing conditions of their communities is an important precursor to actively assessing the needs and opportunities that can be created through their education. In response to the challenges previously stated to implementing science education of this nature, several factors support this process: 1) interdisciplinary texts that direct investigation to the local surroundings and revisit science concepts in new contexts; 2) the cohort model of both training teachers and within communities, where students are supported through continuing engagement with their mentor, who also develops a lasting relationship with community members; 3) minimizing a reliance on scientific equipment or laboratory practices, instead prioritizing the resources already accessible.

As SAT has been adapted for use in regions beyond Latin America, there is proof of concept that this model can be utilized beyond the area of study. What remains to be seen is how this operationalization of CRP translates to regions with more populous areas, or have diverse industries beyond agriculture. Additionally, this study is limited in its ability to support shifts from traditional curriculum towards a critical, place-based model; SAT had been established in Honduras for over a decade prior to this research. While the data presented do represent patterns across several communities, they are ultimately a small sample and should not be generalized to the whole country or SAT as a whole. The contribution of this paper is rather a new conceptualization of culturally sustaining science pedagogy that focuses on the knowledge systems' use of and impact on the network of ecological resources sustaining the local economy. For future work, this theorization could be applied to communities with similar demographics to test its validity.

3 Grounding science in virtual models: A DBR study on school garden ecology

3.1 Developing a framework for technological use in agricultural settings

Content standards in science education promote inquiry and data collection as tools for students to make claims about the natural world. While these claims are often a product of evidence-gathering through technological instruments, students' situated knowledge about their environments are an under-utilized resource in both making science relatable, and scaffolding the use of these instruments. This design study positions students to engage their situated knowledge of a familiar garden in conversation with the instrumented knowledge developed through the use of a computational model of the garden ecosystem, conceptualized theoretically by integrating activity theory and instrumental genesis lenses on their learning process. A retrospective analysis of a sequence of design iterations offers a design framework based on this integration called *PIQ* that unites the *Purposeful application, Instrumented + situated knowledge negotiation,* and *Quantitative reasoning* afforded by the design space as a tool to theorize and guide similar technology-oriented situated STEM learning. Interviews, video narration, classroom observations, and artifact analysis support the design revisions and retrospective analysis. This analysis revealed implications for learning environments to support students' situated ecosystem knowledge and provide meaningful contexts for the use and application of computational models, as well as a framework to ground these principles in design.

3.2 Introduction

When students feel that their learning is purposeful, it can increase their engagement and persistence with tasks, particularly with coding and computer science (Kearsley & Shneiderman, 1998; Lee & Ko, 2012). Too often science has been separated from purposeful applications, and the tools used in practice are afforded authority that limits agency offered to students. Utilizing local complex ecosystems as a part of science instruction is a valuable educational opportunity that can empower students to make science purposeful as changemakers within their community by increasing their awareness of conservation practices (Ozer, 2007), and helping them grapple with large-scale social and political issues like climate change and globalized agriculture (Ardoin, 2006). Including students in the design and development of technological tools has been shown to develop both better technology and their own design skills: namely insights, abilities, and a critical and reflective stance towards technology through their engagement in design work (Iversen, Smith, & Dindler, 2017).

This paper bridges together these two initiatives through a novel design framework that positions students as builders and evaluators of technology by incorporating their experiences and knowledge about a local space that they can then shape and improve; the framework is used to demonstrate coherence across three iterations of the study, and also to describe the phenomena afforded to the intersections of a meaningful setting, technological resources, and classroom activities. First, the primary design features (garden setting, and garden model) are highlighted in conjunction, and then elaborated separately to motivate their affordances in the design space. Then, two theoretical frameworks are described that motivate study of these elements singularly (garden spaces: activity theory; garden model: instrumental genesis) and integrated, providing a focus on the negotiation of knowledge between each realm of activity. The novel framework (PIQ) is presented along with conjectures for the specific activities designed for this space. The framework is also used to show revisions to the design space via the model and classroom activities, presenting the learning opportunities afforded across three iterations of studies. Implications of this framing and lessons learned from the iterative design are shared to support broader applications of student-modified technological artifacts in place-based science education.

This design study represents the collaboration between a graduate student researcher and public school teachers and students within two districts in Northern California. The main goal of the program was to develop inquiry tasks that utilize computational modeling and support hands-on investigation of school gardens, primarily within the context of middle and high-school science class, but also in service of other content disciplines (Figure 13). This focus sought to engage learners in inquiry of a familiar space by cultivating multiple ways of knowing. This began as a collaboration with one school district to incorporate science principles with garden activities, which have historically led to better social-emotional, nutritional, and communal health through contact with nature and fresh food (Fusco, 2001; Krasny & Tidball, 2009). The following subsections provide the motivation for both the context (gardens) and the content (computational modeling) that were centralized in this sequence of design iterations.

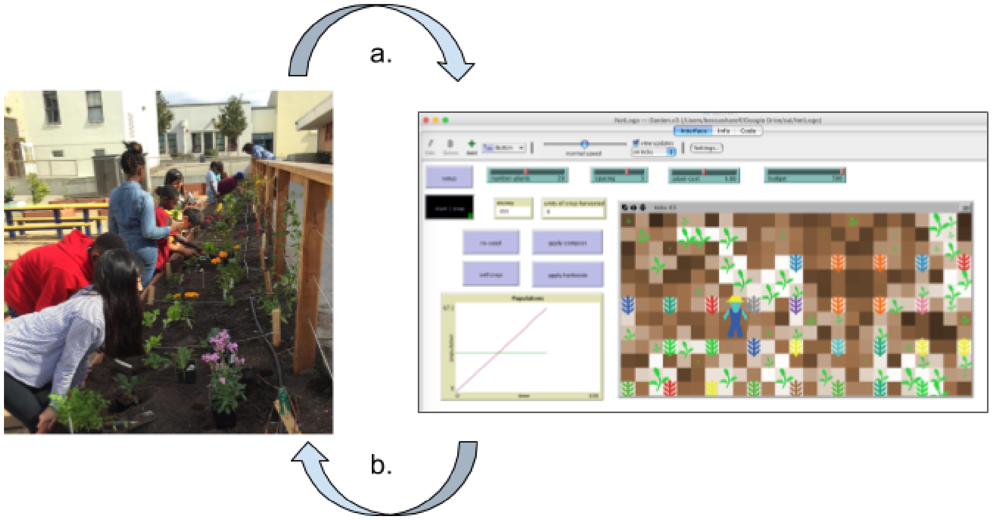


Figure 13. Bi-directionality in study objective.

Note. a) Students' personal interactions in the garden drive their inquiry and sense-making in the model space; reciprocally, b) The model serves as an opportunity to apply a formal educational practice (scientific modeling) to a meaningful context, as it informs their thinking about preserving and protecting the actual garden ecosystem at their school.

3.2.1 Gardens as meaningful, accessible, complex ecosystems

The school garden is a particularly challenging environment to design for given the added resources that an outdoor school "living laboratory" requires. Educators in school gardens list the lack of time, curricular materials, teachers' interest, knowledge, and experience with gardens, funding, vandalism, and adequate support from staff, volunteers, and parents as the biggest barriers to implementing school gardens (DeMarco, 1997; Desmond et al., 2004; Graham et al., 2005; O'Callaghan, 2005; Ozer, 2007; Phibbs & Relf, 2005). Additionally, there is great variability in the design environment as weather can make a particular visit to the garden full of dynamic conditions (sunny, rainy, cold, dry). However this makes it a useful space for inquiry, as seen in similar studies of natural school-adjacent environments like a creekbed or overgrown schoolyard (Lehrer & Schauble, 2004; Manz, 2012) in that it can elicit embodied cognition (thinking like a plant or animal, Keller, 1984; Wilensky & Reisman, 2006), connect to personal experience, and become a relevant application of ecological knowledge.

Having prolonged interaction with a garden space, whether during instructional time or informally, provides students with a wealth of knowledge about the ecosystem and its functioning. While observations and experience with plants and pollinators can leverage to science content in particular, more exploratory and informal activity can allow students to develop personal and emotional connections to the space through tending to plants, tasting, choosing plants to cultivate, and learning the cultural history behind some practices (Bell et al., 2009; Blair, 2009; Rahm, 2002). Designing activities to mobilize these ways of knowing in the classroom acknowledges students' lives and experiences as relevant and resourceful in formal learning opportunities (Bang & Medin, 2010; Warren & Rosebery, 2004). The combination of communal and exploratory experiences in gardens, which I refer to as *situated garden knowledge* (Lave, 1988; Lave & Wenger, 1991), validates ways of knowing beyond the formal institution of science, which historically grants power to objective, 'irrefutable' scientific claims. Centering learning around the garden environment seeks to expand equity by inviting all those with situated experience to share in the practice of scientific reasoning to nurture their land and surrounding community. This place-based approach is particularly seen as a powerful pedagogical opportunity to improve the social, economic, and environmental equity within agricultural communities (McKim et al., 2019), as well as support teachers' ecological mindfulness and promotion of local cultural values related to environmental sustainability (Chinn, 2015).

Beyond being a resource for situated knowledge, as a relatively contained ecosystem, gardens have appeal as a familiar type of complex system that researchers suggest are especially important to understand in contemporary science (Eilam, 2012; Hmelo-Silver, Marathe, & Liu, 2007). Plant ecosystems both wild and cultivated have been investigated as a resource for students' data collection and representation of concepts such as natural variation and reproduction (Lehrer & Schauble, 2004; Manz, 2012). These systems involve sophisticated chains of causal relationships and emergent behaviors that arise from "micro-macro" interactions (between individual members of a collective whole, the collective whole itself, and the surrounding environment; Wilensky & Reisman, 2006). Complex ecosystems such as gardens invite a multitude of opportunities for investigation, both socially and scientifically, and can connect broadly to the study of global climate change.

3.2.2 Agent-based models afford powerful opportunities to reason about complex systems

In particular, the use of computational models to investigate complex systems is widely utilized in domains such as biology, social studies, economics, and epidemiology; additionally, they are considered to be capable of promoting interdisciplinary academic concepts such as planning and problem solving (Borrill & Tesfatsion, 2011; Miller et al., 1993). This interdisciplinarity emerges alongside outcomes in both the content being modeled, and fluency in constructing and manipulating the coded language of the models (Yoon et al., 2018).

Agent-based computational modeling environments (ABMs), such as NetLogo (Wilensky, 1999) allow users to understand the relationships between individual agents, such as plants, animals, and humans, while observing systemic outcomes, through exploration of visuospatial simulations. The models are flexible, can run countless times, and encourage construction and manipulation of their underlying code (Wilkerson-Jerde, Wagh, & Wilensky, 2015). Wilensky & Resnick's (1999) work shows that ABMs have been used as a powerful tool to study complex systems given their ability to demonstrate emergent phenomena, such as birds flocking or traffic patterns. With respect to ecosystems, and in particular the complex relationships between animal and plant species, there have been several studies that show how ABMs help students scaffold their reasoning to better understand interdependence by having students first "think like a wolf" (or other singular agent; Wilensky & Reisman, 2006) as they program agent behaviors (Basu et al., 2016; Sengupta et al., 2013).

Specifically having students program as a part of the modeling experience allows them to use logic-based mathematical equations to explore conjectures and ideas from science, as a means of improving the predictive power of models. It also helps students develop the practice of critiquing existing representations rather than seeing them as static versions that are inherently correct. There is momentum to increase this practice for students as an authentic way to do science; beyond the fact that scientists are using these models, they demonstrate the fallibility of representational tools to make sense of the world, and can involve the scientific method in a robust way by having students pose a question, gather data, and test and retest their models (Weintrop et al., 2016). Drawing from Verillon and Rabardel's Instrumental Genesis (1995, see next section) in this paper, I refer to students' *instrumented knowledge* as the insights generated from their use, critique, and revisions of an ABM in classroom activities.

While powerful scientifically, researchers have also documented the challenges in having students program in ABM environments, because the text-based language offers little room for error and is not immediately intuitive. Research in this field often comes up against a bind of smoothing the transition into complex coding or limiting the agency for students to conceptualize ideas mathematically, see models as fallible and flexible, and develop their own identity as authors. In particular, GUI's / block based programming (such as Scratch, from the MIT Media lab, or ViMAP, Sengupta & Farris, 2012), ease the burden of creating complex segments of behaviors by having students adjust fewer parameters of the model. Other studies apprentice students into modeling practice by having students compare their model to an 'expert' model of the same phenomenon (Basu et al., 2016), though without explicit awareness this can perpetuate the notion that a model can be correct, rather than an incomplete representational tool used for predictive power. In a method called bifocal modeling, a model is compared to a controlled physical set up of the same phenomenon (Blikstein et al., 2016). Here students look for cohesion between the virtual and physical representations, refining the model until it appropriately captures all the known behaviors of the system. While these strategies ease student entry into developing modeling practices of complex behaviors, they also endorse learning about modeling by replicating some definitive expert model of a phenomenon. Though this type of modeling practice constitutes a valued form of scientific activity, I challenge that it limits students' abilities to consider a model as *a* representation (rather than *the* sole representation) of a complex system, and therefore up for debate.

3.2.3 Combining situated and instrumented knowledge of a familiar complex (eco)system

What has yet to be explored in depth, and what this study seeks to do, is position students to negotiate their *situated garden knowledge* with *instrumented knowledge* from an ABM of a garden ecosystem to enable a balanced and critical investigation of a local complex system and the data they collect about it. Recent studies have developed scaffolds for students' embodied activities as a resource to use in modeling practices (Danish, 2014; Dickes et al., 2016; Levy & Wilensky, 2008; Pierson et al., 2017). Similarly, this study utilizes students' rich prior experiences with the physical environment beyond the structured, rule-based environment of modeling, as a resource for sense-making. Beyond a scaffold for reasoning, this work also uses the situated environment as a context to then apply this instrumented reasoning of ecosystem dynamics (Figure 13). This connection positions computational modeling as more than an end-goal, but a process for developing and applying insights about an environment that will have sustained access and meaning to students as learners (and gardeners). By leveraging their repeated access to the garden, students engage in situated meaning making, bonding, and hands-on engagement with the environment (Blair, 2009). Current research suggests that these types of opportunities enrich students' abilities to make arguments with data, by incorporating personal experience as a frame for interpreting and explaining phenomena (Kamarainen et al., 2015). Not only does this interaction between situated and instrumented knowledge position the scientific practice of modeling as more authentic and relevant to students' lives (Bell et al., 2009), understanding the complexity and ubiquity of ecological systems, such as gardens, can prepare youth to be better stewards of the environment (Fusco, 2001).

Science education research and policy suggest that students engage in epistemologically authentic activities through scientific practices such as model-based reasoning, observation, and data collection (NGSS Lead States, 2013); simultaneously, situated knowledge and diverse epistemologies are often excluded from the framings of western science curricula (Bang & Medin, 2010; Sánchez Tapia et al., 2018). To serve both of these purposes, the garden can function as a living laboratory for incorporating students' situated knowledge with the instrumented knowledge derived from computational modeling, while also re-defining what counts as a 'typical' science space.

3.2.4 Study design

This project uses a design-based research (DBR) approach (Cobb et al., 2003) in the development of both an agent-based computational model and curricular activities to develop modeling practices and ecological sense-making among students as they investigate a complex ecosystem at their own school: the garden. Per the traditions of DBR, the project began with theoretical principles from literature informing the initial design conjectures about the features and potential application of the computational model. These ideas were expanded upon and revised through iterative interventions with multiple stakeholders, in this case public school teachers of different disciplines and students of varying ages and experience. The main design motivations as enacted in this iterative cycle were at three nested levels (elaborated in section 3.3), with the negotiation of situated and garden knowledge in the middle. A framework I call PIQ theorizes how the shift in activity enabled more complex engagement with situated and instrumented knowledge, quantitative reasoning, and purposeful application of the use of the model in activity.

Conjecture mapping (Sandoval, 2014) was used both to document the explicit design decisions through each iteration of the project and a structure for analysis ("Backward conjecture mapping") to identify emergent applications and features of the design environment that could support a more interdisciplinary use of the model (Wilkerson, Shareff, & Laina, in progress). Conjecture maps allow researchers to specify the underlying theories, anticipated behaviors, and intended outcomes that motivate the design of a given tool or learning environment. Backward conjecture mapping restructures this tool with a focus on designer intention by offering a correspondingly detailed analysis of the different ways an environment is perceived and taken up by teachers and students. In this study, I utilized this technique to analyze the features of the design environment that best support uptake in a variety of disciplinary contexts during the first iteration, and incorporated that knowledge into the model redesign (Shareff & Wilkerson, 2018). The research questions this paper explores are:

1) *Which features of the comprehensive learning environment optimize students' opportunities to critically juxtapose knowledge from the physical and simulated gardens?*

2) *How does the iterative development of activity design support theoretical development on mediated artifact use in situated scientific inquiry?*

In the next section, I offer theoretical grounding for the emergence of PIQ, and a way to conceptualize the type of activity that promote students to position their knowledge from two different realms, by considering their social environment as well as their in-depth acclimation to a new technological implement. The data and findings are presented under this lens, both broadly to describe the range of possible actions across all participants, and with singular cases to demonstrate a single participants' experience navigating the reasoning and application of these different knowledge sources.

3.3 Theoretical framework

To contextualize these questions, I consider theory around how students learn to adapt to and use a digital tool in socialized learning environments. Like Bielaczyc (2006), I consider the social infrastructure in the classroom environment equally as meaningful to analyze and design for as the tool itself. From this orientation, my theoretical framework brings together Cultural-Historical Activity Theory (Engeström, 1987) and Instrumental Genesis (Verillon & Rabardel, 1995) to understand the evolution of my design.

Because this work so explicitly utilizes situated learning within a wide context with different behaviors, rules, and experiences from what might perpetuate in the science classroom, I use cultural-historical activity systems as a guiding framework for being clear about the scope of activity within the garden. In particular, I consider how within this system there may be different roles (caretaker, explorer, taste-tester), community members (garden volunteers, the wider school network, and by extension plant and animal ecosystems), historical patterns of behavior (where gardens are, what they signify, who is allowed in them), and cultural connections to garden spaces (particular plants, animals, or other natural elements that have personal meaning, utility, and significance).

Within this activity system (Figure 14), I aim to impact how students are able to connect to, think about, and care for the school garden by introducing a particular instrument, the computational garden model. To analyze how students come to utilize the instrument in service of their actual garden, I use the framework of Instrumental Genesis (IG) (Verillon & Rabardel, 1995) to consider two key phases of this process: first how users acclimate to the model components (via accessibility of certain features, analogous reasoning, question-asking), and secondly the ways they connect the model to their existing ideas about the physical garden and relevant classroom activities (instrumentation and instrumentalization, respectively). IG is shown integrated with the activity system as the blue triangle in Figure 14 below.

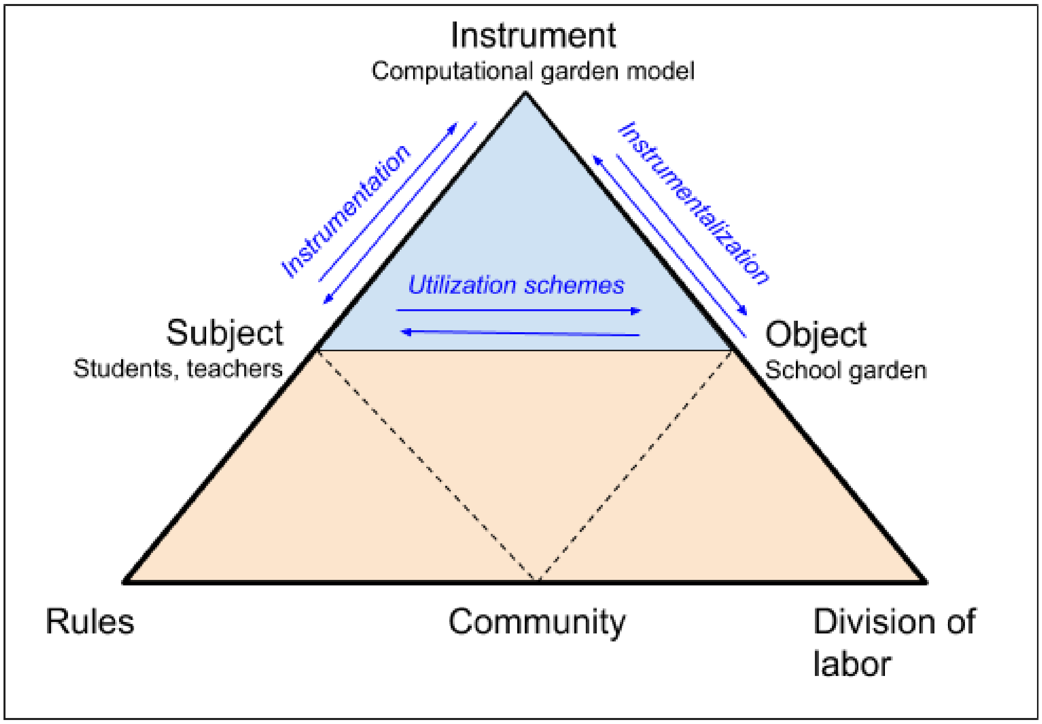


Figure 14. An integrated theoretical model.

Note. A cultural–historical activity system (large triangle) with embedded Instrumental Activity Situation (blue triangle) captures the key features of the design environment.

Whereas identifying particular facets of reasoning is an important step, it is an incomplete framework for the larger work this paper seeks to contribute, in service of the evolution of a tool within a structured activity system. Researchers performing similar investigations using IG in design projects have added to the triadic image represented by the blue part of Figure 14 the influence of the designer-researcher, and their own evolving relationship with both the participants and the designed artifact (Abrahamson & White, 2008; White, 2008). This new configuration considers the evolving theories of learning informed by the designer's observation and modification of the participants' experience with the instrument, and how the designer can shape its instrumentation; I also attend to these evolutions in this study.

As a designer, I wanted to do a retrospective analysis to understand how to integrate CHAT and IG through design to theorize this co-evolution of instrument and activity system. Beginning with IG, the design of the model and scripted activities for working with it evolved to increasingly incorporate situated activity and knowledge from within the actual garden. With respect to CHAT, the use of the instrument (model) can impact the activity system of roles, relationships, and people who feel connected to the school garden by creating different ways of connecting to the space. Through the course of this study, the integration of CHAT and IG helped shape the emergence of a design framework particular to this environment with three nested levels; in the next section I describe this framework and elaborate on how it served as an analytical tool across design iterations.

3.3.1 A design space that blends purposeful activity, instrumented and situated knowledge, and quantitative reasoning

Three particular conjectures at the initiation of this design study shaped the landscape of activities and opportunities for students to connect their knowledge to the garden model, demonstrate their own agency in tinkering with and expanding the model's capabilities, and apply that knowledge in a meaningful way. A secondary pedagogical objective of this study was to co-design a tool that can work across many contexts with different academic and social purposes that builds on strong situated knowledge. These conjectures provided the design space that was initially viewed through the theoretical framing above, as a combination of Activity Theory and Instrumental Genesis. However, as a result of the design iterations I propose a new framework embedded within this hybrid system that more succinctly captures these nuanced elements of students and teachers as they come to use a new tool towards a dedicated space; this is the framework I refer to as *PIQ*, an acronym for three principles described below, and envision as nested spaces for activity (Figure 15).

The primary framing for activity is a community agricultural space that serves as motivation for action and a source of complex and diverse scientific experiences. The activity is then presented as *purposeful*, in that it is inspired by real-life connections, and carried out with an intention to preserve and facilitate the management of a local ecosystem. Purpose can also be derived by students having the agency to select a particular feature or relationship of interest within the ecosystem to focus on for their inquiry.

Conjecture [Purposeful application]: With real life application, students can rely on multiple knowledge sources and also follow through with inquiry. To bolster interest and engagement, students are actively engaged in pursuing a topic of choice from the garden ecosystem through multiple avenues of inquiry.

Within this realm, students are conjectured to develop increasingly complex knowledge of both the modeling space and the physical garden, as they engage in an ongoing back and forth exploration of both spaces. As in Figure 13, their knowledge of the garden shapes how they both interpret and change the model to serve their inquiry.

Conjecture [Instrumented + situated negotiation]: A model invites situated knowledge about gardens to help students acclimate and understand its features, and encourages them to build in more properties of the ecosystem behaviors and elements from this knowledge to change and evaluate the model as a source of reasoning.

Building from this conjecture, the intended outcome for this design is that students evaluate varied and competing evidence from the models and from the garden. In order to evaluate and negotiate, students need to engage in prolonged inquiry with the model instrument; an emergent asset of this inquiry that was increasingly utilized across iterations is the development of quantitative reasoning, which I use as an umbrella term for four cross-disciplinary practices: 1) data generation and representation; 2) integrating scientific predictions; 3) economics activity; and 4) logic-based code generation, manipulation, and reasoning. These are described more completely in section 3.3.2.

Conjecture [Quantitative reasoning]: Support interdisciplinary quantitative reasoning with the model by adding graphs, embedded mathematical relationships, multiple forms of data, and connection to social applications.

These components are interconnected and nested, relating to both cognitive and affective features of the design space. In the diagram below (Figure 15), the three nested design elements derived from the conjectures above are described with respect to how they are informed by the activity of utilizing a computational model (here, the instrument) that models the school garden. I refer to them as <u>P</u>urposeful application; <u>I</u>nstrumented + situated negotiation; and <u>Q</u>uantitative reasoning, collectively abbreviated as <u>PIQ</u>. This diagram utilizes the frameworks previously described and elaborates on their integration, adding a layer of negotiating knowledge sources between the situated and instrumented activity spheres. In the design space, users move within and without the three layers as they work with the model of the garden. I envision the elements of the activity system (rules, division of labor, and community) to inform crossing from layer P into layer I, as the instrument is used for the first time. After users develop their quantitative capabilities with the model (I to Q), their instrumentalization entails negotiating situated knowledge to inform how they reason with the model about the garden (Q to I). Their final movement through the nested framework is to apply their nuanced knowledge back to the actual activity space (I to P). While AT illuminates the situated elements that shape the design, and IG the input and output of learning to use the instrument, PIQ offers a focus on the boundary between the two frameworks, and how different forms of activity support the elicitation and negotiation of knowledge involved in crossing between each nested layer.

As an analytical tool, I use PIQ to track how each iteration afforded different opportunities for engagement, driven primarily by the initial purpose/ intended application; a different version of the Figure is presented at the start of each design iteration to show the evolution of the PIQ elements. Revisions between each iteration were also centered around these elements, with the goal of enriching opportunities for each layer to smoothen this sustained journey between a local space, a tool that represents it, and the action taken with it. The following paragraphs contain the motivation for each piece of the framework, followed by a description of its manifestation in the design environment.

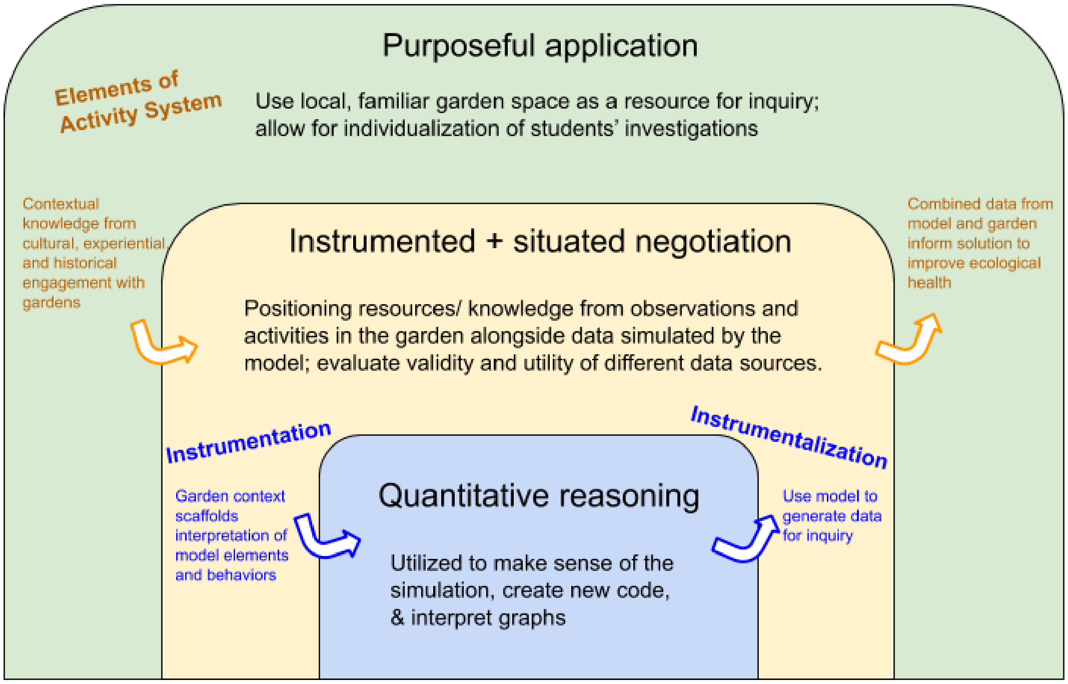


Figure 15. The PIQ framework, as shown to integrate elements of the activity system (orange text), and the process of instrumental genesis (blue text).

Note. The conjectured path of activity for the final design iteration reads from left to right.

3.3.2 Motivating the layers of PIQ in current educational initiatives and elaborating their presence in the design space

3.3.2.1 Purposeful application

What students are taught about in school should connect meaningfully to their lives. The intent of learning a topic without a clear sense of purpose demotivates students and creates a power dynamic between the teachers' selection of material, and the students who must enact it to earn their teachers favor (Dewey, 1938). Jiménez-Aleixandre et al. (2000) characterize this dilemma as "doing the lesson" vs. "doing science"; the former is a procedural display often reliant on social conscription without a true connection to purposeful learning, and competes timewise with scientific thought and argumentation. Alternatively, when students utilize scientific investigation as a means to engage in local problem-solving or community improvement, the synergy of increased agency and motivation becomes apparent, and can create a purposeful outcome of ecological resilience (Aikenhead, Barton Calabrese, & Chinn, 2006; Emekauwa, 2004; Fusco, 2001).

In this design space, users are conjectured to enact the purposeful application of scientific knowledge and inquiry for improving the health and well-being of a shared community space, developing agency with direct action and results. By using a local ecosystem as the focus of the model/learning environment, students are prompted to consider how their actions and investigations can not only lead to an understanding of ecology, but then be applied to establish better conditions for wildlife, soil health, and the human community that engages with the garden. In some agricultural spaces, this can include planning for the financial costs of sustainably running a farm and the many inputs it requires, or engineering how best to manage a small plot that can successfully produce crops and maintain a healthy ecosystem for the humans and other creatures that rely on it. Gardens hold rich possibilities for personal connection by being a feature of many cultures, and how they engage the senses (Ozer, 2007; Ralston, 2011; Williams & Dixon, 2013). Relatedly, the array of possibilities for inquiry and investigation are equally diverse, and students are afforded the opportunity to forge their own path by picking a topic of interest within the ecosystem. In this way, the outcome of their work is purposeful and unique.

3.3.2.2 Instrumented + Situated negotiation

Conventional science education frequently emphasizes the use of standardized instruments for collecting and analyzing data in order to make claims about the world. Yet this representation of scientific practice is incomplete; instruments can be fallible, and the framing of scientific knowledge as objective and quantifiable devalues the contextual and relational knowledge that can be developed through prolonged and situated interaction with a place (Bang & Medin, 2010), such as renowned geneticist Barbara McClintock's development of "a feeling for the organism" (Keller, 1984). These two distinct sources of knowledge—instrumented and situated—can not only share equal footing in scientific reasoning, but can inform and enrich each other in a way that makes science more relatable, inclusive, and engaging (Abrams et al., 2013; Bell et al., 2009; Calabrese Barton & Tan, 2009). Expanding the ways we conceptualize learning to include more relational epistemologies is particularly relevant to studying human-nature relationships and the roles of human-made artifacts in nature (Pugh et al., 2019). However, students rarely have opportunities to develop and use scientific instruments in ways that are directly informed by and applied towards their diverse and relational knowledge of a familiar place, and thus little is known about the intersection of these forms of reasoning. As the world becomes increasingly digital and simultaneously confronted with challenges to prevent ecological collapse, connecting instrumented scientific knowledge with grounded experiences in local environments expands the resources available to investigate and preserve the cultural richness of complex ecologies.

In this design environment, there are two distinct opportunities for students to negotiate instrumented and situated knowledge; primarily, by utilizing their actual school garden as a resource for situated and observational knowledge about an ecosystem, and the garden model as an instrument to supply another source of simulated data about a comparable ecosystem. In scripted classroom activities, students are positioned to evaluate the strength of each source of evidence, and indicate where one is more valuable to their inquiry. Secondly, the modeling instrument can be *infused* with situated knowledge as students customize and tinker with the model code to deepen their investigations. In this way, students' own conjectures about the relationships between ecosystem elements are illuminated in how they shift the model to assess a diverse set of inquiries about the garden. In sum, students can negotiate instrumented and situated knowledge generated through in-class investigations with the model and garden (and previous experiences in gardens), towards making a scientific claim, supporting that claim with evidence, and endorsing an ecological action/solution based on that claim.

3.3.2.3 Quantitative reasoning

With increasing reliance on data and computer-based technologies, quantitative reasoning has become a valuable skill across disciplinary domains. Researchers in the learning sciences are investigating the impact of contextual and experiential factors on how learners engage with data, including their manipulation, generation, and critiquing of data (Wilkerson & Polman, 2020). To communicate authentically with data, learners often have to filter and focus on the right data for their investigative purposes (Erickson et al., 2019) and translate across many representational forms (Wilkerson et al., 2018a). Even as students gain practice working with data and representations, they may struggle to connect it to the phenomena they are studying (Kamarainen et al., 2015). Building investigative environments that connect students' grounded experiences with the phenomena more directly to the data and modeling tools available to them can help ease this transition; in particular, to help them to form scientific hypotheses and evaluate their data to analyze causality and construct an explanation for the phenomena (Dede et al., 2017; Grotzer et al., 2015).

Evaluating quantitative representations not only contributes to meaning making in science, but also carries over to many other realms in daily life (weather, economics, journalism, etc.). Relatedly, considering how different disciplinary domains may use and interpret the same computational modeling tool can help expand learners' perceptions of the underlying assumptions of models and become aware of an array of distinct disciplinary practices (Jurow et al., 2008; MacLeod & Nersessian, 2015). For example, considering how a model can simulate practices in social studies (economics) alongside science (ecology) enables each discipline, and human behaviors, to be viewed as relational and fluid (Epstein, 2007; Macy & Willer, 2002).

Another type of quantitative reasoning afforded by computational models in particular, is frequently called computational thinking (CT), or the practice of reasoning logically with and about algorithms and coded abstractions (Wing, 2006). Weintrop et al. (2016) deconstructs computational thinking into distinct categories, separating computational problem solving practices from modeling + simulation practices, and data practices, while others (Xiang & Passmore, 2015) consider computational practices within modeling to be activities like defining, questioning, and revising the code-based rules of the model. However you slice it, there have been calls to complexify CT beyond the (acontextual) creation and application of computational abstractions to instead consider discursive, material, and embodied experiences with code (Sengupta et al., 2018) and students emergent goals and epistemic orientations that shape how they engage in computational practice (Wilkerson et al., 2018b). This contextualized, embodied view is the approach I take to consider how students reasoning about and with coded abstractions.

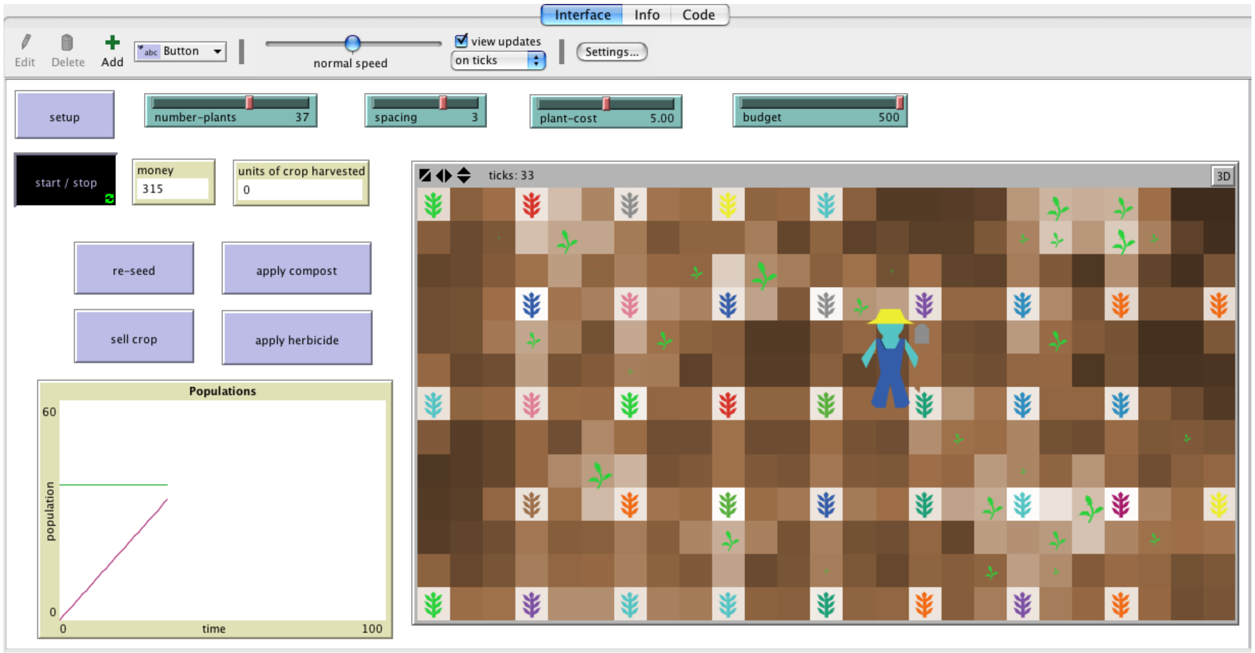
In this design environment, users enact interdisciplinary quantitative reasoning in the computational model in four ways that can overlap or inform one another: 1) to generate and represent data; 2) to integrate or extract scientific predictions; 3) to attend to economics principles (profit margins, financial sustainability) and 4) to build, manipulate, and reason with logic-based code. These are enabled by the graphs, dynamic visualizations, output data, economics and ecological components, and rule-based code in the model (the next section offers a more detailed description of all of the elements in the model, including the elements connected to quantitative reasoning). Graphs encoded into the model dynamically update to reveal important trends, in this case line graphs and histograms. The data that inform the graph can be exported at any instant and pooled to create a larger data set. As the model runs, an internal clock called 'ticks' provides a baseline to show interactions over time. As a model of an ecosystem, ecological properties and components are embedded in ways that afford attention to some features and minimizing of others. The inclusion of some elements and relationships above others (for example, plant growth is modeled but not sunlight) position students to reason about authentic predictions that can be made with the model, or ways to manipulate it to support a causal claim about the ecosystem.

The model also has numerical elements on the interface that motivate social and economic behaviors in an agricultural environment; there is a budget, plant cost, and unit-weight that links the size of plants at harvest to a particular biomass of crop that can be sold to earn money. The money is then used to purchase new seeds or apply fertilizer, herbicide, fungicide, and water back to the garden. These features are meant to emulate authentic social and economic factors involved in the engineering and managing an agricultural space, and therefore reasoning from this perspective offers one avenue into quantitative reasoning with the model, though it is not necessarily privileged or positioned as the grounding orientation.

Computational models such as this one are inherently run on rule-based coding. Within agent-based models, there are mathematical relationships that inform the emergence of systems-level dynamics as individual agents run through their coded behaviors. For example, in this model, a random distribution of soil nutrients is applied throughout the garden plot, yet once the nutrition level in a singular patch reaches below a certain value (set by the code), plants can no longer grow there and will slowly lose energy until they die. Students can immerse themselves in the code to better understand its underlying assumptions, and change elements to afford different interactions in the model, such as drought resilient plants, plants that grow quicker, or apply an even distribution of nutrients, just to name a few. As mentioned previously, reasoning with the code is considered in conjunction with students' intended purpose for doing so and their social and epistemic orientation towards it as a language. Section 3.4 describes more about the specific coded elements of the model, and how they are represented on the interface and on the simulation interface.

3.4 The model

Initially, this project sought to understand the ways learners with diverse experiences and disciplinary approaches adapt to and use an instructional tool: a computational model of a garden ecosystem. In the early stage of design, participants were invited to contribute to the researchers' understanding of the affordances of the tool in service of its redesign towards more interdisciplinary opportunities. The initial model (Figure 16a) was minimally designed with respect to complex ecology (mainly illustrating the competitive relationship between plants for soil nutrients), though it did have several elements listed in Table 1 below. The elements added in the redesign were partly a result of the second study to elaborate quantitative reasoning, and also to support the instructional goals of the classroom teacher from the third study to highlight particular ecosystem elements (keystone species, climate change/ extreme weather) that could be impacted by humans. Another set of revisions focused on scaffolding student interactions with the model interface and code, as initial interviews indicated this was something teachers and students alike found somewhat intimidating to interact with. This was established by adding text instructions next to the buttons (Figure 16b–c) as well as sectioning the code with descriptive headers and in-line notes. The particular data that led to these design changes are elaborated more in Section 3.6, while the rest of this section describes the core functionality of the interface elements (Table 1), info and code tabs, and the general processes involved in running the model from a user perspective[3].



number-plants 37

spacing 3

plant-cost 5.00

budget 500

money 315

units of crop harvested 0

ticks: 33

Figure 16a. Development of the interface of the model; initial interface.

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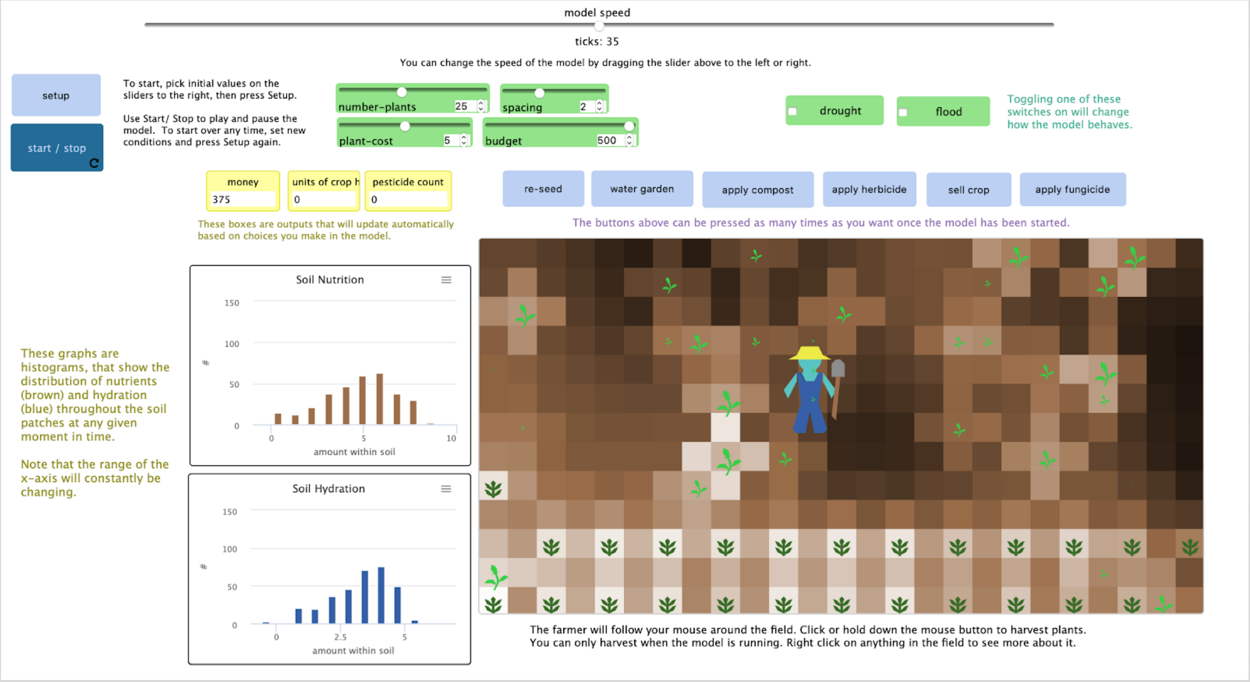
[3] All three versions of the model can be viewed and downloaded through the NetLogo open access Modeling Commons, at http://modelingcommons.org/account/models/2650



ticks: 35

You can change the speed of the model by dragging the slider above to the left or right.

To start, pick initial values on the sliders to the right, then press Setup.

Use Start/ Stop to play and pause the model. To start over any time, set new conditions and press Setup again.

number-plants 25
spacing 2
plant-cost 5
budget 500

Toggling one of these switches on will change how the model behaves.

money 375
units of crop h 0
pesticide count 0

These boxes are outputs that will update automatically based on choices you make in the model.

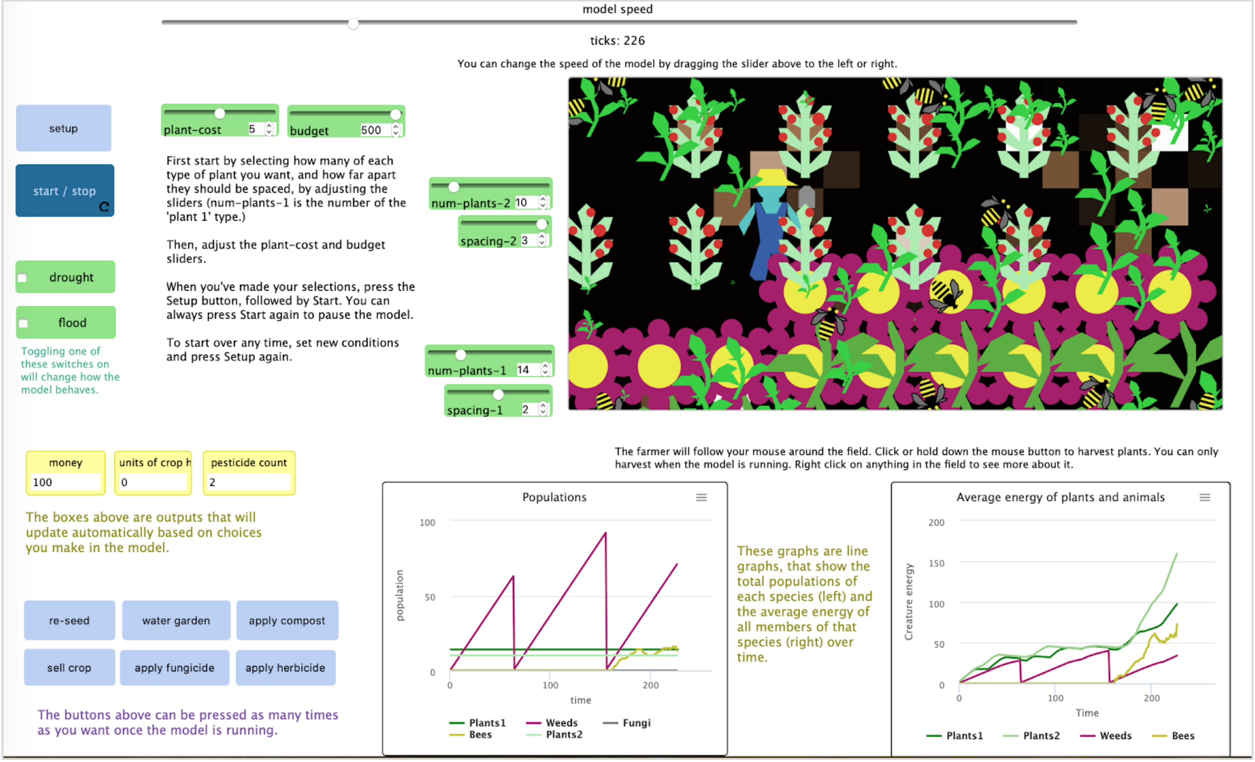
The buttons above can be pressed as many times as you want once the model has been started.

These graphs are histograms, that show the distribution of nutrients (brown) and hydration (blue) throughout the soil patches at any given moment in time.

Note that the range of the x-axis will constantly be changing.

The farmer will follow your mouse around the field. Click or hold down the mouse button to harvest plants. You can only harvest when the model is running. Right click on anything in the field to see more about it.

Figure 16b. Development of the interface of the model; Version 2, with added text explanations.



ticks: 226

You can change the speed of the model by dragging the slider above to the left or right.

plant-cost 5
budget 500

First start by selecting how many of each type of plant you want, and how far apart they should be spaced, by adjusting the sliders (num-plants-1 is the number of the 'plant 1' type.)

Then, adjust the plant-cost and budget sliders.

When you've made your selections, press the Setup button, followed by Start. You can always press Start again to pause the model.

To start over any time, set new conditions and press Setup again.

num-plants-2 10
spacing-2 3
num-plants-1 14
spacing-1 2

Toggling one of these switches on will change how the model behaves.

money 100
units of crop h 0
pesticide count 2

The boxes above are outputs that will update automatically based on choices you make in the model.

The buttons above can be pressed as many times as you want once the model is running.

The farmer will follow your mouse around the field. Click or hold down the mouse button to harvest plants. You can only harvest when the model is running. Right click on anything in the field to see more about it.

These graphs are line graphs, that show the total populations of each species (left) and the average energy of all members of that species (right) over time.

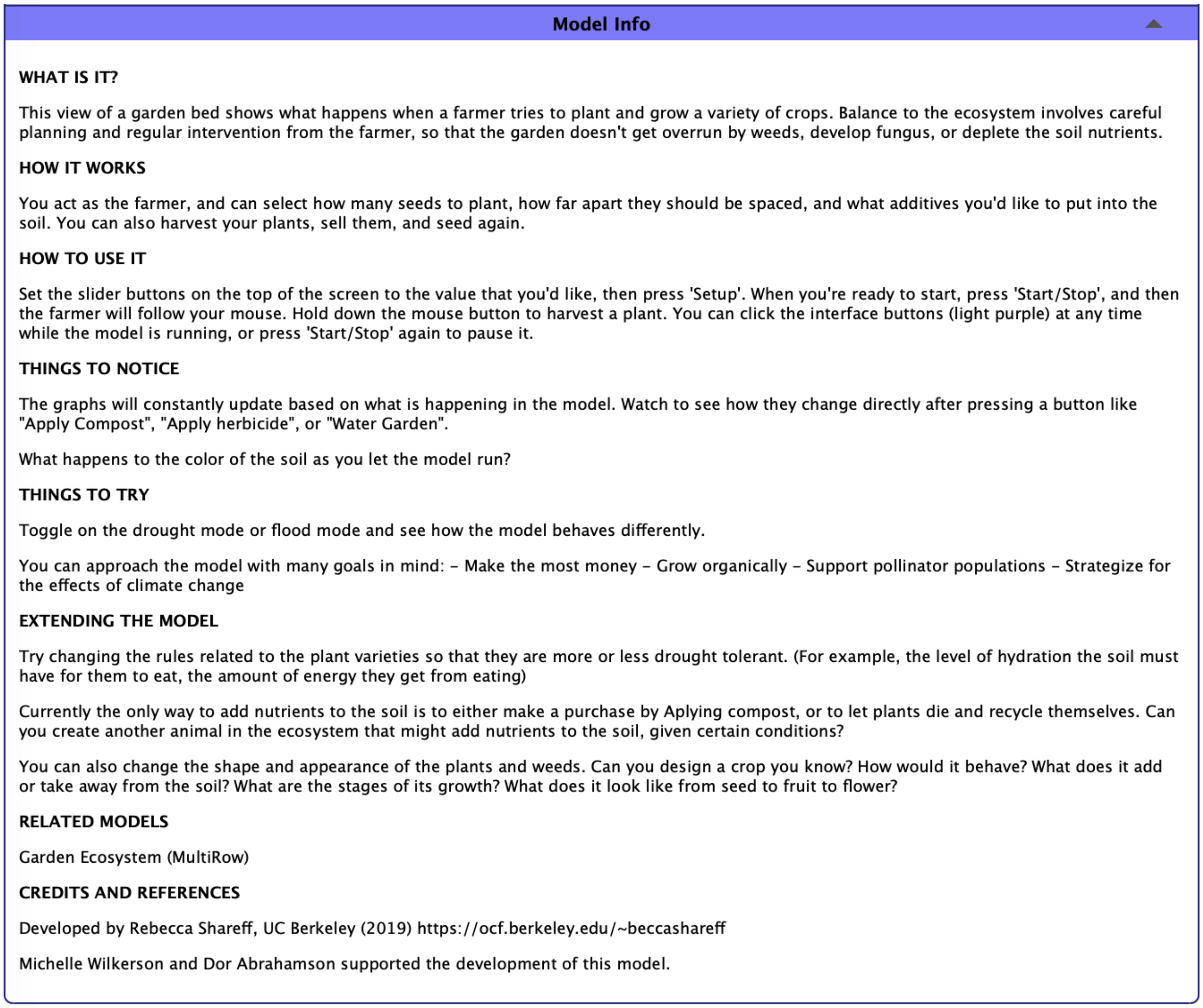
Figure 16c. Development of the interface of the model; Version 3, with 2 crop species.

To populate the model, users set parameters to increase or decrease certain quantities, and provide various inputs into the constantly updating system. The result is a graphic interface of the populations in the model as well as variations in color and size of the components that dictate overall health and vitality of the system. The flexibility in the model lends itself to adaptation by students to reflect the particular sub-system of the environment they decide to examine closer. The table below (Table 1) identifies the main features of the initial design and subsequent versions as well as the way they affect the rest of the components. The foreground of the model contains moveable agents or "breeds", while the background of the model consists of individual squares called "patches" that contain values that can shift and change as the agents operate on them. The primary orientation is the "Interface" of the model, although NetLogo also contains two other display settings: "Info" and "Code" (Figures 17 & 18).

Table 1. Elements in the model, and how they were developed in subsequent iterations

Embodiment / Model Version	Version 1	Versions 2 + 3* (designed concurrently to be used in the same iteration)
Action buttons (light blue/purple boxes): clickable inputs on the interface that run a pre-scripted line of code	● Re-seed (plants new crops) ● Sell crop (convert harvest to $) ● Apply compost (increase soil nutrients) ● Apply herbicide (kill weeds)	● Re-seed ● Sell crop ● Water garden (increase soil hydration) ● Apply compost ● Apply herbicide ● Apply fungicide (kill fungus)
Slider setting bars (green rectangles along top of interface): Parameters that set the initial run of the model	● Number of plants (crops planted) ● Spacing (# of patches between crops) ● Plant cost (price per crop) ● Budget (starting amount of money)	● Number of plants (breeds 1 & 2*) ● Spacing (breeds 1 & 2*) ● Plant cost ● Budget
Breeds + Behavior: Types of 'species' that populate the model and their characteristic behavior	● Farmer (follows mouse, clicks to harvest) ● Crop (viable plants for harvest) ● Weeds (sprout randomly, grow faster)	● Farmer ● Crop 1 ● Crop 2 ● Weeds ● Fungus (grows when wet) ● Bees (appear when flower) ● Water (adds soil hydration)
Plots: Dynamic graphic displays of particular features of the model	● Line graph of populations (weeds vs. crops)	● Histograms of soil hydration and nutrition ● Line graph of populations*: weeds, both crop types, fungus, and bees ● Line graph of average energy of plants and animals*: weeds, both crop types, bees
Output buttons [yellow/white boxes]: Numeric displays of values based on model actions	● Money (ongoing total $ amount) ● Crop harvested (increases with respect to plant size when harvested)	● Money ● Crop harvested ● Pesticide count (# of times herbicide/ fungicide applied)
Additional settings that could be selected on or off while the model is running	(none)	● Drought mode (can't water garden) ● Flood mode (hydration constantly increases)

The Info setting (Figure 17) provides a framework for users to approach the model, a tutorial to the game, and the opportunity to provide set rules and moves. This was not populated in the initial version but was ultimately updated for use in the final classroom study and publishing in the model commons.



WHAT IS IT?

This view of a garden bed shows what happens when a farmer tries to plant and grow a variety of crops. Balance to the ecosystem involves careful planning and regular intervention from the farmer, so that the garden doesn't get overrun by weeds, develop fungus, or deplete the soil nutrients.

HOW IT WORKS

You act as the farmer, and can select how many seeds to plant, how far apart they should be spaced, and what additives you'd like to put into the soil. You can also harvest your plants, sell them, and seed again.

HOW TO USE IT

Set the slider buttons on the top of the screen to the value that you'd like, then press 'Setup'. When you're ready to start, press 'Start/Stop', and then the farmer will follow your mouse. Hold down the mouse button to harvest a plant. You can click the interface buttons (light purple) at any time while the model is running, or press 'Start/Stop' again to pause it.

THINGS TO NOTICE

The graphs will constantly update based on what is happening in the model. Watch to see how they change directly after pressing a button like "Apply Compost", "Apply herbicide", or "Water Garden".

What happens to the color of the soil as you let the model run?

THINGS TO TRY

Toggle on the drought mode or flood mode and see how the model behaves differently.

You can approach the model with many goals in mind: – Make the most money – Grow organically – Support pollinator populations – Strategize for the effects of climate change

EXTENDING THE MODEL

Try changing the rules related to the plant varieties so that they are more or less drought tolerant. (For example, the level of hydration the soil must have for them to eat, the amount of energy they get from eating)

Currently the only way to add nutrients to the soil is to either make a purchase by Aplying compost, or to let plants die and recycle themselves. Can you create another animal in the ecosystem that might add nutrients to the soil, given certain conditions?

You can also change the shape and appearance of the plants and weeds. Can you design a crop you know? How would it behave? What does it add or take away from the soil? What are the stages of its growth? What does it look like from seed to fruit to flower?

RELATED MODELS

Garden Ecosystem (MultiRow)

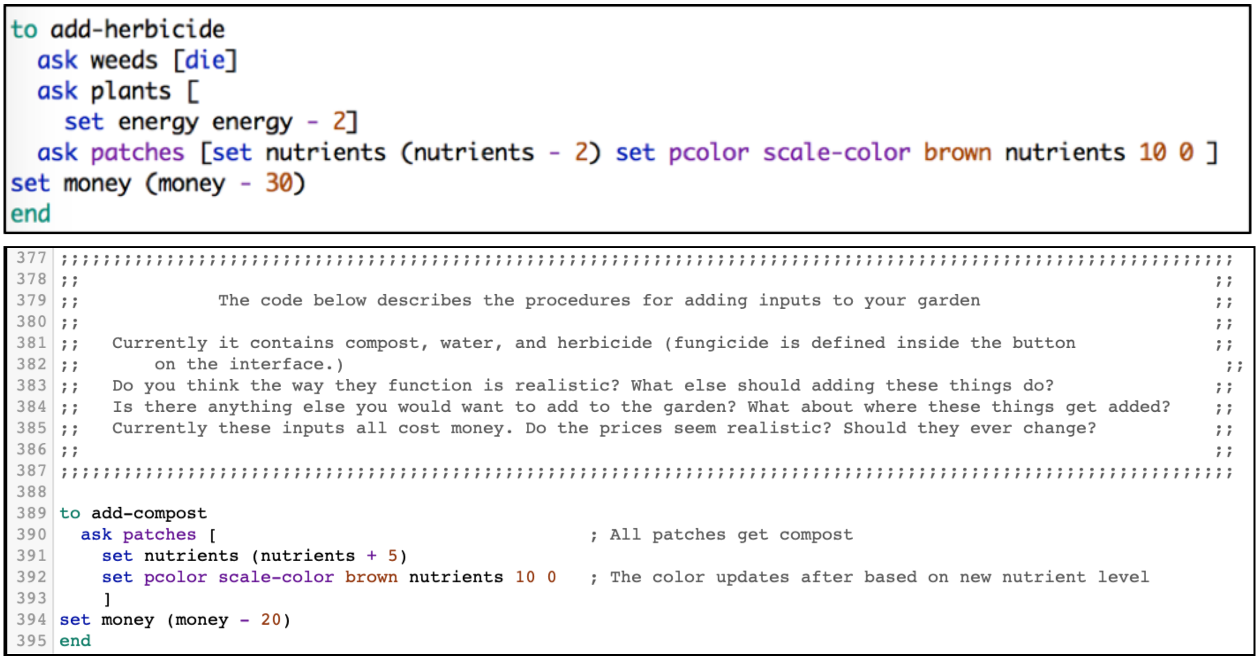
CREDITS AND REFERENCES

Developed by Rebecca Shareff, UC Berkeley (2019) https://ocf.berkeley.edu/~beccashareff

Michelle Wilkerson and Dor Abrahamson supported the development of this model.

Figure 17. Info tab, a description of the model as a reference for users.

The third way to view the model is its skeleton form, the coding that drives its functionality. NetLogo color-codes different syntax for ease in manipulating numbers, agents, and patches; an example of the coding for the functionality of the "Apply Herbicide" button can be seen below (Figure 18). This code is vital to the form, although it is possible as a user to run the model without once looking at the code. Depending on the emphasis of instruction, use of the model can involve manipulation of the code, a practice explicitly involving mathematical and technological competencies by reasoning about the properties, natural randomization, and behaviors of individual elements. At a different scale, to understand the interactions between elements as a feature of the existing system, students could examine the code for numeric relations between the inputs and outputs of the system. After the first classroom pilot, notes were inserted into the code to provide scaffolded support for students to make changes or inferences about relationships.



```
to add-herbicide
  ask weeds [die]
  ask plants [
    set energy energy - 2]
  ask patches [set nutrients (nutrients - 2) set pcolor scale-color brown nutrients 10 0 ]
set money (money - 30)
end
```

```
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;;                                                                                                          ;;
;;              The code below describes the procedures for adding inputs to your garden                    ;;
;;                                                                                                          ;;
;;   Currently it contains compost, water, and herbicide (fungicide is defined inside the button            ;;
;;       on the interface.)                                                                                  ;;
;;   Do you think the way they function is realistic? What else should adding these things do?              ;;
;;   Is there anything else you would want to add to the garden? What about where these things get added?   ;;
;;   Currently these inputs all cost money. Do the prices seem realistic? Should they ever change?          ;;
;;                                                                                                          ;;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;

to add-compost
  ask patches [                                 ; All patches get compost
    set nutrients (nutrients + 5)
    set pcolor scale-color brown nutrients 10 0   ; The color updates after based on new nutrient level
    ]
set money (money - 20)
end
```

Figure 18. The NetLogo code, color-coded by syntax type.

Note. Version 1 (top) had no text scaffolds, while Versions 2 & 3 (bottom) had in-line as well as sections of scaffold text to support inference and tinkering.

3.4.1 Running the model

Once users press “Start/stop", the model starts to populate itself based on the parameters they selected. Crops will appear based on the spacing they selected, and the soil will appear varying shades of brown to depict the nutrient content of each patch. The user moves a farmer with the mouse, and harvests crops and weeds by clicking on the plant they wish to pick. There is a bit of strategy involved in harvesting; harvest too early when the crop is small, and the amount that is harvested will not produce much money. If one waits too long, the crop might turn into a flower or die before it is harvested. The “Crop harvest" display dictates how much has been harvested.

Once they have harvested everything they'd like to, or the remaining plants have died, they can click the “sell crop" button to sell their harvest for the market price (plant-cost, the slider they set) which will increase their money amount. They may then press the “re-seed" button to put new plants in the ground (based on the amount in the “number-plants" slider). However, this process is complicated by the growth of weeds and the variations in the health of the soil. At any time, users may decide to click the Action buttons on their display: these will change the properties of the soil patches (hydration or nutrients), impacting the capacity for plants to grow. The herbicide button also instantly kills the weeds but not the crops in the plot. Pressing these buttons will also decrease the amount of money the user has, to reflect the costs of purchasing fertilizer or compost; while financial components have been included to simulate the process of authentically running a small farm, ultimately money does not inhibit or afford any particular outcome in the model, as one can continue to run all actions in the simulation no matter how much money is available.

Additionally, users can press "Start/stop" to pause the model, and adjust the sliders to new values, and press "set-up" to re-start the model. This allows for opportunities to attempt different settings and view potentially different outcomes of the model. While the specific instructional outcome of using the model varied by iteration, its reflection of a familiar, local ecosystem with which learners could negotiate their situated knowledge against the instrumented knowledge generated by the model, remained central to the study.

3.5 Methods

This study had three iterations that took place over four years (Figure 19). Each iteration involved different methods of data collection, instruments, and analytical approaches; they are described in moderate detail below (and full detail in Appendix B), with the exception of the third iteration, which is described in full detail in the next chapter.

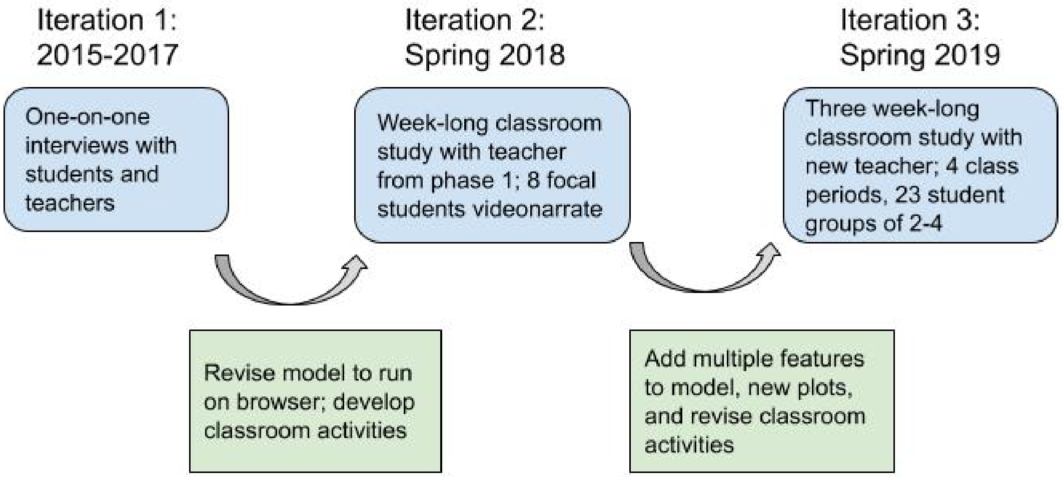


Figure 19. Timeline of data collection periods (blue) and design revisions between iterations (green).

3.5.1 Iteration 1

In the first phase, I consulted with four middle school students and four of their teachers; the sixth graders had received two units of garden instruction with their science class and math class, while the eighth graders had little previous garden instruction. Four teachers at their school who had participated in the garden program in the past year agreed to participate: one 7th/8th grade science teacher, one 6th grade math teacher, one 7th grade humanities teacher (English and social studies) and one 8th grade humanities teacher. Each participant had a roughly 30-minute individual interview to provide feedback on the computer model. a computer program created by the researcher. Participants will be referred to by pseudonyms: Marco and Jorge (8th grade males), Amelia and Catie (6th grade females), Mike (science teacher), Gerry (math teacher), Peter (7th humanities teacher), and Laura (8th humanities teacher).

Participants were asked to employ cognitive think-aloud while they explored the simulation and performed a series of tasks, while responding to questions from the researcher to elicit their reasoning during those tasks (interview protocol in Appendix C). This format was utilized to better understand how people reason with the model, attending to the particular resources that were used, and ones that were requested/ seen as lacking from the tool. After running the simulation, participants were then asked to suggest additional academic applications or design decisions they could foresee implementing with the model. This structure allowed for both reasoning with and evaluation of the model, current practices identified in the Next Generation Science Standards (NGSS Lead States, 2013).

Analyses were conducted using conjecture maps as a framework for categorizing participants' actions and reasoning about the model. Results include a variety of disciplinary applications that were considered by teachers, and a correlation between previous experience with gardens and content-based design suggestions (as opposed to interface-only or content-neutral suggestions). Organizing participants' utilization schema within the conjecture maps revealed particular resources that support learning goals across contexts within the same artifact, providing insight to the design of interdisciplinary instructional tools. I analyzed the curricular connections and contextual resources participants identified when navigating the model, as well as features they proposed to support their own learning, or for teachers, to connect to academic disciplines.

3.5.2 Iteration 2

After uploading the model for use on a browser platform, I conducted a pilot study in February of 2018 with three of Mike's 7th grade science classes. The week-long curricular unit, developed collaboratively, centered on developing student understanding of what computer models are and how they function. The structure for investigating this question included a pre-assessment on computer models and introduction to the research project on the first day, a video on the use of computer models in predicting weather patterns on the second day, and three days investigating the local school garden and garden simulation model, with a post-assessment on computer models at the end of the final day. Students were split into two groups for the duration of the unit, where each group spent 1.5 class periods in the garden or with the model before switching; the science teacher facilitated activities in the garden, while the researcher facilitated activities with the model.

Across the three class periods, eight students participated in the research component; four in one class period, and two each in the two other periods; Mike also consented to participation as a research subject. Students were provided a hand-held camera and told to video narrate their experiences in both settings; for the model, this involved filming the computer screen as they worked. Participating students' worksheets were collected and scanned at the end of the unit. Given the few number of participants, student data were organized in individual cases, connecting their worksheets (where they recorded their initial and final perceptions of a computer model, as well as their notes from each context) to their video data, mapping their journey from the garden to the model and back again.

Analysis primarily centered on how their situated and instrumented knowledge of ecosystem elements were elicited in each activity, and used to support 1) their claim about the impact of one variable on another in the garden ecosystem, and 2) their post-assessment of the purpose/ functionality of computer models. While data were preserved in this case structure, analytical segments were taken with respect to the PIQ framework that emerged in the design study to present potential patterns in activity or thought-process.

3.5.3 Iteration 3

The final round of study took place in April of 2019 in four 9th grade science classes at a public high school in Northern California, with minimal previous garden instruction (full methods reported in Chapter 4). The curricular structure, enacted over three weeks of instruction, was collaboratively designed by the researcher and classroom teacher, who wanted to focus on Human Impacts on Ecosystems, a unit in the CA Living Earth curriculum. Select content standards and science/engineering practices from the NGSS were also used to frame student activities. An early planning session led to major revisions in the garden model to add features that related to this topic.

In this unit, students (n = 101) used the garden and model as evidence sources for designing an action project to protect the garden ecosystem. They initially took observations in their school garden, attending to the biotic and abiotic factors, evidence of human impacts, and began to develop questions for inquiry. Then students explored the model with several guiding prompts and goals to explore its varying conditions and outputs. Following this, the teacher modeled how to develop a testable research question, and students grouped up to develop a question of inquiry for the next phase of the project. Students then specified the evidence they would collect, and gathered it, utilizing the school garden and the model to support investigation of their question. During this time students were encouraged to add and elaborate on the model's code, supplemented with video tutorials from the researcher addressing common questions. Video data was a primary source for this phase: one camera captured lecture instruction and presentation slides from the teacher and researcher for each lesson; 8 research laptops were distributed to different groups of students working with the model that recorded the screen and participant audio/i-sight camera; student groups also took hand-held cameras into the garden to video narrate their evidence gathering, as in Iteration 2.

After gathering evidence, students were instructed to generate a claim about their school garden based on their data. For the last few sessions, students put together a presentation detailing their investigation, using evidence from both the model and the garden, as well as a plan to improve the health of the garden given the outcome of their research. From these activities, the data collected include survey results, all written handouts, copies of presentation slides, html files of student code revisions, video of the classroom, groups in the garden, and screen recordings, as well as audio recordings of participating groups of students as they collaborated on their questions, claims, and evidence.

In the following section, I present how the emergent PIQ framework encompasses the core features of the design enactments that led to revisions of particular program components across iterations (both the model and activity design). The findings are grouped by each element in the framework (Purposeful application, Instrumented + situated negotiation, Quantitative reasoning) to demonstrate the intention of study, and what opportunities were available for the negotiation of these conjectured activities.

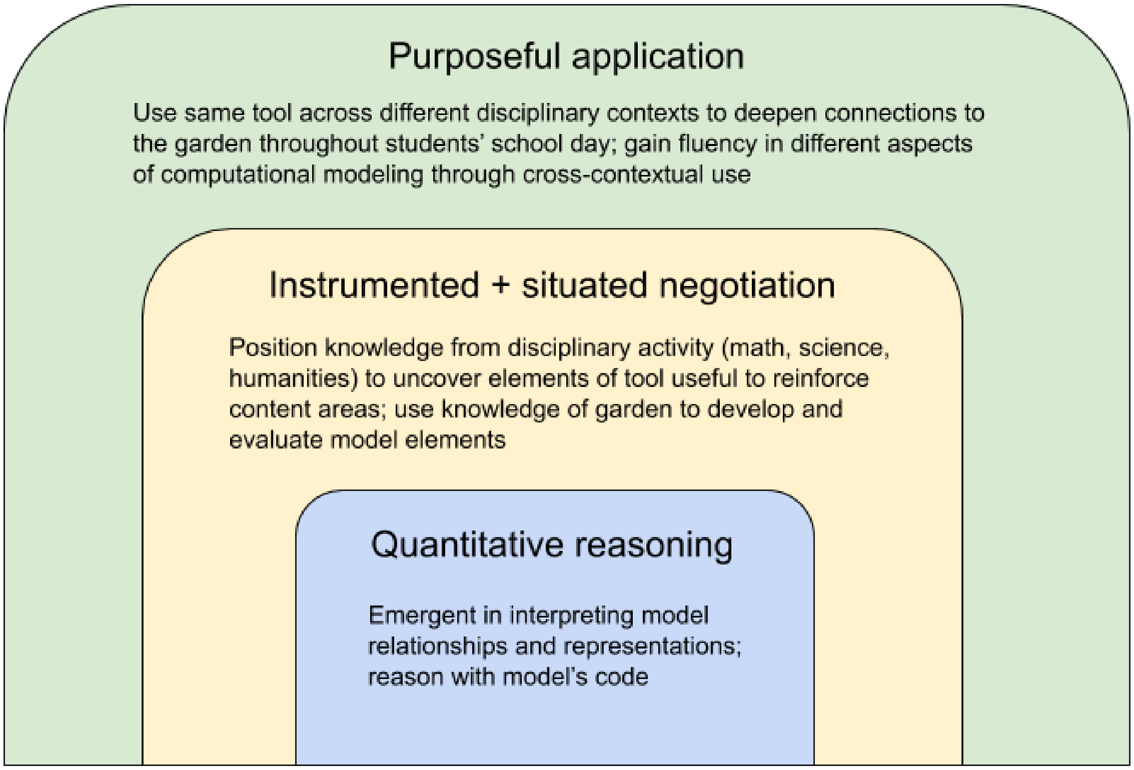
3.6 Findings

Across the three iterations, the purpose and context of the design environment was often facilitated by the desire of the teacher to achieve particular curricular goals. Within this framing, the negotiation of situated and instrumented knowledge are nested, and within the model, the use of quantitative representations (graphs, code) as tools for that negotiation. The findings first show the range of opportunities available for participants in each level of the framework, followed by an integrated example of how a participant navigates all three levels. This framing supports a general design for working with computational models that reference a local space.

3.6.1 Iteration 1

The school district that initially partnered with the researcher sought an expansion of their curricular offerings for use of the school garden at the middle school level. In particular, they had renovated the garden space at one of the district's middle schools and were making a shift from a nutrition-based curriculum to one that incorporated academic content from more subjects, to bring more teacher partners into the garden and increase student participation. The researcher was brought on to collaborate on building lessons that explicitly tied garden activities to new science and math curricular standards (CCSS and NGSS). This led to the proposed design of a computational model as an artifact that could be an interdisciplinary tool used across subject areas to supplement outdoor time in the garden, while developing students' computational practices, a value explicitly written into the NGSS. These factors are represented in the "Purposeful application" section of the diagram below (Figure 20).

Towards this aim, usability interviews were conducted with four students at the middle school (two had received instruction in the garden from their disciplinary teachers, and two had not) to better understand their capabilities for using the model and how they envisioned it relating to their school experiences. Beyond science, many teachers use the school garden as a site of instruction; therefore, a secondary goal was adopted for the next round of interviews with math, science, and humanities teachers: to assess and expand the model's utility as a cross-disciplinary tool. Four teachers (one math, one science, two humanities) were also interviewed to better understand the ways they perceived the simulation could support their teaching and curricular goals.



Use same tool across different disciplinary contexts to deepen connections to the garden throughout students' school day; gain fluency in different aspects of computational modeling through cross-contextual use

Position knowledge from disciplinary activity (math, science, humanities) to uncover elements of tool useful to reinforce content areas; use knowledge of garden to develop and evaluate model elements

Emergent in interpreting model relationships and representations; reason with model's code

Figure 20. PIQ in Iteration 1.

3.6.1.1 Purposeful application

The facilitation of the interviews explicitly prompted reflection on its academic applicability (see Appendix C for interview protocol). Both students and teachers, after spending time reasoning with the model, conjectured about its capabilities for supporting instruction of specific academic content. This involved a synthesis of the disciplinary content that could be embedded within its features, meta-awareness of the cognitive processes users undergo in interacting with the model, or extrapolating to new contexts and scenarios that are analogous to the ecosystem displayed in the model. Generally, teachers responded within their own domain (math, science, or social studies), with the addition of computer science. A partial list of topics elicited from the participants is listed below, followed by quotes from teachers.

- Graphical reasoning
- Linguistic reasoning
- Scientific experimentation
- Ecosystem properties
- Agribusiness/ industrial food systems
- Economics/ cost-benefit analyses
- Math topics (number relations, rates, ratios)
- Problem solving/ strategy development
- NGSS building, using, evaluating models
- Goal setting and execution
- Cause and effect writing
- Demographics/ sociology
- Gardening class/ teaching about planting
- Coding and code-based analysis

> *Gerry (math teacher):* The negative when the money drops down to negative, in a rational numbers unit when kids are learning about negative numbers, when kids are learning about debt.

> *Laura (humanities teacher):* You could do some cause and effect writing, sequencing. Like if you play this game, should you do the compost first, during… emotional, how did it feel, did you get stressed, when things went better than you thought or worse than you thought, getting them to articulate. Sentence starters, 'when my weeds kept growing, I felt…'

Students who had completed a unit of garden-based discipline teaching in science and math (Amelia & Catie) had more expressions of connection to content than those who did not (Marco & Jorge). By design, the tool is conjectured to support possible academic instruction across subject areas; as mentioned previously, the science and mathematical content were seen as the most salient connections by the researcher, and supported by graphs, numerical settings, and ecosystem relationships. Over the course of their interviews, the students and teachers made numerous connections (50 in total) to topics and content that exceeded the expectations of the researcher.

In particular, the span of applications offered by Laura, a humanities teacher, included both depth within her own field (demographics, cause and effect writing, problem solving and goal setting), science-fair type activities within the garden, and peer-coding activities. Peter, the other humanities teacher, along with Jorge, an 8th grader, acknowledged applications to economics, agribusiness, and industrial food systems; in other agricultural settings, these could serve as primary objectives and orientations towards the garden space. Towards this purpose of illuminating and strengthening connections to cross-disciplinary content[4], participants negotiated their situated knowledge of their content domains with the instrumented knowledge generated through using the model, understanding how it worked, and what was possible (Figure 20). A second negotiation of these resources is described below.

3.6.1.2 Instrumented + Situated negotiation

Beyond considering its cross-contextual application, participants utilized their situated knowledge (of gardens, academic content, and the lived realities of students) to make suggestions for how to improve or develop the computational model . This second type of negotiation included critiques about particular actions or design choices of elements, attempts to understand the purpose of actions as a user (like harvesting or applying compost), and supporting decision making around performing certain actions, such as spacing, or herbicide. All participants did this at least once, with students and teachers doing it roughly equally (Table 2).

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[4] The computational model was shown to administrators of a secondary curricular program in rural Honduras, where agriculture is used as a medium for STEM instruction as well as the primary occupation for most students and their families. The instructional opportunities they envisioned with the model were for students to project the associated costs and impacts of fertilizer use (both organic and chemical) on crops, animals, and human health; practice in creating a sustainable system without the need for external implements; a space to try out farming strategies either new or used by their parents; and to model symbiotic plant relationships that students struggle to visualize. These values were also considered when revising the model to maintain instructional utility across school-based agricultural contexts.

Table 2. Counts of evaluating opportunities to change the model tool, by participant

	Students				Teachers			
Participants	A	C	J	M	P	M	G	L
Counts	1	2	2	3	4	3	1	3
Totals	8				11			

Many of the suggestions from students and teachers were to add elements into the model ecosystem that explicitly related to their situated experience with gardens, including more varieties of plants, more compost sources, animals, irrigation, weather, and pollinators. Occasionally the suggestions utilized specific details of the model instrument by incorporating particular actions and behavior structures, such as Catie's vision that a worm would have a pre-defined behavior to create compost, or Laura's preference to click to apply compost in a particular spot.

> *Catie (6th grader):* A worm could come in and just like, (swirls mouse around) they could like, you could apply compost or like a worm could come in and just like… poop out compost, yea.

> *Laura (humanities teacher)*: I would want to put the compost where I want it, it'd be nice if I could click an area, because that's what you would do in real life.

Other suggestions from teachers incorporated their disciplinary domains; for example, Peter considered that there could be multiple goals embedded in the model: a business-owner looking to make money, and a farmer looking to have a healthy tract of land; these purposes also vary across contexts, where a garden might be primarily a source of enjoyment and personal food production, or a source of income. These varying perspectives are ones that might be considered in a social studies/ humanities class, and therefore his suggestion to have an explicit goal or set-up wizard at the beginning of model-use negotiates his situated and instrumented knowledge of how to adapt the model for varied instructional purposes.

> *Peter (humanities teacher):* Couldn't your intro still be the same and the actual tool still be tailored for that, because isn't it, have a successful garden? Then I'm not worried about money, I'm worried about my garden. If I'm studying about the industrial food complex I know I could make a lot of money. This isn't a business model, it's my garden, but if I'm in charge of a company it could be a different intro.

While teachers had slightly more ideas about changing the model, it is important to consider that for the students, there was a distinction between those who had taken garden-based academic units (Amelia, Catie) and those who hadn't, in terms of their suggestions. Amelia and Catie offered ideas for model elements that related explicitly to their situated experience in the garden: Catie's quote about worms, above, and Amelia, who described adding features like planting different crops in rows, and an irrigation system (both were ultimately utilized in the redesign). Marco, conversely, had little connection to gardening, though he offered several points of feedback for the development of the model related to the user experience, in terms of navigation, and interface display. This finding indicates that, while those with more situated experience in gardens offered suggestions for model changes specific to garden ecology, this knowledge is not a precursor for an evaluative engagement with the model; participants could, and did, frequently evaluate other features of the model that did not rely upon their situated knowledge of disciplinary content or gardens.

3.6.1.3 Quantitative reasoning

While student participants and the math teacher were expected to make connections to mathematical content by explicit prompting in the facilitation ("How could this relate to math class?"), an unanticipated event was that as all participants used the model for the first time, they actively reasoned about mathematical relationships they noticed between model elements.

Table 3. Total counts of "Finding mathematical relationships" mediating process by participant

	Students				Teachers			
Participants	A	C	J	M	P	M	G	L
Counts	1	1	1	2	3	3	3	2
Totals	5				11			

As seen above (Table 3), this was much more frequent among teachers than it was among student participants. This could be because of the multi-varied and complex nature of the mathematical relationships; additionally, students might not have had the language (i.e. around 'debt', 'deficit', 'unit') to express the relationships. For example, Mike the science teacher narrated his thought-process while using the model:

> *Mike*: Oh I have to pick them. Where's it going? Oh it's going into this bin right here [crop harvest]. So if I have a negative number in my money, can I still spend it? Can I deficit spend? Sell that crop. Oh those were units of crop! So was that multiplied by the plant cost? Each plant is like a certain amount of biomass and each unit of biomass is worth 3.65.

While the math teacher, Gerry, was not alone in noticing these relationships and articulated his attempt to understand them better, he emphasized that the ability to reason with unit rates, ratios, and negative numbers (such as the deficit spending mentioned above) were valuable features of the model that would reinforce the topics taught in his 6th grade classroom. In his words, however, "The big mathematical thing to me is the graph." The graph included in the first iteration of the model intentionally had no legend, and demonstrated the populations of weeds and crops in the model at any given time. While meant to prompt inference, this lack of information led half of all participants, Gerry included, to misinterpret the graph. Participants who were unable to determine the values of the lines in the graph believed them to be related to their spending, "performance" in the game, or a spatial analogue of the garden plot itself. This then became a somewhat frustrating resource for reasoning, one which both students and teachers suggested needed more support to be utilized successfully in the model (a legend was added for the model redesign).

Another intended opportunity for quantitative reasoning was through investigating the numerical relationships charted in the code. However, only one student was able to successfully conduct this type of reasoning, and many of the teachers expressed that while this was an important academic goal, and the model was a valuable tool in achieving this goal, they anticipated some level of anxiety for their students. All teacher participants discussed the opportunities for their students to code with a bit of reservation about disparities in ability across their students; each also offered a unique suggestion for how instruction with the model could support students in their development.

> *Laura (humanities teacher)*: The digital divide- kids who don't, the way I kind of shut down in the coding, kids who have been exposed to this will, teachers might want to do a pre-survey, who has done some coding and who has no idea, and pair them together.

3.6.1.4 An integrated case during iteration 1

This segment will use data from a particular participant, Mike the science teacher, to indicate how the three components of the design environment (PIQ) are integrated and nested, and also used as points of feedback towards the next iteration. This type of lens could have been applied to many of the participants, though Mike was selected as his classroom was used in the next round of study. Returning to the initial Purposeful application for this round, few participants in this iteration saw the model as an opportunity to connect to explicit activities in the school garden; conversely, Mike thought that the most beneficial application was to use students' situated knowledge of their school garden to help them learn more about computational models. With this approach, he subsequently engaged in negotiation of the models' elements to support this particular tactic for instruction, used in the next round of study.

In suggesting model revisions, Mike considered data displays specific to the scientific elements of the models, such as nutrient distributions throughout the soil patches, and a chart of the biomass as the plants grow. These incorporate both the scientific content (nutrients, biomass) and the output features of the model (graphs, data displays), features valuable for science instruction. Reflecting on the perceived benefit of coding with a computational model, Mike approached the model code as a resource for activities to develop quantitative reasoning within his classroom. In particular, he noticed the rates at which the nutrients deplete from the patch where the plants are situated, and a slightly smaller rate for the adjacent patches, commenting that students could change the numbers to model different systems. He also introduced the idea of coding scaffolds for modeling relationships between plants and nutrients, anticipating that this is a complex step that also mirrors authentic practice in computer science:

> *Mike:* So it'd be interesting when the students start inserting code, maybe if they had some, 'Well I heard somewhere the relationship between nutrients in the soil and plants is a linear equation, and I have an idea of the equation', and to have a snippet of code that they could put in. Because I'm guessing for them like, well two things. For them to come up with the code, themselves, for something that complex would be difficult so to have snippets that they could drop in would be helpful. And then also, if they are going into computer science, the amount of code that's done by stacking different snippets together is sort of nature.

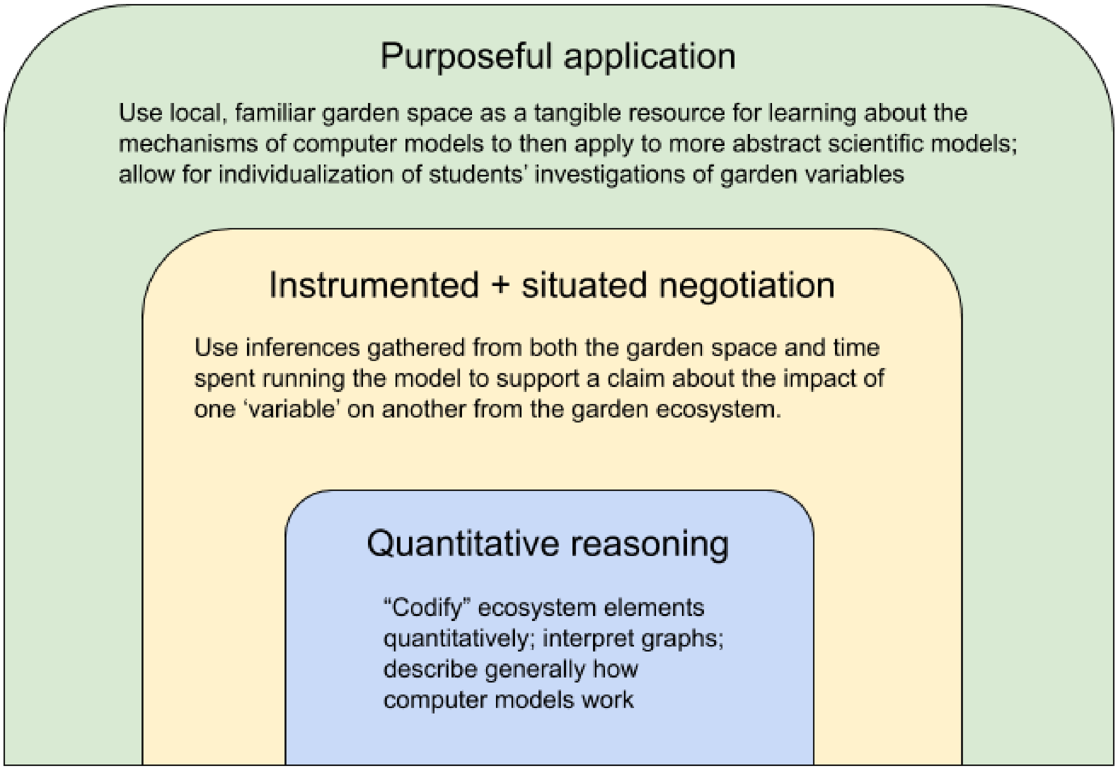
In these examples, Mike's *purposeful application* of the learning environment, using a computational model of a familiar environment to scaffold future knowledge development of using and building computer models, directs his *instrumented + situated negotiation*, where he uses his situated awareness of representations useful to teaching and ecosystem elements to suggest changes in the model; these changes also support his goal to facilitate *quantitative reasoning* within the code in specific ways. These changes were reflected in the classroom activities designed for the second iteration of the study in Mike's classroom.

3.6.2 Iteration 2

For the second design iteration, Mike and I co-designed a weeklong unit within the 7th grade science curriculum on understanding computer models. As indicated in Figure 21 below, the purposeful application changed from the development of a cross-contextual tool to one intentionally designed for a science classroom. Mike's intended purpose for using the model during instruction was to connect to NGSS practices on building and evaluating models, with a familiar context as a reference point:

> *Mike:* Typically students at middle school age haven't been asked to develop the model themself especially if it's mathematical or computational so it totally does that. I can see that the garden gives them something really tangible to work with that they can observe phenomena in nature and then apply them in this model definitely. It can give them some experience for if they were to do some activity like this with something more abstract like a chemical reaction or something, where the physical things of the phenomena are less observable. Having had experience with this would make that easier, definitely.

With these goals in mind, the sequence of activities developed for the unit centered around computer models broadly, how they can simulate the garden environment, and that they are composed by quantifying relationships between variables. For these purposes, Mike did not feel the model needed a redesign, as the existing elements were complex enough to establish the connection to the school garden (with the exception of a change in format to be accessible on a web browser). For this unit, students spent half of their time investigating the school garden for variables that affected plant health and success, and the other half using school laptops to explore the garden model. This sequence of activities reflected a shift in how instrumented + situated negotiation was intended to be enacted; rather than *evaluating the model*, students negotiate these knowledge sources to e*valuate the relationships between elements of the garden* ecosystem. They then generated a causal claim about the impact of one variable on another in the garden, and attempted to quantify those claims to approximate coding language. Investigating the graphs, an activity for students to pseudo-code the claim they generated, and synthesizing to understand computer models broadly, were the anticipated ways quantitative reasoning would be enacted in this iteration.



Purposeful application

Use local, familiar garden space as a tangible resource for learning about the mechanisms of computer models to then apply to more abstract scientific models; allow for individualization of students' investigations of garden variables

Instrumented + situated negotiation

Use inferences gathered from both the garden space and time spent running the model to support a claim about the impact of one 'variable' on another from the garden ecosystem.

Quantitative reasoning

"Codify" ecosystem elements quantitatively; interpret graphs; describe generally how computer models work

Figure 21. PIQ in Iteration 2.

3.6.2.1 Purposeful application

This iteration was intended to help students develop a generalized definition of how computer models function, by using the garden and garden model as a familiar context, and allow students to independently choose a topic from the garden to investigate. Students were asked initially and at the end of the unit to describe their perception of a computer model; all 8 participating students' initial and final model descriptions can be seen in Appendix D. Many folks drew computers for the initial model, not able to distinguish between a computer 'game' and a model; others believed models were direct virtual representations of the visual elements in a specific space. No students listed quantitative relationships in their initial models. While many students were not able to complete both a diagram and paragraph for their final model, those that did draw diagrams overwhelmingly drew things that resembled the computer model (Figure 22). Most used the garden as an example, and variables from the computational garden model to support their explanation of how computer models work and why they are used. While limited, these findings suggest the exercise helped some students generalize about the purpose and functionality of computer models.

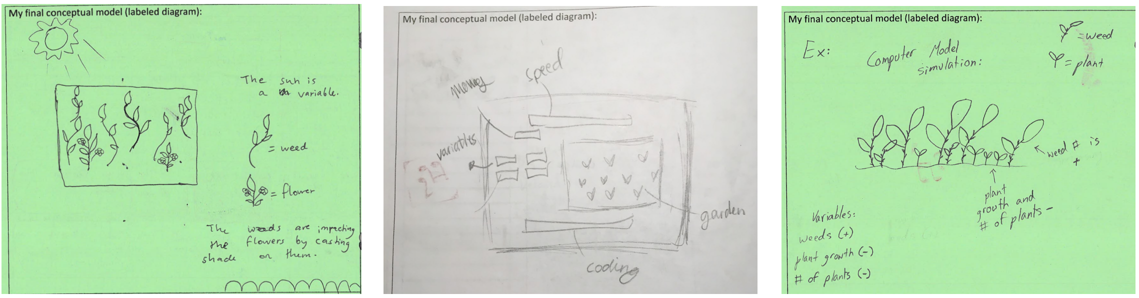


Figure 22. Samples from students' final illustrations of a computer model, resembling the garden model.

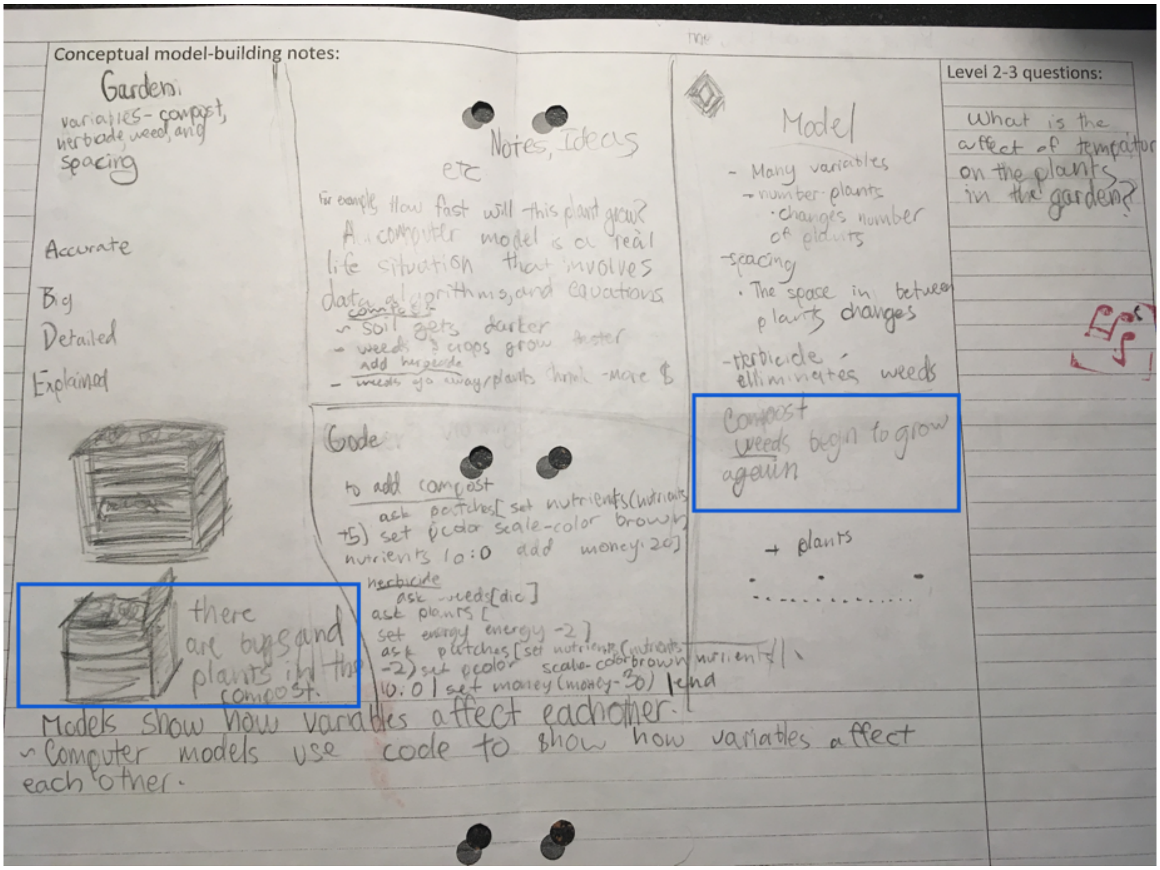
Another intended opportunity for purposeful application during the activity was for students to have agency in selecting different topics to pursue as they explored the garden and the model. However, this range was more limited than anticipated because of the number of available elements in the model. Therefore, most students condensed their investigations to the same few variables that could be observed in both environments (number of plants, number of weeds, spacing, compost). Below, Lola changes her investigation from her time in the garden (Lines 1–3) to her time in the model (Lines 4–6), which did not account for sunlight/shade.

1	Ok. My question is, *[reads from notes]* "What is the effect of sunlight on the number of plants?"
2	My prediction is, "I think plants need sun to grow, and more plants will grow where there's enough sun"
3	So I'm going to be investigating areas with more sun, and areas with less sun, and the amount of plants.
[a day passes, she switches to using the computer model]	
4	Ok here I am, ready to start the garden model *[focuses camera on her computer screen]*. Now, I don't really see my— ok so I have spacing, number of plants, I don't… have… shade, which isn't great.
5	But I have number of plants, I think, I'm going to change my question I think.
6	I'm going to go for spacing to number of plants, because I don't have um, and so, um… [shade]

3.6.2.2 Instrumented + Situated negotiation

While Mike and I conjectured that having the shared garden context would allow students to negotiate insights on the same topic between the physical garden and the virtual one, the mechanistic structure of the computer models seemed to overpower situated knowledge. In the example below, Cassidy draws a picture and description of the bugs in the compost bin (Figure 23a), and in a class discussion acknowledges that compost is created by decomposing old plant parts. These two moments demonstrate her relatively rich situated knowledge of the composition and function of compost in the garden ecosystem. When she explores the model, however, her reasoning about the 'apply compost' button is framed by its correlation with the increase of weeds, which she writes in her notes (Figure 23b).

In her final reflection about the process, she writes, “A garden and its variables can be a computer model. Some of the different variables are compost, herbicide, cost, and energy. If you apply herbicide, the amount of weeds decreases. If you apply compost, it increases.” This illustrates that the setup of the learning environment doesn’t promote coordination of her situated knowledge, that we actively create compost in the garden by recycling plants, and her instrumented knowledge of compost, that it is a catalyst for weed growth. These findings provide evidence that in this context, students can access both situated and instrumented knowledge, but more attention and theorization is needed around coordinating these two sources, both in instructional design and analysis.



Conceptual model-building notes:

Garden:
variables- compost, herbicide, weed, and spacing

Accurate
Big
Detailed
Explained

there are bugs and plants in the compost.

Notes, Ideas etc

For example How fast will this plant grow?
A computer model is a real life situation that involves data, algorithms, and equations
compost
~ soil gets darker
- weeds & crops grow faster
add herbicide
- weeds go away/plants shrink -more $

Code

```
to add compost
  ask patches[ set nutrients(nutrients
+5) set pcolor scale-color brown
nutrients 10:0 add money:20]
herbicide
   ask weeds[die]
ask plants [
set energy energy -2]
ask patches[set nutrients(nutrients
-2) set pcolor scale-color brown nutrients
10:0 | set money (money-30) | end
```

Model
- Many variables
→number plants
·changes number of plants
-spacing
· The space in between plants changes
-herbicide
eliminates weeds

Compost
weeds begin to grow again

→ plants

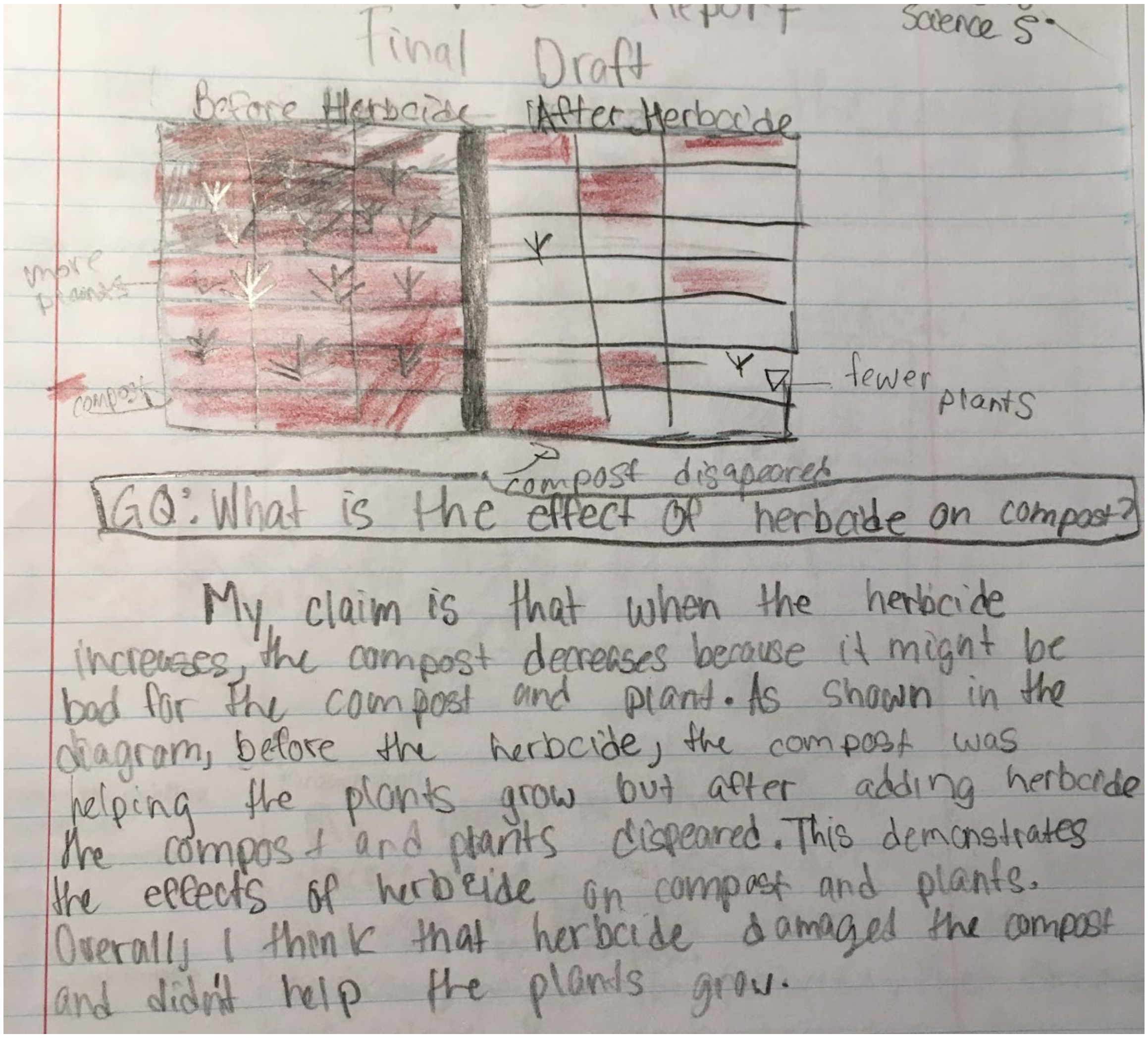
Level 2-3 questions:

What is the affect of tempature on the plants in the garden?

Models show how variables affect eachother.
~Computer models use code to show how variables affect each other.

Figure 23a. (left box) & **b.** (right box); Cassidy’s notes on compost change by context and ultimately are not integrated.

For other students, the instrumented knowledge generated through the model seemed to collapse relationships that are more complex and connected through different means in real life. For example, Diana used the model to describe the impact of herbicide on compost (Figure 24); realistically, the two are discrete entities that a human would choose to apply to the garden to either stifle weed growth or encourage plant growth. Relatedly, they impact different elements of the ecosystem, rather than directly affecting one another (herbicide would kill weeds, lessen nutrients in the soil; compost would increase nutrients in the soil). While Diana appears to utilize limited situated knowledge about compost to support her investigation (“compost was helping the plants grow") this knowledge does not translate into the model as an increase in nutrients (information only available in the code), and therefore she uses the color of the soil in the model, an indicator of nutrient level, to speak of the impact herbicide has on compost.



GQ: What is the effect of herbcide on compost?

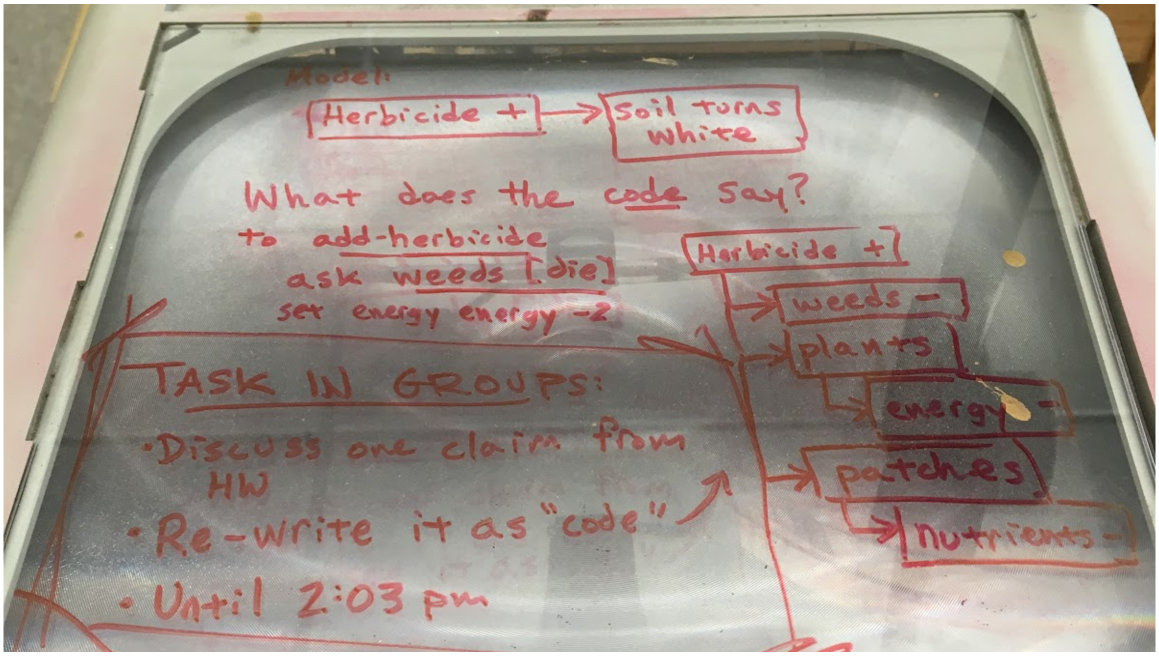
My claim is that when the herbicide increases, the compost decreases because it might be bad for the compost and plant. As shown in the diagram, before the herbcide, the compost was helping the plants grow but after adding herbcide the compost and plants dispeared. This demonstrates the effects of herbcide on compost and plants. Overall, I think that herbcide damaged the compost and didn't help the plands grow.

Figure 24. Diana's argument that herbicide decreases compost, which leaves out the actual impacted variable of soil nutrition.

To better support this negotiation in the next iteration of study, I lengthen the activity sequence and re-design prompts to more explicitly focus on the interaction between knowledge gathered in the model and the garden spaces, and the affordances and limitations of each.

3.6.2.3 Quantitative reasoning

In this iteration, quantitative reasoning was intended to be characterized by students' interpreting the graphs in the model, generating pseudo-code from their claims, and synthesizing all information towards a better understanding of how computer models function. Towards one of these goals, the teacher developed an exercise for students to quantify relationships from the model (Figure 25). For some students, this mapping of numerical relationships between elements in a computer model made its way into their final descriptions of a computer model, though given the number of activities students were responsible for and the limited time they had for this exercise, it was not as prominent of an opportunity for quantitative reasoning as initially intended. While this activity was not included in the next iteration, towards a similar opportunity for quantitative reasoning, the redesign of the model included scaffolds in the code itself to help direct attention to and suggestions for manipulation of the numeric variables in particular lines of code.



Model:

Herbicide + → Soil turns white

What does the code say?

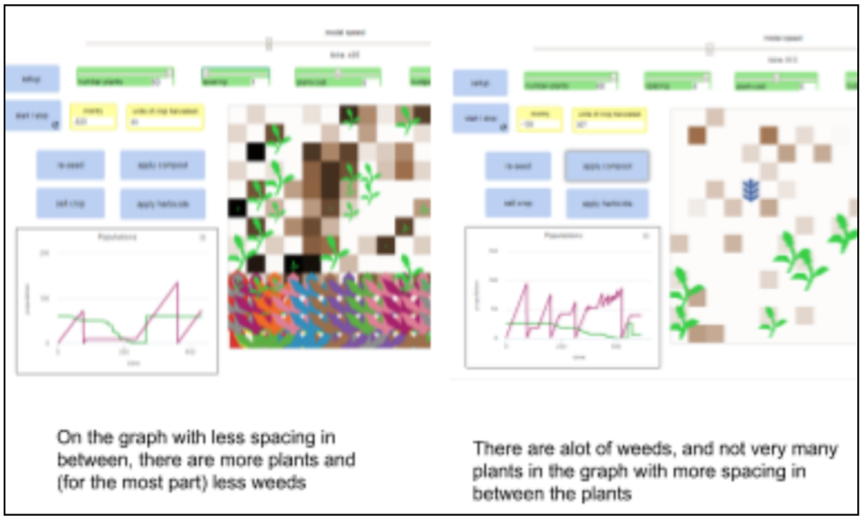
```
to add-herbicide
  ask weeds [die]
  set energy energy -2
```

TASK IN GROUPS:

- Discuss one claim from HW
- Re-write it as "code"
- Until 2:03 pm

Figure 25. Instructions for pseudo-code reasoning activity, which was limited by time constraints.

While the coding exercise may not have been a prominent opportunity for quantitative reasoning, much like in iteration 1, the graph in the model continued to be a major source of evidence for students as they negotiated claims about the relationships between elements in the garden; however, it also led to scientifically unsound reasoning. In the examples below, two students use the graphs to represent causal claims between plant spacing and number of plants (Cassidy) and weeds and number of plants (Lola). While both students correctly attribute the green line to crops and the pink line to weeds, Cassidy invokes the erratic shape of the graph as justification for there being fewer plants in the model. Her excerpt below (Figure 26, in italics), which explains her screenshots of two different runs of the simulation, posits that narrower spacing contributes to more plants, without incorporating her own simulated actions of selecting the number of crops to plant and applying herbicide as factors that impact the graph shape.



On the graph with less spacing in between, there are more plants and (for the most part) less weeds

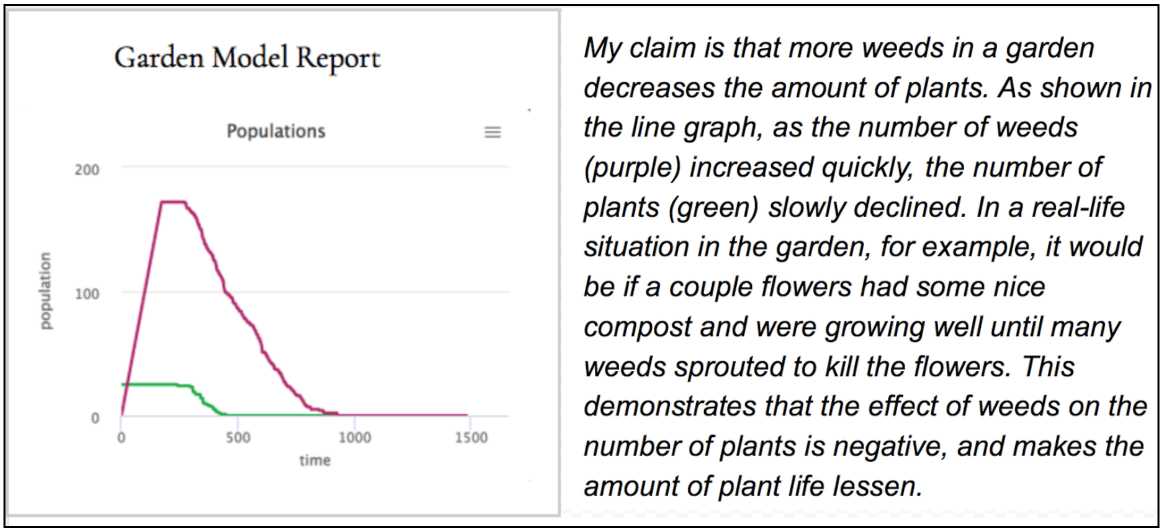
There are alot of weeds, and not very many plants in the graph with more spacing in between the plants

"I found that when the spacing decreases, there are more plants in the garden because they are closer together. As shown in the 1st graph, the green bar goes up higher, signifying that there are more crops when there is less spacing. The second graph shows that there are alot of weeds, and not very many plants. The 1st graph is also more steady, whereas the second graph goes everywhere. These graphs show that if there was less spacing for plants in a real garden, the amount of plants would increase."

Figure 26. Cassidy's claim about the spacing impacting plants, drawing from her inference of the two graphs.

Note. The screenshot on the left shows a model run with a spacing of 1, while the screenshot on the right shows a run with spacing of 4. Spikes before drastic drops in the pink lines (weeds) indicate moments where herbicide was applied and killed off all of the weeds.

Lola also uses the model graph to support her inquiry on the relationship between weeds and crops (which she calls plants) in the garden, claiming that the presence of weeds in the garden decreases the number of plants (Figure 27). Her reasoning includes an interpretation of the population graph's sloped lines to assess the rate of growth and death, stating "as the number of weeds increased quickly, the number of plants slowly declines." Her claim incorporates situated knowledge of a perceived example ("In a real-life situation…") to justify the direction of the claim, and incorporates an additional ecosystem element of compost. She alludes to the knowledge of growth and nutrient availability ("flowers had some nice compost and were growing well"), yet does not quite connect this piece of the situated knowledge to the instrumented knowledge derived with the graph, applying the weeds' purpose as "to kill the flowers" rather than also take advantage of nutritious soil. This segment is illustrative of the rich reasoning strategies at the intersection of the two contexts, and the role of each in her claim. The directional nature of her claim, that "weeds decrease plants," reflects a novice understanding of causal complexity (Grotzer, 2012), as scholars dictate a more nuanced and bi-directional dynamic exists between ecosystem elements; yet what is unclear is whether she is actually bridging the two contexts, rather than reasoning solely about the model when she makes this claim. However, she ends her claim with a nod to the quantitative relationship between model elements, specifying a negative effect.



My claim is that more weeds in a garden decreases the amount of plants. As shown in the line graph, as the number of weeds (purple) increased quickly, the number of plants (green) slowly declined. In a real-life situation in the garden, for example, it would be if a couple flowers had some nice compost and were growing well until many weeds sprouted to kill the flowers. This demonstrates that the effect of weeds on the number of plants is negative, and makes the amount of plant life lessen.

Figure 27. Lola's claim that the increase in weed growth led to the decline of the plants, based on her interpretation of the graph.

3.6.2.4 An integrated case during iteration 2

Lola's work during the unit can help illustrate the interconnectedness of PIQ during this iteration, and the design changes her enactment helped facilitate. As mentioned previously, the attempt to provide a purposeful application of her investigation by allowing her to choose elements she was interested in was not facilitated by the sparse number of elements also present in the model. To better accommodate a diversity of student preferences and opportunities for investigation, the next iteration of the classroom study offered more guidance on the selection of a topic, facilitation in designing a testable question that can be answered within both the model and the garden space, and many new elements added to model to account for more variety in questions/topics (see Table 1 for full list).

To be more aligned in her ability to negotiate her situated and instrumented knowledge, Lola changed her topic to one that could be investigated in the model. However, she foregrounded the instrumented knowledge, in particular through her interpretation of the graph, and used a hypothetical example from her situated knowledge of gardens to justify the claim that the weeds sprouted in order to kill the flowers. For the next round, careful facilitation around the limitations of models, and structured activities that prompt students to indicate the strengths and constraints of each piece of evidence they gather were added towards a more balanced negotiation of situated and instrumented knowledge.

Acknowledging that the graph is an interdisciplinary opportunity to develop quantitative reasoning, as well as a highly utilized resource for creating claims in scientific activities, its presence in the modeling environment is a valuable asset. Yet this version led students like Lola to minimize other factors that affect the relationship between model elements. Therefore, the next iteration included a variety of graphs that concurrently address different elements of the ecosystem changing at any given time; more elements included in each graph; and facilitated activities around the generation and interpretation of graphs.

3.6.3 Iteration 3

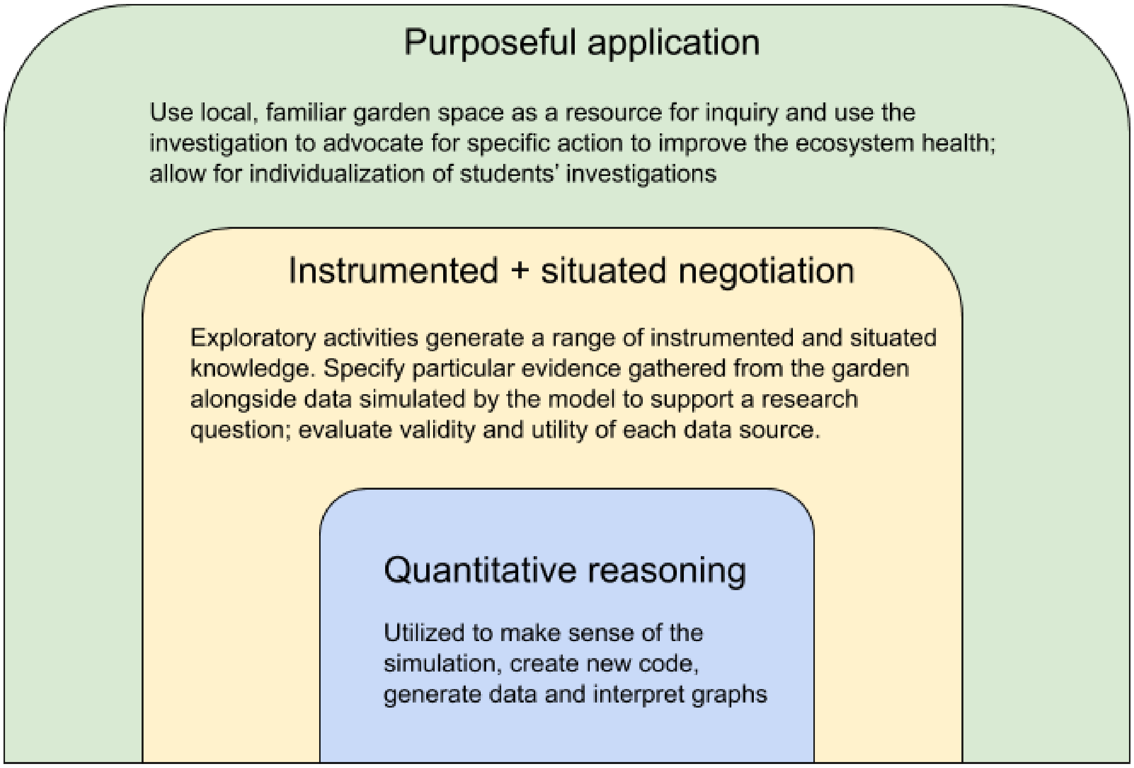
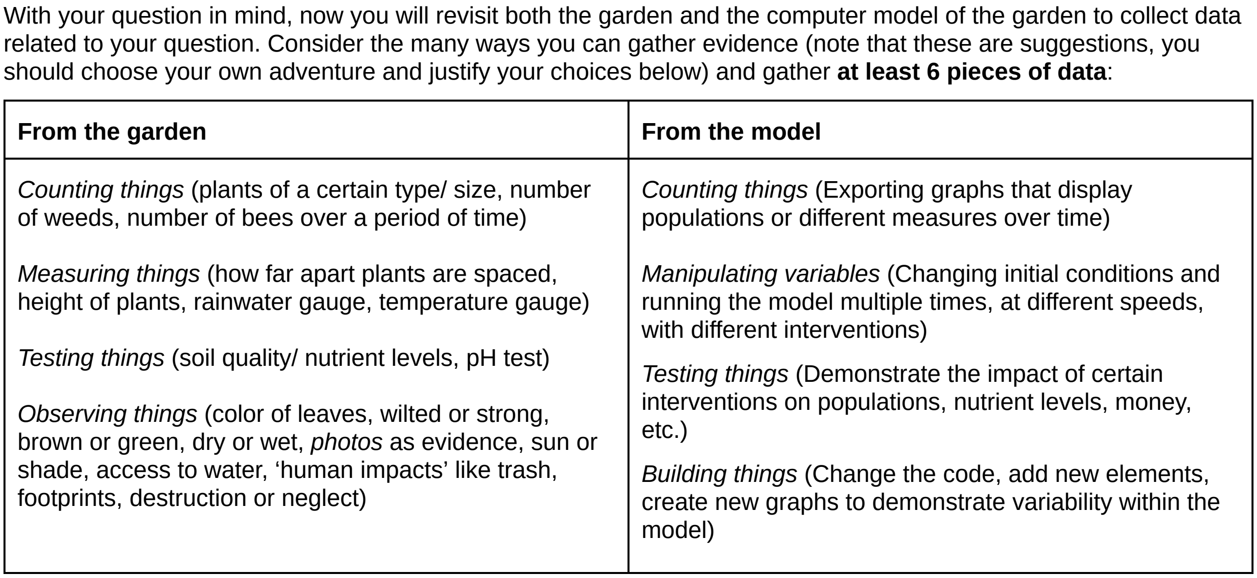


Figure 28. PIQ in Iteration 3.

Taking the findings from the previous design iterations into consideration, major changes in both the model and the activity structure were enacted to maximize all three possible elements of the PIQ framework; these design changes are described here, though a full write-up of the enactment is discussed in the next chapter. Specifically, towards authentically purposeful application of their work (Figure 28), students not only explored their garden, but used their inquiry to propose and advocate for particular actions to improve the health of the garden ecosystem; based on the strength of their arguments and their feasibility, the cooperating teacher intended to enact some of the proposals from each class. Additionally, the re-design of the model led to a much greater diversity of topics for students' inquiry, and even those with the same elements of investigation came up with different action proposals.

To support a nuanced and even negotiation between instrumented and situated knowledge, students were offered a variety of evidence-gathering strategies for each context, and prompted to gather at least three pieces of evidence from each setting (Figure 29). This was conjectured to allow for the generation of multiple kinds of evidence, with the task of selecting the best evidence for their inquiry left up to the students. Towards the beginning of the unit, a brief lecture also emphasized that models are inherently incomplete and based on assumptions; it was conjectured that this might prevent students from favoring the model as an authoritative source of 'correct knowledge' instead of their own observations. An early activity also prompted students to explore many different outcome goals of working with the model: organic farming, highest profit, maximum yield, surviving extreme weather, and supporting keystone species; it was anticipated that these would demonstrate many orientations one could take to use the model for purposeful reasoning.



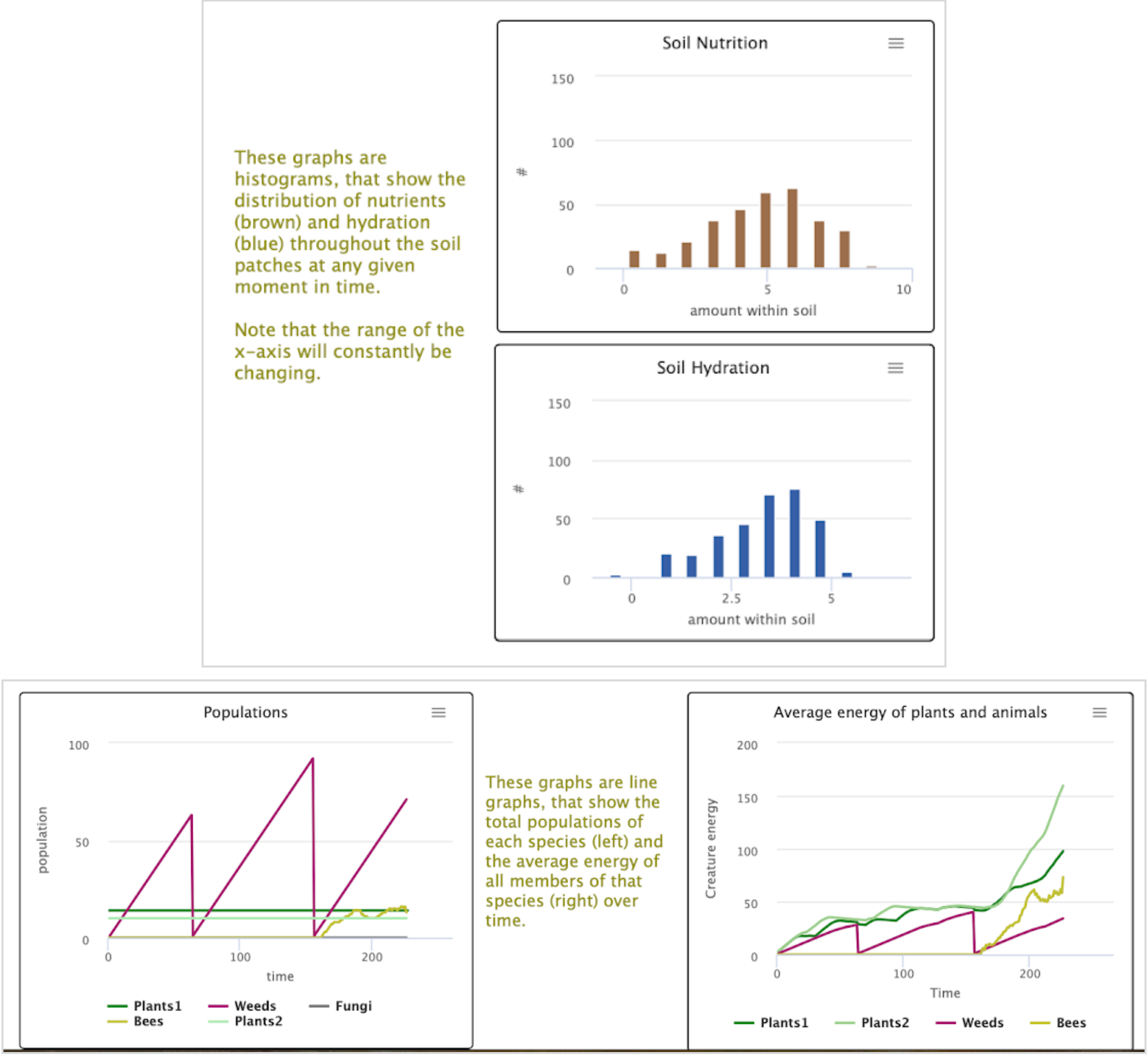
With your question in mind, now you will revisit both the garden and the computer model of the garden to collect data related to your question. Consider the many ways you can gather evidence (note that these are suggestions, you should choose your own adventure and justify your choices below) and gather **at least 6 pieces of data**:

From the garden	**From the model**
Counting things (plants of a certain type/ size, number of weeds, number of bees over a period of time) *Measuring things* (how far apart plants are spaced, height of plants, rainwater gauge, temperature gauge) *Testing things* (soil quality/ nutrient levels, pH test) *Observing things* (color of leaves, wilted or strong, brown or green, dry or wet, *photos* as evidence, sun or shade, access to water, 'human impacts' like trash, footprints, destruction or neglect)	*Counting things* (Exporting graphs that display populations or different measures over time) *Manipulating variables* (Changing initial conditions and running the model multiple times, at different speeds, with different interventions) *Testing things* (Demonstrate the impact of certain interventions on populations, nutrient levels, money, etc.) *Building things* (Change the code, add new elements, create new graphs to demonstrate variability within the model)

Figure 29. Excerpt from student worksheets that helped students plan to collect diverse and expansive types of evidence.

Several design changes were also made to support multiple opportunities for quantitative reasoning. Primarily, scaffolds were added into the code to both help with readability and interpretation, as well as suggest patterns, connections between segments of code, and points where students could manipulate the code (Figure 18). As no student had any previous knowledge of the coding language, these scaffolds were seen as integral, in particular with those who were not skilled or confident in coding. Additionally, once students developed some fluency with the model, they were invited to pose questions for particular changes they wanted to make in the code to support their evidence collection; these led to seven tutorial videos generated by the researcher, so students could have repeated, in-depth access to instruction.

Given the previous iterations where the model graph was both heavily utilized and also often misinterpreted towards students' inquiries, for the third iteration the models were redesigned to increase opportunities and support for reasoning. In particular, new graphs were added to offer data beyond the 'agents' (animals/plant types) to include the soil patches as well, and more scaffolding was provided within and outside of the model. This included reviewing the types of graphs (line vs. histogram) during instruction, text and legends within the model to support interpretation, and in-class activities on generating single and overlapping histograms. Additionally, each version of the model supplied multiple graphs, attempting to minimize reliance on a single source without considering other representations (Figure 30).



These graphs are histograms, that show the distribution of nutrients (brown) and hydration (blue) throughout the soil patches at any given moment in time.

Note that the range of the x-axis will constantly be changing.

These graphs are line graphs, that show the total populations of each species (left) and the average energy of all members of that species (right) over time.

Figure 30. New graphs in updated model interfaces.

Note. Each version of the model contained two graphs, either histograms (top) or line graphs with multiple values (bottom), and supports within the model interface, including labels and text on how to interpret the graphs.

In light of these changes in the model and the activity structure, initial results indicate that student groups took many different paths when creating and using graphs as evidence:

- Generating hand-drawn bar graphs of data from the physical garden
- Utilizing the histograms and line graphs from the same model set-up to represent multiple moments in time
- Exporting the data to generate overlapping histograms so that the distributions over time could be shown in one graph
- Generating quantitative data directly from the model output features (averages, etc.) and graphing these values
- Creating their own quantitative variables not present in the model to help define relationships between their items of inquiry

This reflection on the design space revealed the ways the graphs in the models were consistently utilized in students' meaning-making about the ecosystem, and therefore the design evolved to accommodate an increasingly complex array of quantitative reasoning opportunities. This was facilitated by more scaffolds in both model design and activity. Further work details a more extensive analysis of how quantitative reasoning was relied upon by students in the third study with respect to the ecosystem dynamics that informed their action-plans, and how it emerged through development and manipulation of the model code.

3.7 Retrospective analysis of program design

Over three iterations of design, the framework used to motivate the learning environment of a school garden and accompanying computational model of a garden evolved in a way primarily driven by the school district and teacher's instructional goals (Table 4). While these goals directed the purposeful application of the garden and modeling activities, opportunities for students to develop scientific inquiry unique to their own situated knowledge and personal interests were also highlighted through the evolution of the design. Specifically, this involved increasing the number of elements in the model, along with structured activities for helping students determine a testable research question that they could use both the model and their school gardens to help answer.

While the negotiation of instrumented knowledge from the model and situated knowledge of gardens and disciplinary content was anticipated at all three stages of design, this activity was linked to the purposeful application; while it was a cross-contextual activity in iteration 1, as this became localized to the scientific domain in iterations 2 and 3, students focused on ecosystem elements they could observe in both the garden and model spaces. However, this negotiation did not necessarily appear on its own; in the shift from iteration 2 to iteration 3, more structured activities were added to first explore the parameters of each environment so that students could have a wider set of available knowledge about both the relationships in the garden and the possible outcomes of running the model many ways. Additional activity prompts helped students gather a diverse array of evidence and also explicitly evaluate the validity and purpose for each piece of evidence that they gathered from both the garden and model context.

To support this type of evaluation, explicit attention was given to how the model produced and encouraged dynamic graphs. As one of the clear foci of quantitative reasoning present in the model environment, and a more familiar/ potentially easy resource to evaluate than the code, the evolution of the graph designs expanded to involve more model elements and incorporate scaffolds to support proper interpretation. By iteration 3, students were encouraged to change the model's code as means to address all elements in the PIQ framework: as an additional resource to further their investigations, to indicate that models are fallible and malleable, and facilitate deep quantitative reasoning.

I argue that for any learning environment where a computational model is used to motivate study of a local space, the elements of the PIQ be considered as valuable design principles to guide purposeful investigation of the physical space; encourage a thoughtful negotiation of knowledge sources; and incorporate agentive opportunities for students to grow in their quantitative reasoning and motivate their individual inquiry paths. The evolutions in design continued to improve both the model and the garden, as students were able to expand on the model in a variety of ways to support their own investigations, which then led back to opportunities to support the health and vitality of their school garden ecosystem.

Table 4. How the manifestation of the PIQ framework evolved over the design iterations

Framework Element/ Iteration	1 (indiv. interviews)	2 (7th grade science)	3 (9th grade science)
Purposeful application	Cross-contextual instructional tool; increase modeling opportunities	Provide scaffold for more abstract models; individualization of inquiry	Individualization of inquiry with action proposal to improve garden ecosystem
Instrumented + situated negotiation	Content/disciplinary knowledge informs evaluation of the model	Time in garden and with model used to develop claim about relationship between ecosystem elements	Increase available knowledge resources with exploratory activities; evidence-gathering strategies and evaluation of evidence as negotiation tools
Quantitative Reasoning	Connect to math practices, interpret graph, reason with code	Codify student claims, interpret graph, synthesize about computer models	Coding scaffolds and tutorial videos for active code building; export data and generate graphs; interpret multiple graph styles

3.8 Implications for design

I return to the research questions to offer generalized design recommendations:

1) *Which features of the comprehensive learning environment optimize students' opportunities to critically juxtapose knowledge from the physical and simulated gardens?*

2) *How does the iterative development of activity design support theoretical development on mediated artifact use in situated scientific inquiry?*

Towards question 1, I argue that initially coherence between the representational form and the situated environment was a constraint in that it minimized students' ability to utilize situated knowledge (Lola changing her question to ignore the role of sun/shade) and alone was not enough to promote negotiation (Cassidy's disconnected knowledge of compost). Therefore I recommend that structured activities to both elicit knowledge and compare affordances and constraints of the two environments be implemented before students pick a topic for inquiry, as was done in iteration 3. These activities also should include an overview of the incompleteness of models, and how a model of an ecosystem could still be used for reasoning even if it does not initially include a variable under investigation. To further refine this negotiation, the scaffolds for quantitative reasoning allowed students to then edit the model to implement their situated conjectures about elements that were initially not present in the model, affording a more advanced negotiation of these knowledge sources. For this to be possible, scaffold in the coding and access to instructional resources about how to code with the model were essential. I also argue that including a variety of graphs with multiple elements supported negotiation of situated knowledge in that students had to determine which graph / data best supported their inquiry, rather than a single graph that only showed relationships between two elements (crops and weeds), which constrained reasoning to just those elements of the ecosystem.

Towards question 2, I posit that the framework's emphasis on the situated knowledge and purposeful application afforded by a local complex environment were not only valuable in scaffolding understanding of the computational model, but expanded the possibilities for personal and meaningful adoption of the instrumented knowledge generated through work with the model. Bi-directionality was a pivotal theme in this study, where gardening practices, traditions, and familial knowledge served as resources to understand, evaluate, and evolve the computational model; additionally, the computational thinking and model-based reasoning developed with the tool were applied to strategizing and tending for the garden environment in return. By incorporating a context that is familiar to students from experiences outside of class, repeatedly accessible during school, and rich with biodiversity, modeling a complex system became infused with learning that is both personally meaningful and scientifically rich. While not an experimental study, I conjecture that these affordances decreased some social barriers to coding and modeling to students that were less familiar with the practice, as they had other contextual resources to reinforce their investigations. Using and adapting models as a tool in ecological activism afforded not only authentic scientific practice, but also repositioned students as promoters of knowledge rather than recipients of instruction ("learn how this tool works").

Utilizing PIQ in this context helped elaborate the nested and integrated interactions that drive the co-development of instructional and tool-based decisions in design-based research programs. In this case, the instrumented knowledge was offered through a computational model, though this could be extrapolated to any type of instrument used in instruction to help facilitate new knowledge. One of the implications of this retrospective analysis is identifying the ways that the purposeful application of a sequence of design-based activities can set the tone for what is possible within the interactions. As this sequence evolved, the space for the work to be purposeful for students, not just from the teacher's perspective, took more shape and helped shift the embodiments of the design environment to best support their goals and resources.

3.9 Discussion

This sequence of studies examines the type of learning afforded in a unique educational context that is distinct from its epistemological predecessors in outdoor science education, and separate from the nutrition-focused research often conducted in school gardens (Hazzard et al., 2011). In examining the interaction of situated garden knowledge and instrumented knowledge with a computational model, I address the stated need to better understand how contextual factors support the learning of complex systems in science education (Yoon et al., 2018), and expand the applications of agent-based modeling beyond content and computational knowledge, to that of an applied practice, a skill practiced by computational biologists.

This study shed light on the more general question of how contextual knowledge can be used as a resource in scientific reasoning, which has implications for equity, community participation, and curriculum design in formal science education. The juxtaposition of knowledge frames explored in this study invite variation and adaptation in the inquiry styles utilized in science learning. Navigating multiple epistemologies has been studied within urban and rural Native American students (Bang & Medin, 2010), as students incorporate and selectively apply scientific traditions from groups they may ascribe to across time. Descriptive analyses of the learning environment, tangible materials, and framing of student knowledge in these studies are valuable not just for theories of learning, but also in modeling how students incorporate communal scientific traditions alongside western science practices. To solve large-scale environmental concerns, learning opportunities that incorporate students' lived experiences in their local communities, and allow them to then shape the instruments used to promote knowledge, hold promise for meaningful, equitable, science education.

4. Contextualizing evidence from physical environments and agent-based models towards environmental solutions

4.1 An in-depth examination of evidence use within the PIQ framework

Two connected practices that students are regularly tasked with in science class are generating evidence, and using computer models in scientific inquiry. When these practices support epistemic agency and non-deterministic outcomes, more can be understood about students' reasoning with and values of the technological instruments that support their process. This study investigates how 9th grade students utilize evidence collected from their school gardens, as well as generated through a computer model of a garden ecosystem, in a project to design an ecological intervention for the garden. As the third iteration of a design-based research approach, the garden model and supporting curriculum were specifically crafted to enable students' to investigate and report on their school garden, by collecting in-person evidence as well as simulate data from the model.

In this study, a computational model and supporting curriculum were designed to enable 9th grade students to conduct investigations using in-person and simulated data about their school garden. Over three weeks of instruction, 24 student groups' (n=101) conversations, written work, and computer activity were recorded as they investigated ecological relationships and proposed solutions to improve garden health. Instrumental Genesis was used to theorize how the model and the data it generated were leveraged alongside data collected from the garden towards students' scientific claims. Though the curriculum was designed to support balanced integration of evidence sources, students' evidentiary usage was widely diverse: Eleven student groups contextualized the evidence from both the physical and virtual garden, with other groups privileging the model evidence (8), the garden evidence (3), or an outside data source (2). In-depth vignettes from four groups explore how students' experimental designs, perceptions of model utility, and attention to limitations impacted their prioritization of evidence. Findings suggest students hold complex epistemological stances when working with different forms of scientific evidence, which should be attended to when teaching about computational models.

4.2 Introduction

Current curricular reforms, both in the US (National Research Council, 2012; NGSS Lead States, 2013) and internationally (Mostafa et al., 2018), seek to support students in developing *scientific practices* as opposed to merely content knowledge (Duschl, 2008; Linn et al., 2016). Most educators agree that this increased focus on practices offers students more *epistemic agency*—that is, it can position students to contribute and evaluate scientific knowledge for themselves, rather than simply receive it from books or authority figures (Berland et al., 2015). However, to become epistemic agents students must be allowed to develop their own epistemological stances to a diversity of evidentiary sources and ways of doing science (Bang, 2015; Miller et al. 2018).

This paper investigates students' stances toward two epistemologically complex evidence sources—a computational model of a garden ecosystem (Shareff, 2018) and a familiar school garden. Working within this context, practices associated with scientific modeling and the use of data and evidence[5] are deeply interconnected. Models, including computational models, are based upon and validated by empirical data. But computational models also generate their own simulated data, which can in turn also be used as evidence and inform further experimentation. The approaches students take towards models and data are often shaped by context (Wilkerson & Polman, 2020). In particular, the (1) Role of students in data collection; (2) Relevance of data to students' lives; and (3) Ways data interface with technology (generated/ simulated) have been shown to impact how students think about data as evidence in science class—making the intersection of local, physical, and digital ripe for study.

Letting students collect their own data (Hug & McNeill, 2008), especially from familiar local contexts (Manz, 2016), can increase agency, though this may come with tradeoffs in terms of measurement error or pre-conceptions about phenomenon. However, while it is increasingly common that students engage with computational models in science classrooms (de Jong, Lazonder, Pedaste, & Zacharia, 2018), they are rarely granted similar opportunities to explore how these tools generate data, and to what degree that data is valid and representative of the natural world. One approach that might improve students' opportunities to develop epistemic agency is to offer inquiry-based exercises (e.g. Wagh, Cook-Whitt, & Wilensky, 2015), where a provided model is used in pursuit of student-generated questions and ideas. Another approach includes having transparent and malleable computational modeling tools, so models themselves can be crafted based on student ideas, rather than coming from an invisible authority (Clariana & Strobel, 2008). However, these approaches still fall short of allowing students to directly contest a given computational model's perspective of the world by deciding for themselves how, when, and for what purpose the model should be used. In this study, I use theories of Instrumental Genesis (Verillon & Rabardel, 1995), nested within an activity theoretic framework (see Chapter 2), to examine how students leverage a computational model alongside and in service of a physical school garden. My driving hypothesis is that open-ended investigations that utilize these multiple evidentiary sources can extend students' worldview beyond that of the technology (Oliveira et al., 2019), as they attend to the ways in which different evidentiary sources may (or may not) inform the improvement of a local ecosystem.

4.3 Literature review

The review contains three sections that motivate why it is important to focus on students' use of computational models (henceforth, "models") as a window into the development of epistemological stances toward modeling more generally. My central argument is this: it is well-established in the literature that exploring students' use of data as evidence provides insights into their epistemological stances. However, this focus on how students approach data is rarely explored within the context of

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[5] Throughout this paper, 'data' refers to raw measurements, quantitative outputs, or qualitative observations; 'evidence' constitutes the application of select data towards a particular argument or outcome.

computational modeling activities. Given that computational modeling curricula typically involve (a) the production of simulated data and (b) explicitly student-driven inquiry components, this context is especially well-suited for the study of students' developing epistemological stances toward models and simulated data as sources of evidence during inquiry.

4.3.1 Data as evidence in science instruction

Using scientific evidence is a complex practice that entails selecting data from a larger set, manipulating or inscribing that data to demonstrate patterns, and communicating how those patterns relate to established scientific theories and explanations (Duschl, 2000; Manz, 2016). Since scientists’ and students’ investigative contexts are quite distinct, students develop different ideas about evidence than practicing scientists. Students tend to see data as factual, rather than a evidentiary resource (McNeill & Berland, 2016). This is particularly likely when a classroom investigation is pre-determined to generate specific data (Duschl, 2008). Students also have trouble distinguishing between systematically collected data, beliefs, and experiences (Hug & McNeill, 2008). To expect students to see patterns in data, or to connect those data to causal claims, they need experience designing and conducting investigations; practicing scientists rely on these skills, as well as extensive content knowledge, to engage in this practice. Without this experience, students often attempt to replicate evidence-based claims by grounding claims as living ‘within’ data, for example, stating that a claim ‘is shown’ by a graph (Sandoval & Milwood, 2005).

To ease these challenges and support student agency, researchers suggest adjusting the (1) framing; (2) complexity; and (3) social nature of data used in classroom investigations to emphasize data as an evidentiary resource. Hardy and colleagues (2020), for instance, suggest reframing data collection as data *production* to emphasize its expansive, value-laden, and theoretical nature. McNeill & Berland (2016) suggest data should be *transformable* to prevent students from seeing raw data alone as the answer. Instead, they argue, students should filter, manipulate, and evaluate data for patterns that can be linked to their hypotheses. Working with multiple types of data, such as in Kerlin et al. (2010) where students combined a more simplified data source (geology textbook) with a complex one (USGS data), was found to lead to more nuanced and deeper understandings of how data can serve as evidence.

To emphasize the social nature of data, researchers suggest collecting and working with data related to empirical phenomena situated in the real world (McNeill & Berland, 2016), and establishing scientific activity systems where students can critique and question data and claims (Manz, 2015). As students develop routines for collecting data themselves, they develop a better understanding of the source of data, as well as its limitations or errors (Lehrer & Schauble, 2004). Understanding the social histories of data, including the connection between data and the materials/technologies that generate them, can help students consider whether a given dataset provides sufficient evidence for claims (Hardy et al., 2020; Manz, 2016). However, this attention to social history of data cannot be limited to only the datasets that students construct (Wilkerson & Laina, 2018). Indeed, Hug & McNeill (2008) found that students who used both first-hand and second-hand data tended to be more open to critiquing the data they collected themselves, and viewed the second-hand data (also collected by students) as authoritative.

4.3.2 Computational models in science class

While computer simulation models are used by practitioners in many scientific fields, and increasingly in the social sciences (Epstein, 2007; Macy & Willer, 2002), their role in science education is important and unique. In the classroom, students typically use pre-populated models and simulations to study a known topic, whereas scientists often build models to seek solutions to unanswered questions about the modeled phenomena (Seoane et al., 2018). This distinction has prompted scholars to call for shifts in teaching practices to include model construction (Gobert et al., 2011; Wilensky & Reisman, 2006), and research to include more focus on the methodological and epistemological approaches to models in classroom instruction (Gravel & Wilkerson, 2017; Greca et al., 2014; Seoane et al., 2018; Wilkerson et al., 2018b).

Historically, computer modeling tools have been used in science instruction in two ways: simulated experimentation, and model-based learning. The type of instruction used can impact how students perceive models, and can lead to a variety of perspectives on model trustworthiness. As Greca et al. (2014) review, *simulated experiments* allow educators to minimize the costs, time, and complexity of guided inquiry as students can manipulate variables and quickly observe and analyze results. Exploring simulations enables students to engage in ways that can feel like a game, increase their motivation, and increase conceptual understanding (Plass & Schwartz, 2014). However, if students use pre-populated models, they tend to assign authority to the information within the model (Seoane et al., 2018). Conversely, other studies indicate that situated experience with a local space can impact the perceived trustworthiness of a model of that space. For example, in a study of participatory mapping of coastal waterways (Cravens & Ardoin, 2016), while scientists and staffers viewed the large-scale model as an authoritative data source, individuals who knew specific details about rocks and kelp in the area, which were not represented in the map, became concerned about the data legitimacy, and the entire planning process.

Given these challenges to epistemic agency, we focus on *model-based learning,* which involves having students (de)construct a computational model to understand how relevant components, behaviors, and interactions in a system are theorized, how those theorizations can be computationally expressed, and to validate and refine those theories and expressions for increased empirical power (Greca et al., 2014; Louca & Zacharia, 2012; Wilkerson-Jerde, Gravel, & Macrander, 2015). Model-based learning tends to follow a cycle of building, testing, evaluating, and revising models by comparing the model to empirical observations and data (Xiang & Passmore, 2015). Giere et al. (2005) present a snapshot of the stages in model building and assessment (Figure 31), incorporating predictions, observations, and hypothesis building. Distinct from experimentation with simulations used *to understand* a phenomenon, model-based learning emphasizes an iterative procedure that determines the validity of the model *as a representation* of the phenomenon (Seoane et al., 2018).

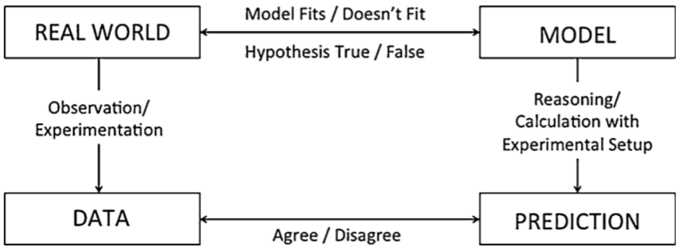

Figure 31: The model-building process represented as a cycle between the real world and the model, with iterations of predictions and empirical data validations.

Note. From Giere et al. (2005)

The process above mirrors authentic scientific practice and supports epistemic agency, as the underlying theories, equations, and parameters of a model are constantly evaluated. Scholars advocate that explicit framing and instruction around the theoretical or hypothetical foundations of models (Louca & Zacharia, 2012), followed by opportunities to empirically validate models with real world data (Greca et al., 2014; Plass & Schwartz, 2014; Seone et al., 2018), are integral in helping students to avoid making ungrounded assumptions about models' experimental validity (Develaki, 2019).

4.3.3 Contesting the use of models as evidence sources for scientific investigations

There is still a need, then, to understand how students evaluate a model's validity as a representation and as a source of evidence during scientific inquiry. In this study, I address this need by positioning students to contest not just the model's validity as a representation, but whether and how it gets used as an evidence source. To afford students' contextual power in evaluating the model as a resource to support an investigation of a local environment, I utilize place-based dynamic modelling (Clariana & Strobel, 2008) to scaffold their interactions through situated and embodied activities in the environment being modeled. Using this approach while investigating real-world problems in outdoor environments such as school gardens has enabled students to develop multi-level reasoning of the complex ecosystem behaviors being modeled (Dickes et al., 2016), and develop sophisticated modeling practices (Pierson et al., 2017); though in these cases, the use of a model itself to support reasoning about that space was not contested by students. Other scholars (Grotzer et al., 2015; Kamarainen et al., 2015) have supported students in comparing experimentation strategies from physical and simulated versions of the same space through technologically-augmented outdoor environments. While these environments do enable students to select and determine the validity of a variety of evidence sources, the simulations are pre-programmed, so students are not granted full agency in determining the mechanisms through which the simulated environments can produce evidence to begin with.

Like Wagh, Cook-Whitt, & Wilensky (2015), this study encourages students to build and revise model code to support their own inquiry topics. The collaborative process of doing so enables a visualization of the multiple approaches and theoretical assumptions taken to represent a single scientific idea (Brady et al., 2015). Yet what has not been fully explored, and this study aims to do, is investigate the epistemological stances towards modeling that students develop when they are: (1) modeling a familiar local space; (2) scaffolding model knowledge through embodied activity; (3) building and revising the models to further their inquiry; (4) generating evidence from the model; and (5) contesting the model's validity as a source of evidence.

4.4 Theoretical framework

Instrumental genesis (Verillon & Rabardel, 1995) has been used to examine how students engage with and apply digital tools— such as dynamic geometry applications or computational simulations— towards specific pedagogical or epistemic goals. In Chapter 3, I introduced the PIQ (Purposeful application, Instrumented + situated negotiation, and Quantitative reasoning) framework to elaborate how a digital tool designed to emulate a local space mediates the activity system within which it is embedded. PIQ situates instrumental genesis within particular phases of activity including when users: first elevate their knowledge about the system being modeled (garden), learn to use the instrument (model), generate data from the model, and leverage that data as situated evidence to determine a solution for the garden (Figure 32).

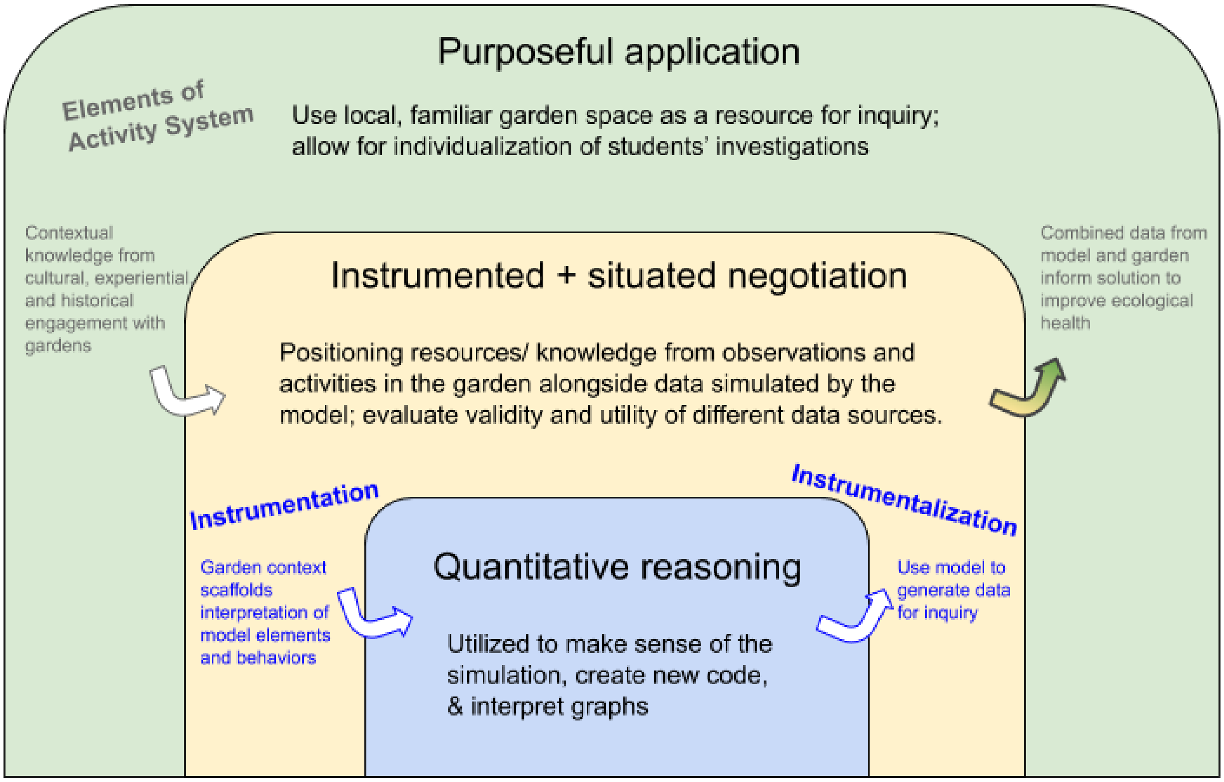

Figure 32: PIQ interfaces Instrumental genesis within an Activity system.

Note. The shaded arrow indicates the focal component reviewed within this study, as students negotiate evidence from the garden and the model to apply toward an environmental solution within the garden.

In this study I focus specifically on the second half of this practice, where instrumentalization generates data which then interfaces with additional evidence sources, including the physical garden, students' knowledge of garden practices, and resources from the internet. While the majority of the designed lesson went as expected, considerable variety emerged as students worked to decide which evidence would be used to support their final project claims and ecological solutions. To better assess the diversity of reasoning that occurred at this stage, and consider its relationship to diverse model epistemologies, the research questions for this study are:

1. In what ways do students select and apply evidence collected during an investigation about the garden towards a scientific claim and ecological solution?
2. How is the model, in its representation of the garden and production of simulated data, viewed as an instrument?

4.5 Methods

4.5.1 Participants

The study took place in April 2019 in four ninth-grade science classes taught by the same teacher at a public high school in a Northern California suburb. Demographically 38% of students at the school are minorities, and 1% are economically disadvantaged. 101/116 students and the classroom teacher consented to participate in this study. The class had completed a previous unit that used the garden as a site for evidence collection, and participating students had received an average of 2.5 years of previous garden-based education (based on self-reported survey data).

4.5.2 Activity design

Gardens are an accessible ecosystem for relating to science content and students' everyday lives (Upadhyay et al., 2017), that afford embodied activity to increase engagement (Kervinen et al., 2020), and scaffold into modeling practices (Dickes et al., 2016; Pierson et al., 2017). The use of the school garden in this study follows a sustained tradition of using local outdoor spaces as a site for communal problem solving and inquiry, as situating action locally facilitates participants in observing and measuring the direct outcomes of their actions (Ardoin et al., 2020); I provide a detailed description of this design decision in Chapter 3.

The curricular materials used in this research were collaboratively designed by the researcher and participating classroom teacher to support the teaching of *Human Impacts on Ecosystems*, a unit in the CA Living Earth curriculum. Specifically, the unit incorporated content standards evaluating the impacts of humans on ecosystems through claims, evidence and reasoning, revising simulations, and modeling the relationships between ecosystem components, as well as most of the Science and

Engineering Practices from the Next Generation Science Standards (Lead States, 2013)[6]. Activities were enacted over three weeks of instruction. Each week consisted of one 45-minute session and two 90-minute sessions. Table 5 below features a daily overview of the activity sequence and participant data collected.

Table 5. Overview of activity and data collected

Week 1	Day	1 (45 min)	2 (90 min)	3 (90 min)
	Activity	Intro to unit, survey. Classroom activity to elicit prior knowledge of garden and human impacts on ecosystems	Observations in garden to evoke situated knowledge for inquiry topics, develop initial RQ	Intro to model, demo and multiple goal-driven model activities to develop instrumented knowledge
	Data	Survey responses Worksheet packet Video (class)	Worksheet packet Audio recording (class)	Worksheet packet Video (class) Screen recordings (indiv.) NetLogo program code
Week 2	Day	4 (45 min)	5 (90 min)	6 (90 min)
	Activity	Refine RQ in groups, define evidence to be generated from garden and model	Generate evidence from garden	Generate evidence from model
	Data	Worksheet packet Video (class) Audio recordings (groups) Evidence collection form	Worksheet packet Video (groups)	Worksheet packet Video (class) Screen recordings (indiv.) NetLogo program code
Week 3	Day	7 (45 min)	8 (90 min)	9 (90 min)
	Activity	Evaluate evidence, generate claim & begin to plan presentation	Finalize presentations; Present findings	Present findings
	Data	Worksheet packet Video (class) Audio recordings (groups)	Video (groups) Presentation slides (groups)	Video (groups) Presentation slides (groups)

4.5.3 Activity sequence

The first week focused on exploring ecosystem interactions in both the situated (garden) and instrumented (computer model) contexts. Participating students took a survey and had a short lecture about the unit project to propose a design to improve the health of their school garden. They were also given a worksheet packet (**Appendix E**) that was meant to serve as a research journal throughout the unit. The following day, students conducted initial observations in their school garden, attending to

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[6] Specific content standards included HS-ESS3-4; HS-LS2-6; HS-ETS1-3; HS-LS4-6; HS-ESS3-6; HS-LS2-2.

biotic/abiotic factors and evidence of human impacts, and began to record individual research questions on their project worksheets. Finally, students had a lecture on scientific modeling and agent-based models taught by the researcher, and were introduced to the NetLogo (Wilensky, 1999) computer model they would use for their project (Ch. 3 Figure 16b–c). They individually used the model to complete a variety of goals, like increasing profit, growing organically, supporting the bee population, surviving severe weather, and maximizing crop yield, and completed a class-wide activity designed to help them interpret the histograms generated by the model. At the start of the next week, the teacher led an activity on developing a testable research question. Students organized into groups of three to four to evaluate each other's questions, and select a single question as a group that could be answered with evidence from the computer model and the garden. Each group listed evidence they would gather from the school garden and the model to support their investigation in their worksheet packet. During the rest of the week, they used soil testing kits, measuring tape, and their phone cameras to gather evidence from the school garden, and used the NetLogo computer model to collect simulated evidence. Students were encouraged to modify the model's code, and were given video tutorials for common programming questions (how to add an element, track a new variable, etc.).

During the third week, students were instructed to generate a claim about the school garden based on their research question and evidence. Then they evaluated solutions to improve the health of the garden based on their claim. They put together a presentation detailing their investigation, presenting evidence from both the model and the garden, and advocating their proposal to improve the health of the garden as the outcome of their research. This activity sequence was designed to elicit movement through particular layers of the PIQ framework, as illustrated in Table 6.

Table 6. Activity design: Relationship between activity structure and PIQ framework

Day/ activity	2. Observe garden	3. Observe model	4. Generate RQ / evidence plan	5. Collect garden evidence	6. Collect model evidence	7. Evaluate evidence and craft claim	8. Compile findings and present
Movement between layers of the PIQ framework	Ground in purpose, elicit situated knowledge (P→I)	Use situated knowledge to help learn about model (I→Q)	With sense of possibilities from model/garden, re-connect to purpose of class activity (Q →I→P)	Use garden as a resource for evidence, frame thinking about what other evidence is needed (P → I)	Use model as resource for evidence towards research question (Q → I)	Negotiate evidence sources and design argument for scientific claim & solution (I → P)	Select key evidence and present claim & justification for solution (I → P)

4.5.4 Data collection

Table 5 details the data collection methods used to capture the range of individual and group activity across classroom, garden, and computer contexts. In terms of *external artifacts* collected, the project worksheet packet was the main instructional artifact during the unit, with different segments for students to fill out during each day of activity. Participating students were also asked to save a copy of their NetLogo program code for the research records if they changed the model code for their investigation, though many did not successfully save their changed codes. Students' final presentations were video recorded and their slides were obtained as research materials. Some participating students also elected to create short feedback videos detailing the parts of the project that surprised them, were pleasing to them, and challenged them after their final presentation. The pre-survey administered on Day 1 asked students to self-report years of previous experience with both gardening and computer programming, and other details about these experiences.

To capture *in situ* activity, lecture instruction and presentation slides from the teacher and researcher for each lesson were video recorded, and an audio recording captured the instructional activity on Day 2 in the garden. Participating groups of students were audio recorded as they collaborated on their questions, claims, and evidence on Days 4 and 7. Randomly selected participating groups were provided laptops equipped to capture screen activity and student audio/video through embedded webcams during Days 3 and 6.

4.5.5 Data preparation

All paper files were scanned, and audio/ video files were saved to an encrypted hard drive. Data including worksheets, presentations, and video/audio files were organized by student work groups. Audio recordings were transcribed. All names were changed to pseudonyms to protect participants' identities.

4.5.6 Data analysis

My primary analytic focus was on how students selected and applied evidence during the inquiry task (RQ1), and what their work revealed about their stance towards the model as a source of data (RQ2). I began by conducting a preliminary review of final presentations, in which students provided a claim, selected evidence from their investigation, and advocated for a particular solution based on that claim. This review led me to identify four emergent categories describing how students leveraged different sources of evidence to warrant their claims: (1) *claim based on garden evidence;* (2) *claim based on model evidence,* (3) *claim incorporates both evidence sources,* (4) *claim relies on evidence beyond model or garden*. Given that final presentations did not always reflect the full scope of students' work, I then conducted a follow-up analysis of student groups' use of evidence at five stages of the inquiry process: (1) research question selection and evidence plan (Day 4); (2) garden evidence collection (Day 5); (3) model evidence collection (Day 6); (4) presentation preparation (Days 7-8); and (5) claim generation (Days 7-8; see **Appendix F** for all groups' analysis). The specific applications and model manipulations during evidence generation were also categorized and quantified to illustrate the diverse ways the model was utilized across the groups. After this analysis, all groups were sorted into one of the four categories, outlined above, which were renamed in shorthand as (1) *Garden > Model* (G>M); (2) *Model > Garden* (M>G); (3) *Model = Garden* (M=G); (4) *Other data > Model* (X>M; in this category, the other data was only ever used instead of model data, alongside garden data).

Next, to gain further insight into the specific negotiations between situated and instrumented knowledge that led students to rely on the evidence they did, I identified four cases (one group from each category) for deeper analyses. These cases were selected based on the availability of multiple data sources, and to illustrate the complexities in evidence use. To support data selection for these cases, I developed a coding system based on the PIQ framework (**Appendix G**) to identify segments of student talk that demonstrated movement across the three layers, and particularly components of model and garden activity that shape student reasoning on what to use as evidence.

This coding enabled me to select transcripts of student discussion when students evaluated the generation and incorporation of data from both the garden and the model (with the exception of the case from category 4, where transcript data were not available). This included Day 4 where they decided which evidence to collect, and Day 7 when they determined their claim and selected evidence to use in their presentations. I reviewed these moments specifically because they were likely to contain student conversations about how they valued different forms of evidence and found them useful for the project. The transcripts were supplemented with data from the worksheet packets, presentations, and computer videos when available.

4.6 Findings

Towards addressing parts of both RQ1 and RQ2, I first sought to broadly understand the ways the model was instrumentalized during the research process. I examined students' worksheets and final presentations, categorizing the ways they used the model to generate evidence for their work into eight types of action (Table 7). The two most frequent instrumentalizations of the model, used by over half of the student groups, came from altering a segment of code using a tutorial video, and changing a variable on the interface and running the model multiple times. Most student groups made edits to the model code to engage in evidence collection; while many students utilized coding tutorial videos to make changes (most frequently to add a new soil property, or make a new creature), others made novel code changes to remove plant types from the model. Groups varied in how many of the above actions they integrated in their model-evidence generation. The relative frequencies were: 0 actions (1 group); 1(1); 2(12); 3(8), 4(1); 5 (1), indicating that the majority of groups completed 2-3 different categories of actions. This shows that the majority of students were able to see multiple utilities of the model as an evidence collection tool, which was supported by the lecture demonstration and worksheet packet.

Table 7. Range of instrumentalization: What was done with the model?

Model actions	Example of type of changes (#)		Groups (#)
Change code using tutorial video (add/change creature behavior, add / change soil additive behavior, add new environmental condition)	Nitrogen (5) Plant behavior (5) pH (3) Worms (3) Phosphorous	Potassium Shade Slugs More nutritious compost	14
Change 1 or more variable, let run multiple times, compare outputs	Compost/ water (2) Drought/ flood (2) Worms/ no worms (2) Compost/ herbicide Organic/ pesticides Spacing	Nutritious compost vs. regular Weeds / no weeds # of plants Plants with different behaviors Nitrogen / no nitrogen	13
Add implement every X ticks, track output variables	Compost (2) Water Herbicide	Compost & water Compost, water, & weeding	8
Change code without video example (novel)	No weeds (4) No plants		5
Focus on relationship between emergent model element (e.g. bees) & other output variable	Weeds (2) Bees	Fungus Slugs	4
Cost-benefit analysis of solution options	Used $ output in model to show savings from running with compost or with fertilizer		4
Find ideal conditions needed for particular outcome	For worms to thrive For fungus to emerge		2
No intervention, just description of current model patterns / relationships	*The bigger the plant grows, the more nutrition it takes from the soil.*		2

To better understand factors influencing the balance of evidence and ultimate instrumentalization of the model, I focused on different stages of the activity where students' external artifacts reflected either a balanced or imbalanced negotiation of the garden and model realms, defined with respect to each activity stage below. On Day 4, students must utilize their initial understandings of what both the model and garden consist of to devise a research question that enables an investigation of each environment. The evidence collection on Days 5 and 6 set students up to negotiate their evidence from both sources, and Days 7 and 8 involve synthesis of evidence to produce a claim, and selecting the best evidence to warrant that claim and advocate for their ecological solution. Based on these phases of activity, an analysis of all groups' data was used to determine where negotiation of the model and garden contexts happened during (1) RQ selection, (2) garden evidence collection, (3) model evidence collection, (4) presentation preparation, and (5) claim generation. A full table of the data used to determine these results is in Appendix F, and a summary of the results are presented below in Table 8.

Table 8. Range of contextualization: At what phases of the project were students' data contextualized?

	RQ fits both contexts	Garden data relates to RQ	Model data relates to RQ	Model data builds off garden data	Pres. incorporates model + garden data	Model data in pres relates to claim	Garden data in pres. relates to claim	Claim integrates model + garden data
n of groups /24	21	23	23	19	22	19	18	13
% of groups	88	96	96	79	92	79	75	54

Nearly all (88%) groups started off on track to leverage the model and garden evidence, by having a research question that was a good fit for both contexts. The other 12% either had a question that solely spoke to what the model was capable of (drought / flood over time) or the garden (which soil type is better between these three beds). While some of these groups creatively programmed the model to better fit their question, the group with the model-driven question ultimately did not utilize garden evidence towards answering their question.

For most groups, the evidence that they *collected* was related to their research question (96% of both garden and model evidence), indicating contextualization was not as challenging at this stage (students were able to think about, collect, and record data that related to their questions). However, fewer groups were able to connect the evidence sources together at this stage, with only 79% of groups approaching the collection of evidence from the model in a way that built off of their garden evidence. By this I mean they considered their garden evidence and tried to collect evidence that either shed light on the same phenomenon, or triangulated their findings with more supporting knowledge, as opposed to approaching model evidence collection without a clear idea of how it would connect to their garden evidence; this determination was made based on their answers to the guiding questions on their worksheets on Days 4 and 5.

Another point in the process where students had to contextualize their evidence sources was in the creation of a claim, and then selecting evidence to provide in their presentation that supported their claim. While most groups followed the task to put model and garden evidence into the presentation (92%), only some of the evidence they used (79% of model and 75% of garden evidence) directly related to the claim they formulated to make sense of their evidence. Beyond providing evidence that related to the claim, the phrasing of the claim itself did not always incorporate both evidence sources (only in 54% of groups). This indicates that for 46% of students, the claim was founded on either the model evidence, the garden evidence, or another evidence source. This finding could indicate many things: students may have felt some evidence was more convincing than others; one context may have seemed more important than the other; students didn't know how to make sense of some evidence; or other reasons.

To visualize the findings from Table 8, a flow diagram (Figure 33) shows the analysis of groups' contextualization of model and garden realms throughout the inquiry process. Read from left to right, it provides a visual of the number of groups that were successful at contextualizing the model and garden realms at each phase (indicated by the purple area) by tracking each group's evidence use. Grey areas indicate unsuccessful contextualization for that stage. The green vertical bars indicate an activity that involved contextualizing the garden, while orange bars indicate contextualization of the model, and purple bars involved both realms. In many cases, groups unsuccessful in one stage were able to re-contextualize their evidence later in the project, either by changing their question, changing the computer model, or with careful wording of their claim; this is shown in the figure by orange or green curves rejoining the purple areas. After reviewing these data, groups were coded into the four categories based on their treatment of evidence, shown by the four different colored blocks on the far right of the figure, with the number of groups in each category in parenthesis, or in percentages in Table 9.

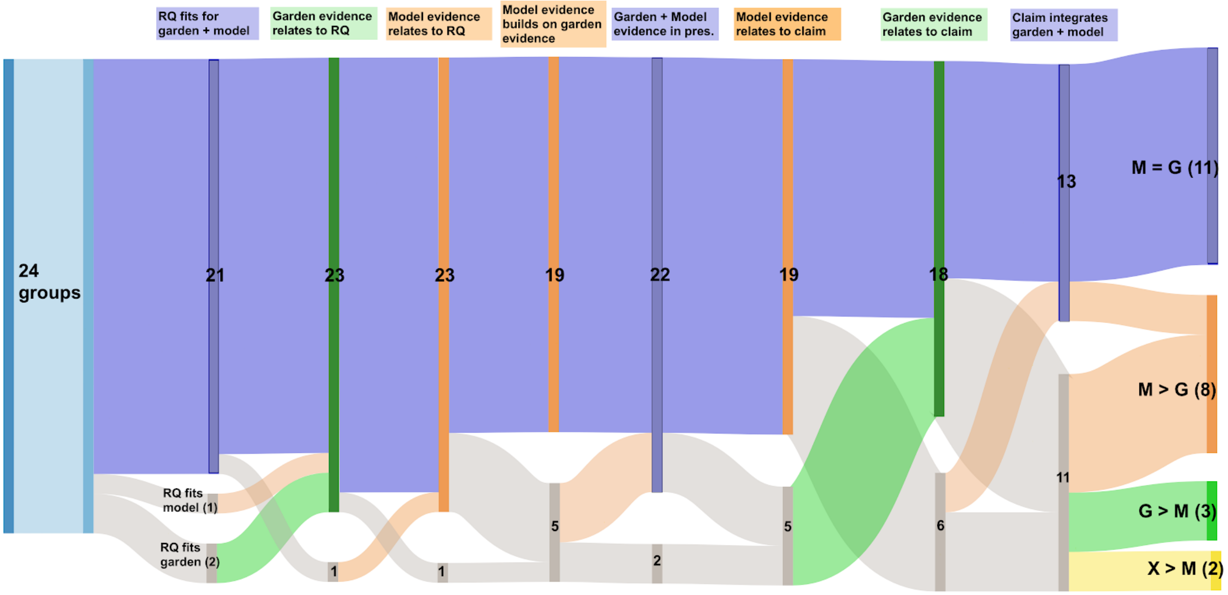

Figure 33: A representation of the student groups' abilities to contextualize model and garden realms throughout the research process, that ended with the eventual coding of groups into four categories based on evidence use.

4.6.1 Case categorization and selection

As demonstrated in Figure 33, after initial data review, groups were coded into the following four categories (Table 9) based on their treatment of evidence. To consider why students were so varied in their contextualization of the garden and model during the inquiry process, I provide an overview of the student groups in each category, followed by a deep-dive into four cases to demonstrate the range of contextualization possibilities found in the classroom data.

Table 9. Categorizing of groups based on evidence treatment

Garden > Model	Other data > Model	Model > Garden	Model = Garden
3 (12.5 %)	2 (8.3%)	8 (33.3%)	11 (45.8%)

One group from each category was selected for an in-depth case study based on the complexities of their evidence negotiation and amount of available data. The following sections detail the set of student groups within each category, starting with the shared characteristics of their evidence-treatment, then offering details about their evidence, claims, and presentations, and followed by conjectures about their process. Following that, I present an in-depth look at one group in the category, focusing on their evidence selection and experiences with the model.

4.6.2 Garden > Model (G>M)

The three groups coded as members of this category privileged evidence collected from the garden above that collected in the model. While all of the model evidence collected by these groups was indeed related to their research question, the challenge appears to have been in selecting representations from those models as evidence that best supports their claim. For one group (examined below in more detail), no model evidence was used in their presentation. For the other two groups, model evidence was provided that did not relate to their claims.

As an example, one of these groups explored the impact of nitrogen on plant growth. This group's presentation included two graphs representing plant growth in the computer model with and without nitrogen. However, both graphs appeared to show similar population levels and therefore did not speak to the claim that nitrogen impacts plant growth. In another case, the group precisely described their process for setting up the computer model to explore the impact of soil nutrition on plant height. However, they did not explicitly report the results of these investigations, so their evidence was coded as not relating to their claim.

I conjecture that for this category of student groups, there were a few reasons why they ended up utilizing the garden evidence above model evidence: (1) privileging the real life context as more relevant for their claim and goal; (2) struggling to connect the model outputs to their research question; or (3) discomfort with the model as a tool. In the case described below, the group's process was affected by all three of these conditions.

4.6.2.1 "The model screwed us": Removing model evidence as unsupportive of scientific claim

When Lacey, Ally, & Nia are first introduced to the computer model on Day 3, they differ in their comfort levels and what they deem as 'success' in using it. Working with the model, Ally struggles to identify how to distinguish weeds from crops in order to make a profit. Her interactions with the model focus on trying to make money, which include changing values in the code so that actions like applying compost and water add money, rather than subtracting it. However, she struggles to execute these code changes successfully, leading her to wonder aloud, "How do I do this? I can't do this, I'm so bad at this." Later during the activity, when Ally is praised by the teacher for having bees survive in her model, she continues to voice frustration about not being able to make money. Nia expresses a similar frustration with the activity more generally, noting on her worksheet repeatedly that "plants are all gonna die." Lacey, on the other hand, seems more comfortable with the activity, completing the tasks by describing her predictions and the actions she took in the model.

The next day in class, the group comes together to converge on one research question, deciding to explore how different plant types impact soil quality. They comfortably discuss what types of evidence they may collect from the garden to explore this question, including what types of plants are present in the garden, which nutrients those plants need or produce, and which garden beds might be most appropriate to test. The excerpt below marks the moment when the group shifts their discussion from using garden evidence to considering what evidence they would collect from the model. This change is characterized by hesitant talk and a growing uncertainty about the question they should explore.

DAY 4: Finalizing RQ, determining evidence to collect

	Speaker	Transcript
1	Ally	Would we be able to use the model for it do you think?
2	Lacey	(*4 second pause*) Um—
3	Ally	We might be able to.
4	Lacey	Well, you know how, okay, in the— in the model, you— you're able to put like a lot of soil.
5	Nia	Oh, you're allowed to put in like a lot of compost.
6	Lacey	Yeah, so—
7	Ally	So that could be, like, part of it
8	Lacey	'Cause when, if you don't add any soil
9	Nia	Or like if you want to add a lot of water
10	Lacey	Yeah
11	Ally	I feel like we need to narrow our question down more.
12	Lacey	Yeah. It is pretty broad. Um—
13	Nia	How might— how might nutrients change depending on what is growing. How might nutrients in soil change depending on what is growing in the soil. It's like, we could kinda look at the difference between like what the fava beans would do to like a tomato plant, which are then grown in the same box as well.
14	Lacey	Or we could say, I mean, we could do how do different types of plants affect the nutrients in the soil.
15	Ally	Okay. That's good, because it's like, it makes sense.
16	Lacey	I feel like it's— it's narrowed down and we can use different types of plants. We also can test the amounts of nutrients that are in the soil. Well we can't really test that, but you know what I mean.

When Ally first asks whether the model might be useful for exploring their original question, Lacey and Nia do not seem to have a clear sense of how to do this, indicated by the long pause. They attempt to connect certain model components, like compost (Line 5) and watering (Line 9), to the question. These model components the group considers modifying are not well aligned with their research question about how plant type will impact soil quality. Nia proposes a refinement to their research question with a continued eye on which evidence from the garden would help their investigation (Line 13), which is affirmed by both Lacey and Ally (Lines 14–16). However, these refinements appear to dismiss Ally's prior concerns about integration with the computer model (Lines 1, 7, and 11).

Soon after this exchange, the teacher suggests the group pick three garden beds with plants that affect the soil differently (a light feeder like lettuce, heavy feeder like cabbage, and soil replenisher, like fava) and collect soil measurements from each. They incorporate this into their plan for evidence collection; however, a conversation with them later that same day suggests they are still struggling with how to collect evidence from the computer model.

DAY 4: Plan for answering RQ

	Speaker	Transcript
1	Becca	When it comes to, um, answering this question in the model, do you have a sense of what you might do or are there some things that you still—?
2	Nia	Probably like look at how the nutrients have like changed and then within the interactions of different things
3	Becca	Okay.
4	Lacey	We can— We can show— We can see like the— the— the amount of nutrients in the soil as per the chart.
5	Becca	Mm-hmm.
6	Ally	I'm not really sure how we're going to measure the nutrients—
7	Lacey	— in like real life in the garden.
8	Ally	Like I know that— cause I— I don't know if there's a good way to measure nutrients.
9	Becca	So yeah, there's these soil tests, um, NPK tests, pH tests.
10	Nia	So we would do that.

In this interaction, I prompt the group to consider how they will use the model for answering their question. Nia and Lacey acknowledge that the model provides a chart of soil nutrient levels (Lines 2 and 4), yet attention to soil nutrition alone does not address the variety of plant types they intend to study. Ally once again raises concerns about whether the model is well suited, questioning how soil nutrition can be measured (Lines 6 and 8). While it is not explicit whether Ally is referring to measurement of nutrients in the garden or the model, Lacey's interjection leads us to discuss garden soil testing strategies (Line 9), which appears to satisfy Nia as an approach. After this segment, I offer more detailed suggestions for how to adapt their model to the research questions, however, the group does not continue to discuss how evidence from the computer model might integrate with garden evidence and help address their research question. From this excerpt, I interpret that their initial understandings of how to connect the model to the garden are not well defined, and though Ally attends to the limitations of soil measurement practices, these concerns are not discussed further with her group members. In both excerpts, talk about the model is quickly diverted to discussing the task framing or garden evidence. Without a clear plan for model evidence collection, the next day they follow their plan to collect soil tests on the Nitrogen, Phosphorus, and Potassium (NPK) levels of three plant beds in the garden[7].

During the next phase of the activity, collecting evidence from the computer model, Lacey and Nia use separate model versions to collect soil-related data from multiple trials. Lacey uses a version of the model with one crop, and Nia uses the version with two crops. Ally asks questions of each of them as they work, and keeps the group coordinated as they record their results. While both Lacey and Nia create data collection strategies, they do not discuss or consider how the conditions they explore may map to their research question of how different plants affect the soil.

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[7] Nitrogen, Phosphorus, and Potassium, or NPK, are the three 'macronutrients' that are commonly used to describe soil composition and quality. The test results are displayed as a color scale that ranges from 0 (depleted) to 4 (surplus).

Lacey's trials with the single-crop model are based on a structured approach. She records the average soil nutrient levels at the same time (65 ticks) in three cases: one where she composts, one where she waters, and one where she weeds. Nia's trials, by contrast, are less structured, though also involve manipulation of a variable (control, water, and compost); like her previous work, she seems most aware of when the plants die. Based on their worksheet notes, rather than collecting data on different plants' effects on the soil, they observe what other elements in the model have an impact on either the soil nutrition (Lacey) or the number of plants that lived (Nia). From this activity, I argue that they approach the model evidence collection scientifically by setting up a variety of trials using both models. However, to collect the exact data from the garden (soil nutrition for three types of plants) in the model, they would have needed to change the code to model the different behaviors; as they never express an inclination to change the model code to answer this question, they adapt their evidence-collection strategy to attend to other features that impact soil nutrition. Their results seem to indicate that weeding helps preserve soil nutrition, as does adding compost, however these results do not explicitly answer their research question, and they do not talk about what these results mean during the evidence-collection phase. While this activity demonstrates their recognition of the model as a tool for simulating multiple outcomes, they do not initially discuss what data they will collect, instead adjusting their plans as they go along. For the next day of activity, they are prompted to create a claim based on both sets of evidence, and as seen in the transcript, they struggle to connect their claim to their model evidence.

DAY 7: Claim generation

	Speaker	Transcript
1	Lacey	What claim could you make that incorporates the evidence of, uh, okay. I'm going to try to write it again.
2	Ally	Wait. What was the evidence we got from that other model? You know like—
3	Lacey	Oh, and the garden. Correct, uh—
4	Ally	From like the simulation.
5	Lacey	Um, I think we should use N's. Well, actually, I think mine, 'cause mine actually says the nutrients.
6	Ally	I'll start it. I'll say, "Based off the data we collected—"
7	Lacey	Okay, okay. It's a good start, a good start.
8	Ally	Based off data collected.
9	Lacey	Based off the data collected, uh, that's different depending on the amount of nutrients needed, uh, the amount of nutrients in the soil—
10	Ally	I don't know what to say 'cause we have to incorporate both in the, we have to incorporate the actual model and uh, the real life one. Uh, I don't wanna—
11	Lacey	Okay, we just— We started off by based on the data collected—It's a good start, it's a good start. Based off the data—
12	Ally	I don't really know what to say about the like model, 'cause I didn't do it.
13	Lacey	Well for mine, I think just show the nutrients in the soil.
14	Nia	Basically, based on the e-evidence we— the data we have collected. Claim is just what you wanna do. Based on the data we've collected— the data we collected—
15	Ally	But we just have to incorporate it from both.
16	Lacey	I feel like we can collect more evidence from yours *(to Nia)* because yours showed pH levels, right?

17	Ally	But we're not using pH levels.
18	Nia	We're not using pH levels.
19	Lacey	But the new— From mine, I only have one plant in mine.
20	Nia	No I looked at it, since I did the two one (*model version with two crops)* I didn't have any pH levels or nutrients.
21	Lacey	Oh.
22	Nia	I just had calculations.
23	Lacey	Yeah, for me I feel like if we need to combine the two programs because for mine to work I need two.
24	Nia	Two plants
25	Lacey	And then for yours to work, you need the nutrients in the soil.
26	Nia	[nutrients in the soil] yeah.
27	Ally	So—
28	Nia	The model screwed us over.
29	Lacey	The model didn't really help us.
30	Nia	No, it didn't.
31	Ally	All we needed is evidence from the garden.
32	Nia	Exactly.
33	Ally	The model is just like— Let's just change it to evidence from the garden.

Once again, Ally leads her group in the conversation towards integration of the model with their garden evidence (Lines 2 and 10). Lacey believes her evidence should be considered, as it contains the soil nutrients (Line 5). While they work on phrasing a response to the worksheet prompt, Lacey asks what can be included from Nia's work in the model (Line 16), though both Ally and Lacey refute the suggestion to include pH levels. Lacey says "for mine to work, I need two (plant varieties)… and then for yours to work, you need the nutrients in the soil" (Lines 23 and 25). While it is not exactly clear what they mean for their evidence to "work", they seem to believe that regardless of the investigations they conducted previously, the models do not have the right combination of elements and output displays to satisfy their investigation, and therefore reject the model entirely (Lines 28–29). They change their worksheet response to reflect the evidence just from the garden (NPK tests), rather than from both the model and the garden.

In putting together their presentation, students are tasked to include a solution and a cost-benefit analysis, as well as quantitative and qualitative evidence from both the model and the garden. To incorporate the model, Nia, who self-identifies as having "figured out how to make money," nominates herself to conduct the cost-benefit analysis of their solution, which was to plant more fava beans in the soil beds. Ally and Lacey state that since they were regularly in debt when they used the model, they are happy to cede this responsibility to Nia; this emphasizes their continued belief that success with the model depends on the money made by the farmer, as well as their attempt to address the assignment by including model-generated information in their presentation, even if it isn't evidence towards their claim. Like other groups, they offer screenshots from the model without elaborating on what those images represent, or how they connect to their questions. This group was one of the few that elected to provide a feedback video, offering more insight to their reactions to the project and how their discomfort using the model may have prevented them from incorporating it as an evidence source.

DAY 8: Reflection Video

	Speaker	Transcript
1	Ally	So for the garden project I really liked going outside and doing all the evidence, I think it was really interesting to learn about an environment that we're like, in every so often.
2	Lacey	I also liked using the computer models because it was fun to interact with different situations, and being able to control stuff that you wouldn't normally be able to control in the garden.
3	Ally	I didn't really like when we first started with the computer model because I didn't really understand what we were doing and I had no idea how to use it.
4	Lacey	Yeah it was really confusing but, after the second time and third time the next day it was a lot easier to use.
5	Ally	Definitely
6	Interviewer	What would you change?
7	Ally	Um I'd probably change the worksheets, I feel like some of them got a little repetitive but otherwise it was fine, I think it was good to review what you did but on some of them there were repeating questions and the wording was a little confusing every so often.
8	Lacey	Yeah I liked the websites that we used but on the first model we only had one flower and I feel like it would be easier, it would be nicer to have two different flowers and talking about different things in each model.
9	Ally	And then on the second model to have the graphs be more on the soil nutrients and the water in the soil which was something more of us were testing rather than the population and the population of bees or something, because not many of us in the class tested that.

In this segment, it becomes clear that discomfort with the model affected their approach to the task (Lines 3–4), though Lacey in particular acknowledges that she became more comfortable over time. In Line 8, Lacey also refers to a desire to combine elements of the models, so that the one she worked with could have had two plant varieties. Ally demonstrates an awareness of how this could have helped integrate their evidence sources, acknowledging that fewer people in their class were investigating the populations, and suggesting the graphs generated by the models be better aligned to the variables her classmates studied from the garden (Line 9). This segment succinctly demonstrates the position this group took towards the model: despite their successful evidence collection, and perhaps due to their initial discomfort, they believe that the output variables were not in alignment with the setup conditions they needed (multiple plants in each model) and therefore were not useful for their investigation. Their use of model graphs only for the cost-benefit analysis indicates that they see the model as useful for demonstrating the economic aspects, and attribute 'success' with the model to being able to earn a profit.

4.6.3 Outside data > Model (X>M)

In 2 / 24 cases, student groups utilized outside research to support their claims. In both cases, their claims were based on a combination of garden data and information from the internet. The group described in further detail below attempted to incorporate evidence from the model; however, they reported their model outcome as inconclusive and turned instead to online sources to investigate the mechanisms of pollination. The other group in this category used local weather data to assess how much rain the crops in the school garden had received, and the average amount of water three types of crop need in a year. It was unclear if they used the model to attempt to answer this question, as they did not include any model evidence in their classroom artifacts. I conjecture that for student groups in this category, while the model was seen as a suggested evidence source, it was not viewed as helpful towards their investigations. Instead, a desire to follow the assignment structure motivated them to pursue a second evidence source that was more familiar, easier to interpret, and could directly relate to their research questions. Due to variance in their participation, neither group in this category had audio data to transcribe and code; the case below primarily utilizes the groups' worksheets and final presentation slides as data.

4.6.3.1 "Model was inconclusive": Model appears to contradict preconceptions about pollination

The four students in this group investigated the impact of bees on plants. The students plan for their evidence collection in the garden to demonstrate the direct impact of bees on plants, by observing the plants before and after bees land on them. The specific data they intend to gather include plant height, color, texture, and width, the number of bees surrounding the plants, amount of time bees stay on plants, and which kind of plants attract the most bees. Group member Elsa's notes state the distinction between independent and dependent variables in their work, indicating her attentiveness to study design. However, on the day their class collects evidence from the garden, it is cold outside and therefore few bees are present. While the group still records the heights, colors, textures, and type of plant for five plant varieties, they decide to go back another day to gather more evidence.

Entering the model evidence-collection day, the group decides that they will look at how bees affect the energy of plants, and the hydration and nutrition levels of the soil. Although the model includes code that specifically addresses the distribution of energy to plants via bees, the group members modify a different section of code, related to when bees appear. The original model set-up has bees emerge when a certain number of plants are flowering; the group attempts to change this set-up condition to require nutrient-rich and hydration-rich soil instead. Yet it is unclear if the group's coding attempts are successful, as they are missing a key line of code ('sprout') that would generate the bees. Nevertheless, these initial interactions show an intent to engage with the code, attend to relevant output variables in the model, and hypotheses about the connection between bees, hydration, and nutrients.

Separate from this coding attempt, they record some data on plant energy, hydration, and nutrition from the model. After analyzing the graphs from their presentation (Figure 34), it becomes clear that these values refer to the average energy of three species (two plant types and bees) at 200 ticks in one version of the model, and the most frequent soil nutrition and hydration values from the histograms in the second model. While the screenshot of the soil data model contains bees in the interface, the values on the energy graphs included in their presentation indicate that bees were not present in the model at the time they collected these data (the yellow line in the graph remains constant at 0). This selection of multiple graphs as the primary evidence indicates a potential epistemological stance that the model graphs contain the most valuable information, though their interpretation of the values shows their confusion at how to read the histogram, and how to interpret the actions of the model.

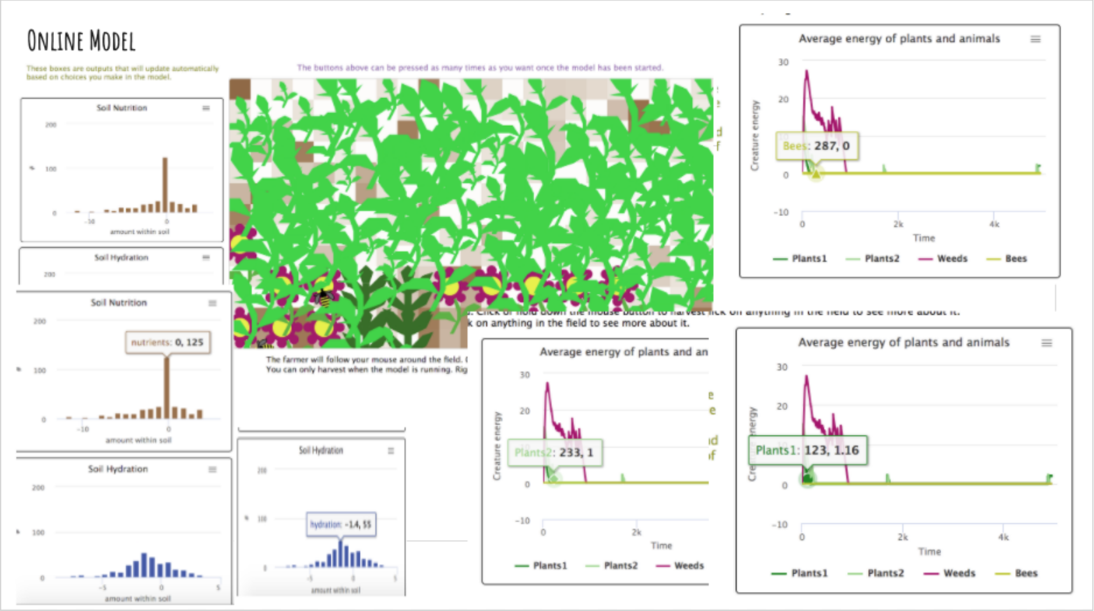


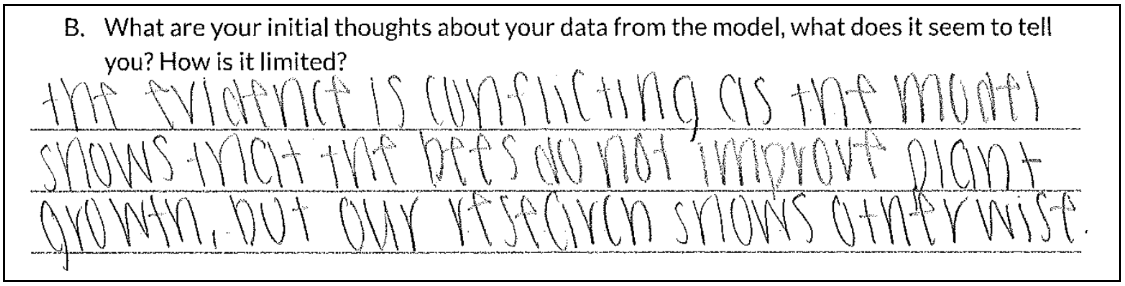
Figure 34: Slide included in X>M group's presentation, containing graphs from both model versions.

Note. The line graphs (right) do not contain bees (yellow line remains flat on the x-axis), while the histograms (left) are from the version on the interface, with a bee present. The graphs appear to be multiple images of the same moment in time, with the cursor moved to display the values of each variable.

While attempting to show a clear connection between bees and soil health, the group finds the data to be 'inconclusive'. In their final presentation, they write:

> "The online model showed inconclusive results as the bees did have a positive/negative effect on the hydration and nutrition of the soil/plant. The highest nutrition level was 125 and 0 within the soil, and the highest hydration level was 55 at -1.4 within the soil. The levels fluctuated up and down. It was conclusive regarding the model version 2 but the results were unexpected as we expected the plants to grow however the data shows that the average energy of the plants kept decreasing."

Though they use the histograms as evidence, the group struggles to interpret them, reporting the frequency (125) as the highest level rather than the actual value (0); these challenges lead them to record the evidence as inconclusive. They interpret the line graphs correctly, yet attribute the decreasing energy of the plants to the lack of bees, rather than the passage of time. Without realizing the connection written in the model's code, they refer to these results as unexpected. For further clarity, I refer to group member Sonia's notes (Figure 35) that "the model shows that bees do not improve plant growth", where she acknowledges this is a contradiction to their prior knowledge, claiming "our research shows otherwise".



B. What are your initial thoughts about your data from the model, what does it seem to tell you? How is it limited?

the evidence is conflicting as the model shows that the bees do not improve plant growth, but our research shows otherwise.

Figure 35: X>M Group member Sonia's notes about the model data.

Much like the G>M group, this group is unable to contextualize the model data with their specific research question, which looks for a direct before / after effect. Rather, they interpret the passage of time in the model, in which soil nutrition and hydration are programmed to decrease slightly every tick, as a direct result of the bees. While they attempt to change the code to support their reasoning, the evidence they ultimately present show a snapshot of nutrient, hydration, and energy levels of one moment in time, in one model that had bees, and one model that did not. Despite their adherence to a before / after structure for their research question, they do not use two points in time for their model evidence, and ultimately deduce that the bees are not helping plants to grow. Unconvinced by this finding, the group intends to collect more garden evidence and supplement their knowledge with research on pollination from the internet.

In the garden, they revisit the same five plants they first observed, and compare their data from the first day to this day, implicitly considering the changes between the two as caused by the bees. Rather than comparing the plants on all of the original variables, they create one they call "roughness", which they notate as a value from 1-7 on each day for each plant, reporting the change in roughness between the two visits. For all plants, the group records an increase in roughness, attributing this change to pollination. As their outside research describes the deposits of pollen bees leave on plants after they visit, it appears this may have influenced their description, and qualitative evaluation, of roughness.

The instinct to make a direct causal comparison between one variable and another, combined with the inconclusive information derived from the model, inspired this group to look for additional information about their research question. In efforts to incorporate the mechanism of pollination to their explanation, they present their garden data to reflect an increase in roughness, attributed to visits by bees between both points of data collection. From this I conjecture that there were not enough modeling supports for this group to explore their question as an emergent process; while their instinct to look at average plant energy was well-formed, the means to look at those values were not well defined and therefore they were not able to access the explicit causal information that, unbeknownst to them, was actually programmed into the model. As a result, they felt the model was contradictory to their prior knowledge, and leaned into another informed resource, the internet, to supplement and structure their garden data. This was also one of only a few groups that elected to return to the garden for more evidence, which was vital in the presentation of their results as a change over time. The activity design did not intentionally support this kind of experimental set up from the garden, as we instead hoped students would lean into the other evidence source (the model) to contextualize their data or show the impacts of the passages of time. However, these results indicate that perhaps this instinct should be encouraged, and more versions of studies like this could consider having prolonged evidence collection from both spaces, where students are able to re-visit and refine their evidence to demonstrate change over time, as is possible in the model.

4.6.4 Model > Garden (M>G)

Eight groups (33.3%) were classified as promoting model evidence above garden evidence in the presentation of their claims and solutions. There were a variety of moments that shifted focus away from balancing both the model and garden: when constructing research questions, evidence for the presentation, or claims. For example, one group wanted to investigate how organic and non-organic ways of gardening affect the number of crops and soil health. As their school garden was explicitly organic, their ability to collect garden evidence to fully address their question was limited, and they ultimately relied on evidence from two model runs (using organic and inorganic settings) to support their claim that pesticides decrease soil health. Though many other groups did collect garden evidence that was well-aligned with their research question, this evidence may have been omitted altogether or in favor of less well-aligned evidence, or it may not have been integrated into the group's final claims.

For example, one group investigated the effect of weeds on soil nutrition and plant growth, but the only evidence presented from the garden (plant heights along with a photo) was from one bed without weeds, leading them to rely on their model evidence to answer this question. While two groups did have claims that explicitly incorporated garden evidence, this evidence was not included in their presentations (though it was referenced in their worksheets), indicating challenges with the evidence selection process. In two other instances, students' claims *refuted* garden evidence, rather than failing to incorporate it. In one of these instances, the refusal was implicit, by ignoring a piece of contradictory evidence: the group claimed that adding compost improves nutrition and decreases hydration in the soil, though they presented evidence from the garden where they describe the compost as moister than the soil in the planter beds. In the case described below in more detail, the group presents a claim that actively refutes their garden evidence, stating that the model offers a more "realistic" perspective on their question than the evidence gathered from the school garden.

In all of these groups, I conjecture that the reasons they ultimately relied on the model evidence over the garden evidence were influenced by: 1) the desire to have a controlled science experiment with two conditions; 2) demonstrating their competency in programming changes to the model; or 3) an epistemological stance that affords more legitimacy to the model / graphs than their observational evidence. The example continued below reflects both the first and third conjectures.

4.6.4.1 "Model was probably more realistic": Refuting garden evidence in scientific claim

This group (Kiku, Jacob, & Mori) decides to investigate whether plants of the same type grow better when they are clustered together or growing independently. From the garden, they look at two beds that have kale plants, recording the height of the plants, number of leaves, and presence of insects as indicators of how well the plants are doing. They also measure and record the amount of space each plant has; they write that the kale group "looks healthy", while the kale alone is "not looking healthy", indicating they have a clear hypothesis that the kale growing together is more healthy than the kale growing alone. When they are ready to use the model, there is some confusion over which model to use, and who will look for which indicators. They decide to use the model with two varieties of crops, and set the spacing for one plant breed close together and the other further apart. They decide that the only human interference in the model will be occasional weeding, and intend to take screenshots of the model at regular intervals to check for some of the same variables they saw in the garden: height of plants and presence of insects (in this case bees, as these were already present in the model). This choice indicates their view of the model as a space to perform a structured scientific experiment that minimizes confounding variables, such as human interference, and directly corresponds to the evidence they collected in the garden.

After doing this for a while, Jacob questions if this is the best strategy as no bees ever arrive in his model (since the garden doesn't get watered/ composted, the plants never go to flower). They end the class period a bit frustrated with the realization that their model choice was not the best for their question, as the two crop varieties have different growing behaviors. Mori commits to re-collecting the data in the other version of the model outside of class, where she can run the model twice with different spacing conditions. From this choice, I conjecture that Mori continued to view the model as a space to perform a precise experiment, and may have developed a sense of ownership over her group's model evidence, as she completed it on her own. Rather than height and number of insects, Mori records the nutrition and hydration histograms, as well as the number of ticks (length of time) each set of crops survived, demonstrating flexibility in her model use by addressing the research question without replicating the results from the garden.

While reconvening to determine a claim, the group members record on their worksheets that in the garden, the kale clustered together appeared to be doing better than the kale alone, yet their evidence from the model seemed to convey the opposite results. While working on this, their teacher Ms. Moss checks in, and Mori asks her for help on dealing with their contradiction.

DAY 7: Contextualizing conflicting evidence with teacher's help

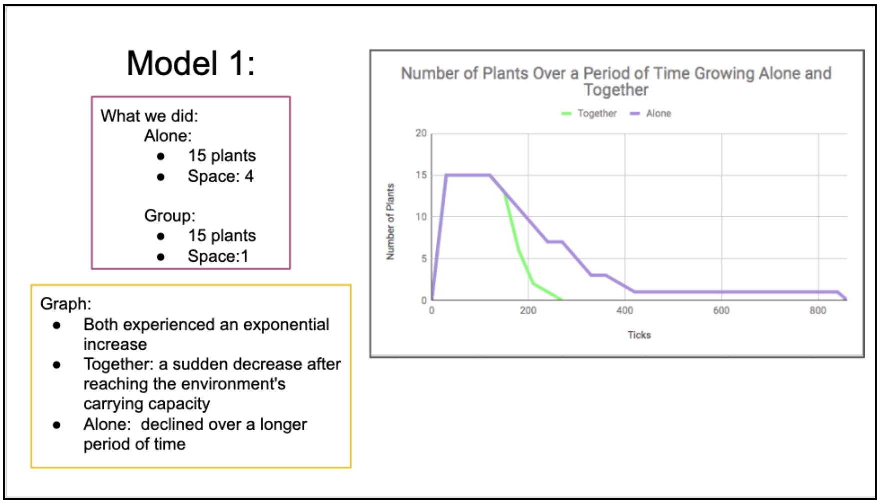
	Speaker	Transcript
1	Mori	Oh, so our conclusions from the outside garden and the model are like, they're basically the opposite
2	Ms. Moss	What is your garden—
3	Mori	That outside the plants growing together grow better um, but on the model, it's been showing that the plant alone grows better so, um, can we like— I think the reason why it's growing outside better is because like one, there are other plants growing around it that are different types that might help it attract like you know more bees to pollinate it and like, stuff like that

4	Ms. Moss	Yeah
5	Mori	—and also the one growing alone, there's a lot of bugs I think in that like um, that bed so like if you could tell by the other plants also that they've been eaten up, so.
6	Ms. Moss	Okay, so here's what I suggest because the way that it works outside is that you choo— like I purposefully planted things that work well together so that when they're together, they're help preventing disease or they're help preventing like soil nutrients from being a competition. So, on your model, did you program it so that like one plant actually adds nutrients?
7	Mori	No, but I was thinking that I could explain why what's going outside happens and what's going on inside the model happens instead of coding and coding.
8	Ms. Moss	You could say that the model is like an example of when you plant things that actually don't complement each other because there's complementary and non-complementary plants, so you could say, 'This is what happens when you plant plants and they compete', they do better on their own but when you plant plants on purpose, like I use a very nice model for organic farming to choose how I plant and so, the ones that are complementing each other and doing well are because they were planted that way
9	Mori	Wait so should we just switch our whole question to like, plants growing like um, complementing each other, how it affects?
10	Ms. Moss	Well, that is kind of what your question is right?
11	Mori	Yeah.
12	Ms. Moss	How do different plants affect? What's your question?
13	Mori	Yeah, when plants grow together, um, do they grow better or when plants grow alone?
14	Ms. Moss	Cool, so that's still a fine question, and then you could say, 'Plants grow better together when they are like complimentary', that's the science part. And you can use your model and the garden as evidence, and then your solution, you could look at solutions to like, companion planting, is what we call it and you could find like the best solution of companion planting
15	Mori	Okay.
16	Ms. Moss	So, you're on a roll, that's great, you don't have to change anything.
17	Mori	So um, can we use like soil nutrition and water levels and like insects from the model as like evidence?
18	Ms. Moss	Soil nutrition from outside and the model.
19	Mori	Okay.
20	Ms. Moss	Yeah. Or plant health from outside. Yeah. I like your—the evidence that you talked about with like the plants growing alone not being well and with the others doing well, that's good evidence.

In this segment, Mori attempts to contextualize the model evidence with her knowledge of the garden in Lines 3 and 5. While the teacher supports her theory, she questions if the model was programmed to account for the ecosystem dynamic of complementary plants (Line 6). Mori's response demonstrates a preference for addressing the distinction through talk rather than coding the model to replicate this phenomenon (Line 7). Ms. Moss suggests a claim that offers a nuanced account of the contradicting evidence, stating, "So you could say, 'this is what happens when you plant plants and they compete, they do better on their own, but when you plant plants on purpose…", followed by the ecological rationale for her planting strategy (Line 8). Mori appears reluctant to engage with this suggestion, expressing concern the group might need to change their question as a result. Ms. Moss affirms that the question can stay, so long as the claim incorporates this nuance, encouraging the use of both evidence sources (Line 14). However, Mori still seems to demonstrate a preference for the model evidence (Line 17), and Ms. Moss encourages her to incorporate the garden evidence as well (Lines 18 & 20). From this interaction, I interpret that Mori feels inclined to use her existing model evidence, without re-coding the model to represent the complementary planting dynamic that appears to be contributing to the results found in the garden.

While her teacher encourages contextualizing both sources of evidence through the phrasing of the claim, Mori wonders if she should change their question, or just present model evidence. I speculate that Mori feels confident in her model evidence, and in her ability to connect the model data to theories about the garden, though the confounding variable of lettuce growing together with the kale impacts her impression of a controlled scientific experiment.

In their presentation, Kiku presents their claim as "Plants grow better alone than together", a finding that does not incorporate the garden evidence or the phrasing their teacher suggested. Jacob describes their solution of complementary planting, as suggested to them by their teacher, and then Mori presents the majority of the evidence, which include graphs that she created from exported model data. In describing the graph that demonstrates plants growing alone survive longer than the plants growing together (Figure 36), she uses the phrase "carrying capacity", which demonstrates her attentiveness to biological principles. She also describes the slopes of these graphs as having exponential increases and gradual decreases. From these actions, I perceive that Mori feels confident in the model evidence and graphs she generated, as she supports their presentation with relatively advanced biological and mathematical terminology.



Model 1:

What we did:
Alone:
- 15 plants
- Space: 4

Group:
- 15 plants
- Space:1

Graph:
- Both experienced an exponential increase
- Together: a sudden decrease after reaching the environment's carrying capacity
- Alone: declined over a longer period of time

Figure 36: Slide from M>G group's presentation, with a student-generated graph showing plants growing together died faster than plants growing alone in the model.

In discussing model evidence that shows decreasing nutrition and hydration over time, Mori offers a contextualization of the garden by providing an explanation for the phenomenon of why plants growing alone survived longer: "The soil nutrition gradually decreases because the plants are more spaced out, so they have a much farther reach, um, that their roots can reach for nutrition, and the same thing occurs with the hydration." With this statement, I conjecture Mori attempts to further promote the validity of her model evidence by describing the trend as a representation of the mechanism of plant roots spreading to absorb nutrients and water. As she reviews the garden evidence, she acknowledges the contradicting trend, that plants growing together did better than the kale plant going alone, and offers the inference that the evidence was likely influenced by the complementary plants (lettuce) that grew within the kale bed:

> And so our garden graphs, um, as trends that we're commonly seeing, were the plants growing together seemed healthier than the plants growing alone. And so our conclusion that we found was that in the garden plants did grow together well, but um, in the model, which was probably more realistic, the plants growing alone grew better. And the garden was different because other plants grew in the same bed with the kale, and um, the kale that grew alone.

In this statement, Mori goes so far as to say that the model was "probably more realistic" than the garden, and the claim they present indicates this viewpoint as well. I interpret this as an indication of the desire for a controlled experiment without any confounding variables; the students saw the garden evidence as sullied by a variable that impacted the causal relationship they looked to explore. Rather than providing a more nuanced claim to incorporate the influence of companion planting, as suggested by their teacher, the students privilege the model evidence, and use the garden evidence instead to support their solution. In this presentation, rather than conceding that the model does not fully represent the phenomenon of the kale bed growing with lettuce, Mori offers the model evidence as describing a clear causal relationship between spacing and plant success (vis a vis nutrition, hydration, and prolonged survival), indicating her epistemological stance on the utility of models for this purpose.

4.6.5 Model and garden evidence balanced (M=G)

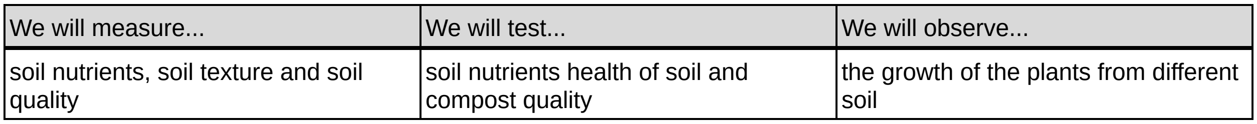
Eleven of twenty-four groups (45.8%) presented a claim and supporting evidence that drew on both the garden and the model context. All of the groups in this category included relevant evidence from both sources in their presentation, as well as had model evidence that built off of their garden evidence. Their evidence contextualization offered either confirmation by finding similar patterns in the model or garden, or more nuanced context on the phenomena under investigation. Their scientific claims integrated both sources of evidence.

In one case, presented in-depth below, students who initially had a question ill-suited for the model were able to program significant changes into the code so that they could ultimately answer their questions; this enabled a balanced use of the instrument. Every group in this category used code-changes as a part of their instrumentalization, with most utilizing code from the tutorial videos, while three made novel code changes to impact the behavior of crops, weeds, and compost. Some of these model manipulations added new evidence unique from the garden evidence, while others used the model to replicate behaviors or patterns they had already observed. Regardless of this distinction, all groups were then able to contextualize the evidence so that their claims related to both sources. Several students in this category were able to speak specifically to the limitations of their evidence sources, including that they had used the model to replicate patterns they had seen in the garden, or projected a pattern they were unable to see in the garden, due to only collecting evidence on one day. Many mentioned that their unfamiliarity with coding limited their ability to engage deeper with the model.

The most successful groups collected evidence from both the garden and model relevant to their question, and used the model to build off of those findings, positioning both as a resource for their claim. Many groups in this category also utilized the model for multiple types of actions (Table 7), demonstrating a wide instrumentalization. I conjecture that the reasons these groups were able to provide a balanced integration of evidence sources related to three factors: (1) alignment between model and garden evidence; (2) attentiveness to limitations of evidence sources; and (3) model leads to new information (rather than confirming an existing pattern), with the most mature contextualizations utilizing all three.

4.6.5.1 "There's no right number": Social and critical process supports nuanced claim

This group decides to investigate which soil type is best for plants, between the fava bean soil[8], compost bin, and worm bin. On Day 4 they debate whether this is a 'testable' question, given that plants have already been growing in the fava bed, and only the compost is present in the model. Initially, the group's question is not answerable with the model, so to make the question more testable, I encourage them to code in worms and fava. They demonstrate openness to the idea, and Doug, who had edited the model components on Day 2, is rather excited. Beyond their certainty of the three soil types, it's not clear to them what else they would test besides nutrients. I talk this through with them, offering the idea of testing the soil texture and pushing on their idea of 'soil quality', yet they are unable to further define this idea. At the end of Day 4, all write on their worksheets, under *What data will you collect from the garden?* "Nutrients in the soil, soil texture, and soil quality." From the group survey they complete on the same day, they write that they will measure these three components, as well as test 'health' and 'quality' (Figure 37).



We will measure...	We will test...	We will observe...
soil nutrients, soil texture and soil quality	soil nutrients health of soil and compost quality	the growth of the plants from different soil

Figure 37: Sample from M=G group's evidence collection survey results on Day 4.

This challenge to break down 'quality' into specific variables contributes to the fact that ultimately, the only data they record on Day 5 are the results of the NPK nutrient tests of the three soil samples. Additionally, they perhaps were aware (as they mentioned on Day 4), that neither the worm bin nor the compost had plants growing out of them, which negates their opportunity to 'observe' what they wrote in the survey on Day 4. After Doug and Trey test the worm bed, they express limitations of this process on their worksheet (Figure 38).

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[8] When fava is planted, it fixes nitrogen into the soil. However, if it grows long enough that it starts to fruit (generates beans), it ultimately uses this nitrogen source. The fava in the garden had already generated beans at the time of evidence collection.

> Doug: It is hard to get the worm soil without getting a lot of worms or pieces of cardboard or rotting plants in the soil sample. This was hard because I didn't know if having those in the sample would affect the measurements of the soil nutrition.
>
> Trey: We only have one real way to test the soil (the soil test kit). It is hard to collect worm soil without collecting actual worms in the soil.

Figure 38: Sample from M=G group members' notes on limitations of garden evidence from Day 5.

At this stage, this group has only one type of data from the garden that enables them to distinguish between the three soils; though the nutrient tests have three components (N,P, & K), their challenge to define 'quality' means they rely heavily on these results as evidence. They have also expressed ample awareness of the limitations of the process: from the setup of their question that limits them from using plant growth as an indicator, and during evidence collection, with their skepticism about the validity of the worm soil results, and only having one 'real way' to test the soil.

4.6.5.1.1 Models as dynamic, malleable instruments that represent theories

On Day 6, Doug and Trey work together to add worms to the model, while Ilyse and Chanda work to first change the model plant to behave like fava, and then add nitrogen as a feature of the soil patches, with levels tracked by changes in color. With tutorial videos to aid them, the groups work through adding these coding changes, though they are regularly frustrated by the tediousness of adding code in multiple places: Doug questions whether this activity is even appropriate for their age group. ["Why is this so hard? I don't think they understand that they're trying to make something for like, middle schoolers, like in the garden, and this is so frickin confusing."] In their coding activity, both pairs go through a process of: (1) questioning whether the changes they make are specific to their existing hypotheses about the element they are adding; (2) observing the impact of their changes to other variables on the model's interface; and (3) discovering how to generate evidence from the model to support their research question. As they only have 90 minutes in this class period, they have the least amount of time to work on the last, and conceivably most important, step (though by saving their model code, they could revisit this on Days 7–8). I provide excerpts from their activity in each of the three stages, illustrating the critical approach they take to their coding process, to the model as a resource for evidence, and the social interactions that reveal insights on model epistemologies. That they went through these three steps, and solicited help from the instructors along the way, indicates their willingness and capability to thoughtfully engage in model-based reasoning and evidence generation.

Firstly, as they change the code (using the videos as a guide), they question whether the changes they are making are specific to their existing hypotheses about worms and fava plants.

DAY 6: Doug expresses theories about worms for model

	Speaker	Transcript
1	Becca	But, what do you want your worms to do?
2	Doug	We just want it to like bring it, we want it to make the soil the same as it is in the garden.
3	Becca	Ok but that's not an answer for me, it's what are worms, what do you *think* worms are doing in the garden that would make it the same?
4	Doug	They're making it better, adding nitrogen
5	Becca	Ok that's something, what else did you notice about the spots where there are worms?
6	Doug	It's moist.

In this excerpt, Doug establishes his desire to integrate the model with the garden (Line 2), and with my prompting, demonstrates that he does have theories for what the modeled worms should do based on observations from the garden (Lines 4 & 6). As he continues to code, Trey asks him why he is coding worms to eat, questioning the relevance of this action to their hypothesis. Doug replies "Because it makes the nutrients," recognizing that it's the output of eating (excrement) that enables worms to create nutrients for the soil, and is embedded in the code lines that he is generating; this dialogue supports the theory that social interactions create opportunities for students to articulate and test out their ideas about modeling decisions.

In their coding process, Chanda and Ilyse have fewer initial theories about what their code should do to the soil to make it represent fava.

DAY 6: Chanda and Ilyse try to make their code resemble fava

	Speaker	Transcript
1	Chanda	Yeah, so how do we know this is the fava?
2	Ilyse	I'm so lost!
3	Chanda	I have no idea
		(*Becca comes over*)
4	Ilyse	We got it? I mean we didn't get it
5	Chanda	(*to Becca*) Does it matter what numbers we put here at all, because like, if you're going to make like a certain type of plant, shouldn't we know like, a certain number?
6	Becca	Again there's no right or wrong,
7	Chanda	Oh
8	Becca	It's a test, so you figure out, you put in one number, see if it does what you think it should do, if it does something that you think is crazy, try a different number.
9	Chanda	Oh ok
10	Becca	Because everything is kind of relational. Did you figure out where to put the code that you want to change?
11	Ilyse	Yeah, yes
12	Becca	So you're not *totally* lost
13	Chanda	No
14	Ilyse	(*silly noise*)
15	Chanda	Ok keep going. (*Becca leaves*)
16	Ilyse	Let's put a number in here (*how plant affects hydration of surrounding soil*).
17	Chanda	No she hasn't done that yet (*in the tutorial video*)
18	Ilyse	Lets go 0.4 (*writes code so that plant adds hydration*)

This segment illustrates that they are skeptical about whether their model represents real fava (Lines 1–3), though Chanda desires to get it right. When Chanda asks if there is a 'certain number' they should 'know' in advance (Line 5), she reveals her desire to lean into my authority as code author, indicating she doesn't yet see models as theoretical and experimental entities. She invokes this again in Line 17, resisting Ilyse's code changes before seeing how the tutorial video plays out. Ilyse on the other hand, wants to change the hydration values (Line 16 and 18), indicating she may have existing theories about fava, or at least is willing to experiment.

4.6.5.1.2 Model as a space to observe systemic relationships

After both pairs succeed in making code changes, they then try to understand what the changes they did mean, by observing the impact on the interface and other model elements.

DAY 6: Doug and Trey figure out what worms do

	Speaker	Transcript
1	Doug	We did it, but we don't know if they're doing anything, but there are worms.
2	Becca	Ok let's figure out what they're doing. (*Doug starts to run the model*) they are red, and they are, taking over. Ok. So, what does it seem?
3	Doug	they're making them, block things turn black
4	Becca	Yeah. So they are adding…..(*long pause*) nutrients to the soil, is what they're doing.
5	Doug	So that's what we want
6	Becca	That is what you want. And what else looks, what else does it look like is happening to them?
7	Doug	They're spreading out, they're moving
8	Becca	They're spreading out, and then are they thriving when they spread out?
9	Doug	Yes — no they die
10	Trey	No they're getting smaller
11	Becca	They're getting smaller, they're dying, so. The way that I programmed it [in the video] was that there are certain conditions (*Doug resets it, starts*) that the worms are able to live in. (*Doug scrolls down to code*) So to keep the worms in, you have to keep your whole garden to have some spaces with those conditions. (*Doug scrolls back up, applies compost, waters garden*) And like you mentioned, it's about having moisture and it's about having nutrients.
12	Doug	Yeah
13	Becca	So, notice how they're everywhere when he starts, and then slowly slowly--
14	Trey	If we keep watering and keep putting compost in...
15	Becca	There you go

In this excerpt, Doug and Trey solicit my help to figure out what the worms are doing by interacting with the interface: they determine the worms add nutrients (Line 3 and 5), spread out (Line 7), and die (Lines 9–10) unless the farmer/ model user continuously maintains a moist soil with a certain nutrient level (Doug's actions in Line 11 and 14). This understanding becomes a key element of their evidence from the model.

Chanda and Ilyse also spend time trying to understand if their changes "work"; while Ilyse shares her explorations on the model by excitedly mentioning the size of plants, and her hack to save money, Chanda tries to focus their attention back to the research question, saying "We just care about the soil." At one point Doug comes over and asks what they've been up to, asking to see the fava in their code. This provides Chanda and Ilyse with an opportunity to articulate the meaning of the representations in their model to their group member, and convince him that they had actually created fava and nitrogen. Then, after spending much more time reviewing the interface, Chanda and Ilyse begin to understand the relationships:

DAY 6: Chanda and Ilyse discover how their model fava impacts soil and weeds

	Speaker	Transcript
1	Ilyse	The fava is where it's most dark. See look the weeds are just sucking it right up. And when I take the fava away (*harvests plants*) it gets darker. Maybe?
2	Chanda	Yea its because the fava used the nitrogen
3	Ilyse	Yeah... no, it creates nitrogen
4	Chanda	Yeah
5	Ilyse	And then the weeds take it away, the little bitches
6	Chanda	Ohhh, so we did do it right
7	Ilyse	See, look
8	Chanda	Haha! Geniuses.
9	Ilyse	See, look (*presses setup*)
10	Chanda	We have like ten minutes
11	Ilyse	Set up. OK Look at how dark it is, and look at how dark it is at where--
12	Chanda	--when it's first growing
13	Ilyse	It's all dark, and then it's getting lighter up here. Like it's getting lighter where the weeds are and it's still dark. Now watch (*harvests*)
14	Chanda	Adios (*watching*) it's because they used the nitrogen to grow.
15	Ilyse	Mmhmm
16	Chanda	We did it! I feel really accomplished.

In this excerpt, Ilyse has discovered a relationship that she wants her partner to understand; Chanda initially seems more invested in determining whether this means they've "done it right" (Line 6), and recognizing how much time they have left in the period (Line 10), while Ilyse repeatedly directs Chanda's attention to the model (Lines 1, 7, 9, and 11), describing the relationship she has discovered between the fava, soil, and weeds. By the end of the segment, they are in agreement about this relationship, and Chanda feels accomplishment (Line 16).

4.6.5.1.3 Model as a tool to generate evidence

After both pairs understand how their model reflects relationships of interest in the garden, they use the limited time remaining to try and generate data to use as evidence. While Ilyse continues to look at the relationship between nitrogen, herbicide, and model manipulation, Chanda repeatedly asks aloud, "How do we get like, a nitrogen chart?" Based on the model settings, they are unable to use the existing graphs on the model, and therefore need to learn to manually generate nitrogen levels to create their own chart. After I help them figure out this practice, Chanda asks me, "So what do I want to do with the data?"; I respond with, "You want to make sure you have data that helps you talk about your question," and suggest they take screenshots or generate nitrogen data at various points, such as after composting. Given the limited time (at this point less than 5 minutes left in class), I encourage them to first save their code so they could access it later on. However, this shift in focus leaves them with minimal time to generate model based evidence related to their research question, and they ultimately do not have quantitative data to use for their presentation.

Doug also asks me about how he moves from having worms to generating data. I have him restate the relationship he discovered on the interface, and suggest taking screenshots that enable him to talk about that relationship, such as when worms are prevalent and when they are dying off, and the human intervention required to keep worms around. He then takes several screenshots: when first starting the model, after he's applied water and compost, and then repeatedly for minutes at a time. He relishes in this activity, showing off to his peers and groupmates, inviting Chanda and Ilyse to "Come see our worms!". On their worksheets, Doug and Trey describe their model evidence as the following (Figure 39):

Doug: I am taking screenshots of worms making the soil more nutritious but also dying off at an equal rate if the soil does not match their needs. The screenshots were to show how the conditions of the soil have to be for the worms to survive. It is limited because getting more would be a lot of coding I don't know how to do.

Trey: The worms made the soil very moist and rich and they needed a lot of water in the model.

Figure 39: Sample from M=G group members' notes on model evidence collection from Day 6.

Yet Doug questions if this data actually supports his research question, and asks his teacher if he's done enough. Ms. Moss encourages quantitative data to support his work, graphs or manual counting of the worm population, plus hydration. This proves challenging as the model does not update to show populations of a new coded animal, so I show him how to print a count of worms at any given time with the observer function. The next segment shows his frustration at the data that he generates, the worm population every five model 'ticks'.

DAY 6: Doug questions validity of quantitative model outputs

	Speaker	Transcript
1	Doug	Five ticks, population of bugs and then put 5 and then 5. And then I'm going to do (*starts, pauses at 10 ticks, prints count*) 10 and 10 again? The amount of ticks is the amount of bugs.
2	Trey	10 and 10?
3	Doug	That's so annoying. (*repeats process at 15 ticks)* if it's 15 I swear to god...it's 10, it's 15 and then 10
4	Trey	This is 15?
5	Doug	And then 10 (*stops at 20 ticks*). It's 10 again, I don't think there can be more than 10, 20 and 10.
6	Trey	(*yawns*) I could really go for some Chipotle™ right now.
7	Doug	*(stops at 25 ticks)* Print, if it's 10 again i'm going to jump off-- OH MY GOD (*it's 10*)

At this point, Doug and Trey stop as the class is coming to an end. I view this segment as a struggle to connect different parts of the modeling process. While they identify the relationships that impact the worms on the interface, when it comes to creating quantitative data, they resort to a methodical “every 5 ticks” process, rather than demonstrating the impact of variables or stages they identified earlier (initial; after lots of water and compost; minimal water/ compost that leads worms to die). The minimal amount of time between measurements doesn’t show much change in the population, and Doug thinks the model has a limit on worm population (Line 5). Because this method of data generation doesn’t create values that align with his expectations, Doug rejects this data (Line 7). This suggests he has a critical stance towards evidence selection; he wants to ensure his evidence both fully supports his question, fits what his teacher is asking of him, and is empirically valid.

In the following two days, the pairs reconvene to discuss their findings. The NPK tests from the garden indicate that all three beds have adequate Phosphorus levels, the worm and compost beds have sufficient Potassium while the fava bed is depleted, and the Nitrogen level is surplus in the compost, sufficient in the worm bin, and deficient in the fava. While most of their talk on Day 7 focuses on determining a solution rather than discussing model evidence, Doug does express surprise that “We just got it wrong; you thought the fava and we thought worm, and they’re really just wrong,” indicating they believe their model evidence did not appear to suggest fava or worm soil was the best. From this stance, they claim that, “Out of the worm, fava, and compost soil, the one that adds the most nitrogen and nutrients is the compost soil,” given that the worm soil requires more water to maintain worm populations, and the fava soil test showed low nitrogen values.

In their presentation, they use a bar chart of the NPK levels as their garden evidence, ranking the soil types as compost having “the most nutrients, worm bin being the second, and fava having the [least]”. For model evidence, Chanda presents a screenshot from her model, though she struggles to explain it. She starts by saying, “Pink represents the nitrogen in the soil, and you can see…” trailing off, while Doug jumps in to add, “It’s a lot.” She agrees with him, saying “Yeah there’s like a lot,” before they move on to the next slide. Ultimately, the relationships between the model plants and the soil, or measurements they started to explore do not get incorporated into their reasoning around their claim, or in particular why even though the garden fava showed depleted nitrogen levels, their modeled fava had “a lot”. I attribute this action to Chanda and Ilyse wanting to demonstrate their competence in changing the model code to make fava, even though they had less understanding of the evidence they could then generate towards their research question.

Despite the disconnect between the model fava and the garden fava, Doug and Trey are able to use their model evidence to add more context and warrant their claim about why the worm soil isn’t ideal. Using selected screenshots, they thoroughly describe the relationships they explored in the model, with Trey indicating that the worm soil is, “Pretty high maintenance, and so it takes a lot of water and nutrients to make that happen.” Doug also refers to one of the hydration histograms to indicate low water levels, appeasing Ms. Moss’s request for quantitative data. The group concludes by advocating for a compost tea machine to apply compost based on its high nutrient profile, proposing to use excess food from the school’s cooking class to save costs; the machine creates a nutrient rich ‘tea’ that can then be quickly and dispersed to multiple garden beds.

4.6.5.1.4 Working with the model for evidence elevates their epistemological stances towards modeling

When working with the models, the group members have different views about the utility, rigidity, and legitimacy of model data. Chanda initially believes there is a 'correct' way to model, and fears straying from the example numbers I generate in the tutorial video. She considers the model as a source of evidence, though one she feels conflicted about. Initially uncomfortable, she remains focused on what the model work *is for*. She is the one framing questions around whether the model reflects fava, reveals information about nitrogen, can generate graphs, and the use of their data. Contrastingly, Ilyse explicitly states to her partner early on that, "There's no right number, we just choose a number, you can choose your own code," and deviates from the values used in the tutorial videos without hesitation. She uses the code as a space to test out her ideas, support her own goals (earn money) and after making code changes, intently focuses on the interface as a space to revisit the relationships between model elements. Doug initially perceives the model as inappropriately hard for his age group, though eventually shifts to demonstrate an element of control and pride over keeping worms alive in his garden model. His desire to share his model changes with his classmates, and check in on Chanda and Ilyse's model, indicate that he sees modeling as a social process that includes justifying one's choices. Additionally, his frustration with the quantitative data generated by the model indicates that he believes the model could contain limits or patterns that he does not agree with, and ultimately chose to reject the quantitative values as a source of evidence. Even though Chanda and Ilyse were not able to fully contextualize their model evidence with the NPK tests to make sense of the fava soil's low nitrogen profile, Doug and Trey's model evidence provided support to the claim that the worm soil was not the primary choice between the three, which led to this group's "balanced" efforts.

4.7 Summary of findings

RQ1: In what ways do students select and apply evidence collected during an investigation about the garden towards a scientific claim and ecological solution?

Qualitative analyses of student work including phrasing of research questions, collection of evidence, evidence use in presentations, and integration of data in scientific claims revealed four categories of evidence use: balanced (M=G; 11 groups), model-privileged (M>G; 8), garden-privileged (G>M; 3), and outside-privileged (X>M; 2). Students' foci varied through different stages of students' activity, and in particular between the generation and application of evidence. Students' beliefs of how convincing certain types of evidence were, their abilities to make sense of certain types of evidence, and their feelings about the model were also seen as influential in their evidence use.

In particular, students that struggled to connect the model outputs to their research question frequently included irrelevant model evidence, or turned to outside evidence to support their claims, likely motivated by a desire to adhere to the assignment structure, or in the case of outside evidence, the ability to find more familiar, interpretable data. As students applied evidence to advocate for a solution for their school garden, it is plausible that some believed evidence collected from this realm was more relevant for their claim. Conversely, the ability of the model to provide a controlled environment with two conditions led others to privilege model evidence in their claims. Many students provided screenshots of the model interface or the output graphs without additional descriptions or interpretation as their primary model evidence, indicating either the epistemic power that students may have attributed to the model, or underlying challenges to interpret it (Sandoval & Milwood, 2005). Persistent discomfort with the model, especially to change the code, was a struggle for many students; if students were unable to find 'success' with the model, they often resisted engaging in evidence generation or doubted their findings. Though many students were able to overcome this initial discomfort, some might have privileged model evidence as a means to demonstrate their competence in changing the code. Most groups (79%) approached model evidence collection as an opportunity to build off their garden evidence, either by attempting to replicate their findings or triangulate them with specific new information. This coordination of evidence sources was necessary, though not sufficient, for categorization in the balanced group. Students that indicated awareness of the limitations of their evidence sources frequently provided a claim that provided a balance between garden and model evidence (Hardy et al., 2020).

In the case studies, two groups rejected model evidence. Lacey, Ally, and Nia felt the model was not useful for their question as neither version contained the combination of elements they desired (multiple crop varieties + nutrient and hydration histograms). Nia, who was deemed "good at the model" based on her ability to turn a profit, presented the model as a resource for the cost-benefit analysis aspect of the presentation. The other group that rejected model evidence (X>M) demonstrated a concerted effort to generate new code and interpret existing graphs, to indicate the impact of bees on plants. However, they appeared to struggle with this endeavor, and ultimately determined the model to be inconclusive. Instead, they researched pollination online and used their findings to reconstruct their garden evidence, demonstrating a causal relationship between bees visiting plants and a change in roughness.

In the M>G case, the teacher helped the group to see that a confounding variable was contributing to the contradiction between the group's model and garden evidence. Mori, who generated the model evidence for her group, provided theories about the mechanism of plant roots' nutrient absorption to justify why the model evidence was 'more realistic' than the garden evidence in support of their claim, rather than attend to the nuance or program the model to represent the phenomenon of intercropping. In the M=G group, challenges to define variables of interest (soil quality) led the group to select garden evidence that explicitly provided a distinction between three soil types, the NPK test. However, their process of changing the models to authentically represent their theories about worms and fava led them to discover relationships between model elements on the interface, which Doug and Trey were able to discuss in their presentation by generating screenshots at different points in time. Struggles to generate quantitative data after spending so much time changing the code limited Ilyse and Chanda's ability to provide model evidence about fava that supported their claim.

RQ2: How is the model, in its representation of the garden and production of simulated data, viewed as an instrument?

At the whole-class level, students demonstrated a wide array of instrumentalization activity with the garden model (Table 7). They tinkered with the construction of models to help with their investigations, as well as innovated on the 'rules' by coding in novel ways, indicating a perspective that models are dynamic and malleable tools that can support a variety of inquiry tasks. For most code changes, the tutorial videos were a vital resource, that perhaps reinforced for some a belief that there was a 'right' way to model (by following the video). Many used models to run a controlled experiment, manipulating one variable to show the impact on another, or showing differing impacts between multiple variables. Students were also able to use models as a space to observe the existing patterns between ecosystem elements without much manipulation, including keeping track of the complex conditions that led to emergent outcomes (such as bees, or fungus). Many students also were drawn to the model as a tool to demonstrate economic principles associated with gardening, and became highly focused onto the money output as a gamifying principle (Plass & Schwartz, 2014), viewing this as a marker of 'success'.

From these variety of activities, most students were able to generate model evidence that was related to their research question; fewer included model evidence related to their scientific claims, and fewest positioned model evidence as something that should be supported or checked by the garden evidence when creating a claim. Those that were successful with this last task sometimes used the model to reaffirm patterns that they observed from the real world, though some also became aware that this was a limitation in that they could program the exact results they wanted to see. Many students also felt they could not use the model without significant knowledge in coding, indicating a stance that models are limiting as a resource without prior experience or skill sets.

The case studies provided a deeper picture of how students viewed the models as instruments, which in turn likely impacted their decisions to select certain types of evidence. In the G>M case, the students perceived the model as a game that could be won by earning money; as a result, their actions that didn't result in profits or successful compilation of the model, led to a perception that the model was something they were bad at, and therefore not worth pursuing for evidence. While their work with the model indicated they could use it to show multiple outcomes from manipulating controlled variables, they ultimately determined the model elements did not show the exact outputs they wanted and so were incompatible with their research question, and therefore no data were used.

In the X>M group, the group viewed the model as a tool that could be edited to incorporate a theory about bees and soil hydration, though it was not ultimately successful. They also intended to use the model as an instrument that could demonstrate a cause/effect relationship between bees and plants; this perspective shaped how they interpreted the model generated graphs, which ultimately led to the conclusion that the model was showing inconclusive results, and therefore was an unreliable source of evidence. Similarly, for the M>G group, the model was viewed as an instrument that could perform precise scientific experiments to show a cause and effect, by running the model twice and changing a single setting. Importantly for this group, this feature of the model appeared to eliminate confounding variables that were present in the garden evidence. Mori used model-generated data to create new population graphs, which served as a visual marker that enabled her to demonstrate mathematical and scientific knowledge to her teacher and classmates. This action, as well as her quote that the model was 'more realistic', indicate a viewpoint that the model has a greater epistemic authority than other types of evidence (Hug & McNeill, 2008).

Pride in the ability to use the model as an instrument was also a factor in the G=M case, though only after the pairs made successful changes to the code. Doug initially thought the model was not an age-appropriate instrument, though after he added worms, excitedly shared his progress with his peers. Both pairs in this group used the model as a tool to better understand their existing theories about elements from the real world, and observe how their coded changes impact other variables. Chanda and Ilyse had conflicting views of the model; Ilyse maintained the (instructed) viewpoint that models can have whatever you want in them, and appeared to enjoy changing the code to save money, and added unique numerical values to change the plant behavior. Her partner, Chanda, rigidly maintained there was a 'right' way to use the instrument, and believed it was embedded within the way enacted in the tutorial video. While Doug and Trey generated screenshots that enabled them to describe a relationship between the worms and the soil conditions, Doug doubted that this evidence was enough for their research question, potentially indicating he saw the model as an instrument that primarily was used to generate quantitative evidence. However, the quantitative data he did generate behaved in a way that defied his expectations, and rather than question his data collection method (like he did in the garden), he rejected the data altogether. Doug appeared to question whether there was a population limitation embedded in the model, indicating that he viewed the instrument as a tool that, like the X>M group, should support his existing theories to be useful.

4.8 Discussion

The results of this design-based research study showed the variety of approaches students took in gathering evidence from their school garden and a computational model of a garden ecosystem to advocate for action to improve the garden. While guided to use both the garden and the model as evidence sources, analysis of the open-ended activity design revealed that students' evolving model epistemologies appeared to influence how they treated data from the model, and their final scientific claims showed four distinct categories of epistemological stances toward model data. This openness was distinct from how many students had experienced science class before, which was visible through ample frustrations to understand and work with the model in a subjective way. For some, however, it led to new experiences in testing their individual hypotheses through computational relationships, and ownership in justifying their choices to their community of peers. Though many student groups were able to balance the use of evidence from the physical garden with evidence from the garden model, this was not the universal experience: several students privileged model evidence over garden evidence, while a few privileged their garden evidence over the model evidence, and some turned to outside evidence from the internet to support their claims. These clusters of student activity were elaborated through four case studies that show links between students' underlying model epistemologies and their ultimate treatment of evidence.

While it is unknown what students' initial orientations or inclinations were entering the activity, they engaged in a social task that involved refining and justifying their experimental approach with their peers, the teacher, and researcher, and therefore were likely influenced by the thoughts and actions of others. The social nature of the task is especially important to consider as students collectively negotiated the meaning of data and evidence over the course of activity, as they became more familiar with the model, identified limitations of their evidence-gathering tools, or confronted the boundaries of their research questions. In particular, students' discussions about evidence sources positioned the model as trustworthy or not, as it "screwed [them] over"; "was contradictory"; and "was more realistic [than the garden]," and included or excluded evidence to support their claims accordingly.

Students also appeared to have experimental epistemologies where demonstrating a causal relationship between two explicit variables shaped how they approached the model, and decided whether it was useful. As scholars have noted (Windschitl, Thompson, & Braaten, 2008), while experimental design is often lauded in science class, educators and designers should consider framing modeling activities so not to rigidly maintain this mindset, as in this case it led some students to see the model evidence as more reliable than the actual garden they were looking to improve. Alternately, educators should be aware of students' perceptions on the reliability of models, and how development in model-based reasoning, or graph interpretations, may impact how reliable they determine them to be. As many have found, for ABMs in particular, the cognitive load required for students to develop inferences from the code, graph, or other quantitative outputs seems more challenging than developing inferences from the interface. In this study, this distinction substantively impacted the degree to which students trusted the model as a sensemaking resource, or incorporated its data as a source of evidence.

4.8.1 Design implications

The type of deep engagement developed through this study was supported by several design elements, and a framework that positioned students as agentive and resourceful throughout the process. Three levels of scaffolding allowed students to explicitly examine the model vis-à-vis other sources of evidence, and each revealed limitations of the design: (1) the activity / assignment structure that incorporated the physical and virtual model; (2) worksheet prompts that encouraged direct comparisons and limitations of evidence sources; and (3) comments within the model code that encouraged hypothesis testing and tinkering.

The open-ended inquiry project situated in students' shared environment put their interests, and the outcome of their efforts, at the forefront of their work; the result was a synergistic impact on the garden ecosystem's health, as the many of the proposals were enacted after the unit concluded. The assignment structure allowed and encouraged change as students gathered more information, and having two evidence sources that were differently complex enabled comparison of the merits and limitations of each. However, having only one day of evidence collection in the garden potentially limited the type and complexity of data that students could attend to. Future interventions might consider extending the time allotted to this portion of the activity, especially so that students looking to observe direct causal relationships could compare the outcomes between physical and virtual experiments, such as in Blikstein et al. (2012). This extension might also enable students to develop a more nuanced understanding of how models can be validated and improved by empirical evidence, which was not fully realized in this study.

Another important design feature that supported students' agency when working with ABMs were worksheet scaffolds that prompted attention to the limitations of the evidence sources. When these prompts successfully enabled students to become aware of these limitations, students could integrate multiple sources of evidence and still critically evaluate the material and technological resources. However, the frequency in which students were asked to reflect on their own knowledge and resources was deemed by some to be repetitive, and as a result not all students engaged in this written reflection. Future designers and educators should consider other modalities, such as whole class discussions, that may enable this type of reasoning without becoming taxing.

The model was a central feature of this activity, and collaboration with the teacher prior to instruction led to the inclusion of several elements that were anticipated to align with students' existing knowledge and content standards. That being said, the act of modeling was seen as new and scary territory for many. While text-based directives within the code were included to support students in adding new features to the model, testing different values, and connecting model behaviors to their knowledge of the physical garden, participants did not appear to engage with them. Instead, they heavily leaned on the researcher for modeling knowledge and troubleshooting, leading to the creation of tutorial videos. These videos were vital in supporting students embarking on code changes, though this was still a challenging feat, and many, though not all, hesitated to deviate from the values used in the tutorial. To support students in individualization and tinkering with code values, those looking to incorporate ABMs as a resource for evidence in science instruction should place greater instructional emphasis on the connections between coding and theory building (Louca & Zacharia, 2012), as the written scaffolds did not seem to be referenced by students during this study.

4.8.2 Conclusion

Together these design strategies enable students to develop an agentive investigative stance, questioning the authority of technological tools while also making them their own (Develaki, 2019). This project reveals the possibilities that abound when models are instrumentalized towards solutions that better a local community. By having their wider experiences as a resource, they could truly ‘do science’ by integrating their own hypotheses, interests, and values to determine the tools and outcomes best suited to their investigations. Additionally, considering models as a tool for evidence, balanced with first-hand evidence collection in an inquiry based project, reveals insights on a variety of underlying model epistemologies that can develop and shift during practice. These insights support educators and designers to expand their efforts to incorporate ABMs into situated contexts, where students can develop epistemic agency and meaningful application of their model and evidence-based practice.

5 Conclusion

This dissertation collection examines the interplay of learners, technology, and agricultural environments through science-class investigations of ecosystem dynamics in two distinct cultures. In the first paper, I used a large-scale activity theory and a social-ecological systems lens to explore the interplay of cultural and community resources in a national secondary education program. Many weeks of field work and text analysis revealed theoretical connections from the SAT program to culturally-sustaining pedagogy and place-based science-reform movements, modeling principles of equitable, meaningful education opportunities in rural Honduras. The second paper followed an iterative design-based research arc through the design of a simulated garden ecosystem that could simultaneously promote deep investigation of a familiar space and strengthen students' understandings of the theoretical and computational contributions of modeling tools. As the design and instruction evolved, I developed a framework (PIQ) to emphasize key features of the learning environment, with nested layers of purposeful application, instrumented + situated negotiation, and quantitative reasoning. The final iteration of the DBR study was reviewed in the third paper, where a three-week inquiry project enabled students to develop and present diverse epistemological stances towards the model as they evaluated its utility as an evidence source.

While the two settings investigated in this study had many distinctions, including the role of agriculture in the community and availability of technological resources, there were a few key themes that arose in both environments. The two instructional environments incorporated similar features of the local ecosystems, including the soil profiles, nutrient contents, planting techniques, and impacts of extreme weather. The overall health of the ecosystem was used by instructors in both contexts as a proxy for students to demonstrate successful understanding of scientific knowledge and efficient use of resources. In Honduras, students were tasked to replicate the practice of developing nutrient-rich compost by establishing garden beds in front of their homes, both to expand their impact on the land and to promote scientific knowledge to their families. In California, students' presentations contained a design solution to improve the health of the garden, which was founded on the collection of diverse evidence sources and cost-benefit analysis of competing solutions.

Additionally, in both contexts, participants varied on their perceptions of the trustworthiness of technology; in Honduras these beliefs were largely held by parents and were mediated through conversations with students, tutors, and administrators. While the texts were overt about honoring and establishing multiple perspectives on technology implementation, the impacts of eventually not adapting the agricultural technologies (including organic compost building, efficient irrigation, integrated pest management) were likely to have dire consequences for the physical health and of both the ecosystem and members of the community. As a result, shifting this perception is a high priority for instructors and a goal of the SAT program. Contrastingly, when students were averse to using the computational model of the garden, they found other ways to adapt and still achieve the same results as their peers; they could continue to use computers to find evidence sources or use the model in other ways that fulfilled their assignment expectations, without any severe impact on their personal well being or the health of the environment. By *not* forcing students to align with the adopters of the model as an evidentiary resource, the activity design afforded them more agency to see the technological tool as a contestable option to support their learning in this inquiry environment. For both sets of students, adapting to new technologies involved persistence, guidance, and confronting their previous conceptions about both their own competence and the local environment they were working to impact.

A comparison of these settings illustrates that communal knowledge plays a much different role in each: whereas in Honduras the involvement of parents and community members was vital to both the enactment of the projects and the persistence of knowledge throughout the community, in California the classroom and school community remained the focal point of interaction. In the SAT program, the tutors, who could be community outsiders, had to work to establish trust and rapport within the community to help develop new scientific knowledge, in the California classrooms, an outsider's (me) technological knowledge was highly valued, despite attempts to create an environment where students felt agency in decision-making and code authoring. These comparisons highlight the cultural differences and values attributed to both longstanding practices, technological innovation, and the impact that education (on ecosystems in particular) can have in the lives of students.

This collection of studies advances knowledge about place-based science education, and in particular how students across global agricultural contexts develop fluency with new technologies to learn about ecosystem science. The design framework developed helps designers and educators ground these technologies within meaningful contexts. Focusing on how learners negotiate their new technological knowledge with their situated knowledge of place provides a unique research context for examining the development of their epistemological stances. Beyond its use as a retrospective design framework in this dissertation, PIQ could be used by teachers as a conceptual tool for planning activities that center the development of technological reasoning within a place-based context. In addition to teachers' benefit, the co-evolution of situated knowledge of place and instrumented technological knowledge offers students the opportunities to develop practical design skills alongside the means to conserve and protect their local environments. For the world of modeling, this dissertation offers a practical tool of an ABM situated within students' lived experiences. The model elements encompass features applicable to many kinds of school-based agricultural environments, and coding scaffolds direct students to use their knowledge of plants and gardens as a starting point for tinkering with the code and developing diverse types of quantitative reasoning.

As a next step, I anticipate more analyses could be done from the classroom study data, in particular of the computer screen recordings of students' modeling work, that can elevate key markers of situated knowledge influencing instrumental genesis, especially as a tool for overcoming challenges to understand and apply the model. The case study data could also be enriched by analyzing more peer groups in depth, and quantifying the degree to which certain factors that were revealed to be influential, such as a student's pride in their code, fixation on the model as a game to be won, or challenges interpreting the model outputs, were present throughout the whole class dataset. Beyond this study, future work in this realm can continue to explore how students develop epistemic agency in their science education, by allowing them to contest the design, use, and application of modeling tools as resources for learning in science class. In addition to modifying an existing model of the garden, students could develop robust epistemological stances through collective activities such as evaluating their peers' models of similar concepts under study (nitrogen, for example), or focusing on one component, such as the relationship between weeds and the soil, and engaging in a class-wide discussion to address the hypothetical nature of the quantitative behavior coded within, tasking students to test and evaluate this component to move towards a communal understanding of models as representations of ideas, that can be validated or changed.

In the year of this dissertation being published, a global pandemic has isolated students from their collective school settings, and teachers have been forced to facilitate online instruction. One possibility for extending this work, that approximates the activity in SAT where students built gardens in their homes, is to have students evaluate the garden model as a tool for reasoning about an ecosystem accessible to them at home, be it a backyard garden or seed in a cup. The degree of focus and prolonged access that an individual could have with the environment, plus the diversity of student experiences distributed across an entire class, could provide valuable hands-on instruction and fodder for class-wide engagement during a time where such opportunities are difficult to manufacture. A way to make this type of instruction even more accessible would be to develop scaffolding questions and curricular guides for students of diverse ages and abilities, as the model design in this study is most accessible to students in high school. Fortunately, new modeling tools such as NetTango can alleviate the cognitive challenge of programming by simplifying code into functional blocks; I see this as one goal for my future work to enable the longevity of the model as an educational tool. Another goal mentioned in Chapter 3 that was not fully realized is to translate the model into Spanish and provide the source code to administrators of the SAT program, such that it could be used as a simulation tool to advance computational knowledge and agricultural planning by tutors and students in Honduras.

In summary, this dissertation provides a wide and deep theoretical perspective of technology-driven ecology education, with an activity system that expanded to include the wider social-ecological system, and narrowed to emphasize individual instrumental genesis. Applying a similar theoretical approach to two distinct instructional environments allows for a greater appreciation of the interaction between context, culture, and cognition that drives learning in place-based science education. In addition to theoretical knowledge, I offer practical tools for educators to envision and plan expansive educational opportunities that aim to make science a more inclusive, generative, and conscious discipline, with the goal to equip students with the resources to understand and protect the natural environments around them.

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Appendix A: Honduras study interview protocols (English and Spanish)

Tutors:

First I want to thank you for taking the time to talk with me today. We are interested in understanding how tutors prepare to teach and students make sense of the SAT lessons. Your thoughts are incredibly valuable contributions to our research! Today I'll be asking you about your personal experience, as well as your thoughts on a few particular SAT workbooks. The interview should take about 45 minutes. Could you please state your name, how many years you've been a tutor, and what grade you work with currently?

<u>These first questions are about your experience as a tutor:</u>

-What about the SAT program motivates you to teach?

-What school activities do you think were most memorable for your students in the past year?

-What are some examples of lessons you taught in the past year that engaged students in improving the social and ecological health of their community?

-How do you prepare for teaching a new lesson?

<u>These next questions will be about the</u> (*fill in with particular training workbook*) <u>text</u> (*Offer the book to interviewee to review)*

-How did you prepare/teach this unit?

-What were the activities like?

-In what ways was the lesson contextualized within the community?

(*Ask about a particular science concept)*

-Could you describe for me this concept?

-How can you tell if students understand this content?

-What ways are they assessed on concepts like this?

-How do they, and you, receive feedback about their performance?

<u>The following questions will be about your perspective of your students.</u>

-What were some concepts that your students struggled with? How do you help them come to understand it better?

-How do you encourage or maintain effort of students as they progress through school?

-Have you ever had a student ask you a question that you don't know the answer to? If so, what have you done?

-How do you think SAT prepares students for their future?

<u>The final questions are about connections between science and agriculture.</u>

-What do see as the relationship between humans and the environment?

-This question has two parts that sound similar but are a little different:

-*Why* should students learn about science through practicing agriculture?

-*Why* should students learn about agriculture through practicing and developing scientific skills?

-What specific technologies would be most beneficial for teaching science and innovative agriculture?

Students:

First I want to thank you for taking the time to talk with me today. We are interested in learning about how students make sense of their school lessons. Your thoughts are incredibly valuable contributions to our research! Today I'll be asking you about your personal experience, as well as your thoughts on a few particular textos. The interview should take about 30 minutes.

Could you please state your name, and what grade you are in?

<u>These first questions are about your experience as a student:</u>

-What about school excites you?

-What school activities were most memorable for you in the past year?

- How do you feel your education will help you in your future?

-What are ways that your tutor uses the workbooks (textos) to make the content interesting?

-What was something you struggled to understand? How have you come to understand it?

<u>These next questions will be about the</u> (*fill in with particular training workbook*) <u>text</u> (*Offer the book to interviewee to review)*

- What do you recall from this unit?

-What were the activities like?

-In what ways did your lesson relate to your community?

(*Ask about a particular science concept)*

-Could you describe for me this concept?

<u>The next questions will be about how school relates to your community.</u>

-What was one lesson you can think of that was related to the health of your community? Describe it in as much detail as you can

- What direct steps do you feel empowered to take to improve the social and ecological health of your community?

-How has your sense of responsibility towards your community developed through the program?

<u>The final questions are about connections between science and agriculture.</u>

- What do you see as the relationship between humans and the environment?

- This question has two parts that sound similar but are a little different:

-How can students learn about science through practicing agriculture?

-How can students learn about agriculture through practicing and developing scientific skills?

Tutores

Antes que nada quiero agradecerle por tomarse el tiempo de hablar conmigo hoy. Estamos interesadas en comprender cómo se preparan los tutores para ayudar a los estudiantes a entender las lecciones de SAT. Sus opiniones son muy valiosas para nuestra investigación. Hoy le voy preguntar acerca de su experiencia personal así como su opinión acerca de algunos libros de texto de SAT. Esta entrevista durará alrededor de 45 minutos.

Por favor dígame su nombre, cuánto años ha sido un (a) tutor (a) y qué grado está dando en la actualidad.

<u>Las primeras preguntas son acerca de su experiencia como tutor (a):</u>

-¿Qué cosas de SAT la (o) motivan a enseñar?
-¿Qué actividades piensa que fueron las más memorables para sus estudiantes el año pasado?
-¿Puede darme algunos ejemplos de lecciones que usted enseñó el año pasado que motivaron a sus estudiantes a mejorar algún aspecto social o ecológico de sus comunidades?
-¿Cómo se prepara para dar una lección nueva?

<u>Las siguientes preguntas van a ser acerca del texto de</u> __________________________ (texto específico/ ofrezca el libro al entrevistado para que lo revise el entrevistado).

-¿Cómo prepara/ enseña cada unidad?
-¿Puede describirme cómo eran las actividades?
-¿En qué maneras contextualizaba la lección dentro de la realidad de la comunidad? (Preguntar acerca de un concepto científico en particular*) (leading)*
-¿Podría describirme este concepto?
-¿Cómo sabe si los estudiantes entienden este contenido?
-¿En qué maneras se evalúan estos conceptos?
-¿Cómo reciben retroalimentación tanto usted como sus estudiantes acerca de su desempeño?

<u>Las siguientes preguntas van a ser acerca de su perspectiva de sus estudiantes</u>

-¿Cuáles eran algunos conceptos con los que tuvieron más problemas sus estudiantes? ¿Cómo los ayudó usted a comprender estos conceptos?
-¿Cómo motiva a sus estudiantes a esforzarse o a mantener sus esfuerzos en sus estudios?
- ¿Alguna vez algún estudiante le hizo una pregunta que no pudo contestar? De ser así, ¿qué hizo usted?
-¿Cómo piensa que SAT prepara a los estudiantes para el futuro? (This is leading)

<u>Las últimas preguntas son acerca de las conexiones entre la ciencia y la agricultura</u>

-¿Cuál piensa usted es la relación entre los humanos y el ambiente?
- Esta pregunta tiene dos partes que parecen similares pero son algo diferentes:
¿Por qué piensa que los estudiantes deberían aprender ciencia a través de la agricultura?
-¿Por qué los estudiantes deberían aprender agricultura a través de la práctica y desarrollo de habilidades científicas?
- ¿Qué tecnologías serían las más beneficiosas para enseñar ciencia y agricultura innovadora?

Estudiantes:
Primero quiero agradecerle por tomarse el tiempo de hablar conmigo hoy. Estamos interesadas en aprender cómo los estudiantes estudian y entienden las lecciones del colegio. Sus opiniones y experiencias son contribuciones muy valiosas para nuestra investigación. Hoy le voy a preguntar acerca de su experiencia personal así como sus opiniones acerca de algunos textos. La entrevista va a tomar alrededor de 30 minutos.

Por favor dígame su nombre y en qué grado está.

Las primeras preguntas son acerca de su experiencia como estudiante:

- ¿Qué cosas le emocionan de la escuela?
-¿Qué actividades piensa que fueron las más memorables para usted como estudiante el año pasado?
-¿Cómo piensa que la educación le va a ayudar en el futuro? (leading)
- ¿Cómo usaba su tutor los libros de textos para hacer el contenido interesante? (This is leading).
- ¿Puede pensar en algo que te costó entender? ¿Cómo logró entenderlo?

Las siguientes preguntas van a ser acerca del texto de ___________________________ (texto específico/ ofrezca el libro al entrevistado para que lo revise el entrevistado).

- ¿Qué recuerda de esta unidad?
-¿Cómo eran las actividades de esta unidad?
- ¿En qué maneras esta lección se relacionaba con su comunidad? In what ways did your lesson relate to your community? (Leading)
(*Preguntar acerca de un concepto científico específico)*
-¿Podría describirme este concepto?

Las siguientes preguntas son acerca de cómo el colegio se relaciona con su comunidad:

- ¿Puede mencionar alguna lección que usted piensa que estaba relacionada con el bienestar de su comunidad? Por favor, descríbala con tantos detalles como sea posible.
- ¿Qué cosas piensa usted que lo empoderaron para mejorar el bienestar social y ecológico de su comunidad (leading).
- ¿Cómo se ha desarrollado su sentido de responsabilidad para con su comunidad a través de SAT? (leading)

Las últimas preguntas son acerca de las conexiones entre la ciencia y la agricultura
-¿Cuál piensa usted es la relación entre los humanos y el ambiente?
- Esta pregunta tiene dos partes que parecen similares pero son algo diferentes:
-¿Por qué piensa que los estudiantes deberían aprender ciencia a través de la agricultura?
-¿Por qué los estudiantes deberían aprender agricultura a través de la práctica y desarrollo de habilidades científicas?

Appendix B: DBR full study methods

Iteration 1

In collaboration with a local public school district in Northern California enacting garden-based education at its elementary and middle schools, I helped design curriculum for and facilitate math and science activities at a middle school with a new school garden. (School demographics report approximately 30% of the student population is Black or African American, 36% is Hispanic or Latino, 64% of students Socioeconomically Disadvantaged, and 17% of students with Disabilities.) The school was selected as a site for data collection because it is within a district that actively designs and implements school gardening curriculum at the K-5 level; the researcher had been a consultant and designer for this larger project. As such, the teachers had provided feedback to the district team on particular garden-based curricular units piloted in Math, Science, and Humanities lessons.

Six middle school students, who were staying after school and volunteered to participate in the study, ranged in age and gender: three were sixth grade females, three were eighth grade males. The sixth graders had received two units of garden instruction with their science class and math class, while the eighth graders had little previous garden instruction due to staffing and space constraints at the school. All student names have been changed to pseudonyms to protect their anonymity. An invitation to participate in the study was sent via email to all middle-school teachers that had participated in the garden program in the past year. Four teachers agreed to participate: one 7th/8th grade science teacher, one 6th grade math teacher, one 7th grade humanities teacher (English + social studies) and one 8th grade humanities teacher. Teachers reviewed a consent form and were compensated with a $15 gift card for their participation; their names have also been changed to pseudonyms.

Each participant was informed that they were to participate in a roughly 30-minute interview to provide feedback on a computer program created by the researcher. After assent was provided by participants, video data were recorded to document the computer screen as participants manipulated the program. All of the interviews were one on one, with the exception of one, where two students requested to do their interview at the same time; however, one of those students ended up leaving early, so the resulting data were largely individual. An additional student had to leave within the first few minutes of their interview. This left a total of four complete student interviews (around 80 minutes of video data) for analysis: Marco, Jorge (eighth grade males), Amelia, and Catie (sixth grade females). Teachers additionally completed a survey on their teaching experience, including their prior use of simulations. The four interviews total 153 minutes of video data. The teachers will be referred to with the following pseudonyms: Mike (Science), Gerry (Math), Peter (7th humanities), and Laura (8th humanities).

Participants were asked to employ cognitive think-aloud while they explored the simulation and performed a series of tasks, while responding to questions from the researcher to elicit their reasoning during those tasks (interview protocol in Appendix A). This format was utilized to better understand how people reason with the model, attending to the particular resources that were used, and ones that were requested/ seen as lacking from the tool. After running the simulation, participants were then asked to suggest additional academic applications or design decisions they could foresee implementing with the model. This structure allowed for both reasoning with and evaluation of the model, current practices identified in the Next Generation Science Standards (NGSS Lead States, 2013).

Analyses were conducted using conjecture maps as a framework for categorizing participants' actions and reasoning about the model. Results include a variety of disciplinary applications that were considered by teachers, and a correlation between previous experience with gardens and content-based design suggestions (as opposed to interface-only or content-neutral suggestions). Organizing participants' utilization schema within the conjecture maps revealed particular resources that support learning goals across contexts within the same artifact, providing insight to the design of interdisciplinary instructional tools.I analyzed the curricular connections and contextual resources participants identified when navigating the model, as well as features they proposed to support their own learning, or for teachers, connect to academic disciplines.

Iteration 2

After uploading the model for use on a browser platform, I conducted a pilot study in February of 2018 with three of Mike's seventh-grade science classes. The week-long curricular unit, collaboratively developed between the both of us, centered on developing student understanding of what computer models are, and how they function. The structure for investigating this question included a pre-assessment on computer models and introduction to the research project on the first day, a video on the use of computer models in predicting weather patterns on the second day (teacher and researcher were absent), and three days investigating the local school garden and garden simulation model, with a post-assessment on computer models at the end of the final day. Students were split into two groups for the duration of the unit, where each group would spend 1.5 class periods in either the garden or with the model before switching; the science teacher facilitated activities in the garden, while the researcher facilitated activities with the model. The teacher developed all physical handouts and assessments; the researcher developed the garden model, and discussion prompts for the garden and model investigations.

Across the three class periods, eight students participated in the research component; four in one class period, and two each in the two other periods; Mike also consented to participation as a research subject. Students were provided a hand-held camera and told to video narrate their experiences in both settings; for the model, this involved filming the computer screen as they worked. In the class period with four participating students, a tabletop camera captured student discussion about their homework and findings on the last day. Participating students' worksheets were collected and scanned at the end of the unit. A camera positioned at the back of the classroom captured whole-class instruction and instructional materials displayed on the board; Mike wore a go-pro camera during sessions in the garden to capture his instruction to students.

Given the few number of participants, student data were organized in individual cases, connecting their worksheets (where they recorded their initial and final perceptions of a computer model, as well as their notes from each context) to their video data, mapping their journey from the garden to the model and back again. Analysis primarily centered on how their situated and instrumented knowledge of ecosystem elements were elicited in each activity, and used to support 1) their claim about the impact of one variable on another in the garden ecosystem, and 2) their post-assessment of the purpose/functionality of computer models. While data were preserved in this case structure, analytical segments were taken with respect to the PIQ framework that emerged in the design study to present potential patterns in activity or thought-process.

Iteration 3

The final round of study took place in April of 2019 in four ninth-grade science classes at a public high school in Northern California, with minimal previous garden instruction; 101/116 students consented to participate in the research component. [28/32 in p.2; 24/26 p..3; 30/32 p.5; 19/26 p.7] The curricular structure, enacted over 3 weeks of instruction (each week consisted of one 45-minute session and two 90-minute sessions), was collaboratively designed by the researcher and classroom teacher, who wanted to focus on Human Impacts on Ecosystems, a unit in the CA Living Earth curriculum. Particular content standards and science/engineering practices from the NGSS were also used to frame student activities. An early planning session led to major revisions in the garden model (see elsewhere) to add features that related to this topic. All hand-outs and assessment rubrics were created collaboratively.

Participating students took a survey outlining their affinity and experience for both gardening and computer programming. Then all students had a short lecture about the overview of the unit and expectations for action projects, models/modeling, and an activity where they made the case for which ecosystems demonstrated the most human impact. The following day students conducted initial observations in their school garden, attending to the biotic and abiotic factors, evidence of human impacts, and began to develop questions for inquiry. The next day students explored the model with several guiding prompts/goals to explore varying conditions and outputs. Following this, the teacher modeled how to develop a testable research question, and students grouped up to develop a question of inquiry for the next phase of the project. Students completed an evidence-collection form where they documented what type of evidence they would gather from both the school garden and the model to support investigation of their question. Then students had one 90-minute period in the school garden to collect qualitative + quantitative data, followed by a 90 minute period utilizing the garden model to collect simulated data. During this time students were encouraged to add and elaborate on the model's code, supplemented with video tutorials from the researcher addressing common questions (how to add an element, track a new variable, etc.). Video data was a primary source for this phase: one camera captured lecture instruction and presentation slides from the teacher and researcher for each lesson; 8 research laptops were distributed randomly to encompass different groups of students as they worked with the model, these recorded the screen and participant audio/i-sight camera; student groups also took hand-held cameras into the garden to video narrate their evidence gathering, as in iteration 2.

After gathering evidence, students were instructed to generate a claim about their school garden based on their data. For the last few sessions, students put together a presentation detailing their investigation, using evidence from both the model and the garden, as well as a plan to improve the health of the garden given the outcome of their research. Some participating students also elected to create short feedback videos detailing the parts of the project that surprised them, were pleasing to them, and challenged them. From these activities, the data collected include survey results, all written handouts, copies of presentation slides, html files of student code revisions, video of the classroom, groups in the garden, and screen recordings, as well as audio recordings of participating groups of students as they collaborated on their questions, claims, and evidence.

Appendix C: Interview protocol for iteration 1 of DBR study

For Students:

Introduction	• Hi, I'm Becca, in graduate school studying how kids can learn math and science in gardens • I also have helped out with the garden classes at this school
What's this all about	• I'm trying to build something that I think would be helpful for students to learn about math and science in a garden • I'm only interested in seeing what you think about it and how you would be interested in learning from it- no scores or anything • The program I'm going to show you is something I built over a few months and is relatively easy to change. I'd like to see how students might change things or add to the model • If you have questions about anything at any time, please feel free to ask me!
Camera	• I'll be videotaping our conversation and what you do on the computer screen, but your face won't be on the video. This is so I can pay full attention to what we're doing and not worry about taking notes until later. • Are you okay with having the camera here?
Set up the model	• Open the program. Explain that environmental scientists and professionals use technology to try to understand how something might work before spending lots of time or money on it. • It might seem like fancy stuff but it turns out kids can build it too, I had never built a program before. o *Have you ever programmed before?* • Explain set up buttons, slider, and set the program to random. • Explain other output buttons and the functionality of the mouse (hold down mouse button to harvest)
Tasks	• First I'll give you a minute or two just to explore the program. I'd like for you to tell me what you're thinking as you're doing things. Then I'll stop and give you a task for your farmer. • How can you set the model to try and keep your garden going for as long as possible with your initial budget? • What things do you need to keep in mind to make sure your plants grow as healthy as possible? • *Reset the model and run with different settings.* What differences did you see this time?
Button Code (if they haven't yet explored these)	• What do you notice is happening to the soil? • What do you think might happen if you click that (refer to each button)? • Click into the code // Can you change something? What might it do? • How would you learn about how this program works? • What would you want to add or change to the model? • How could you find out what happens to creatures in the garden?

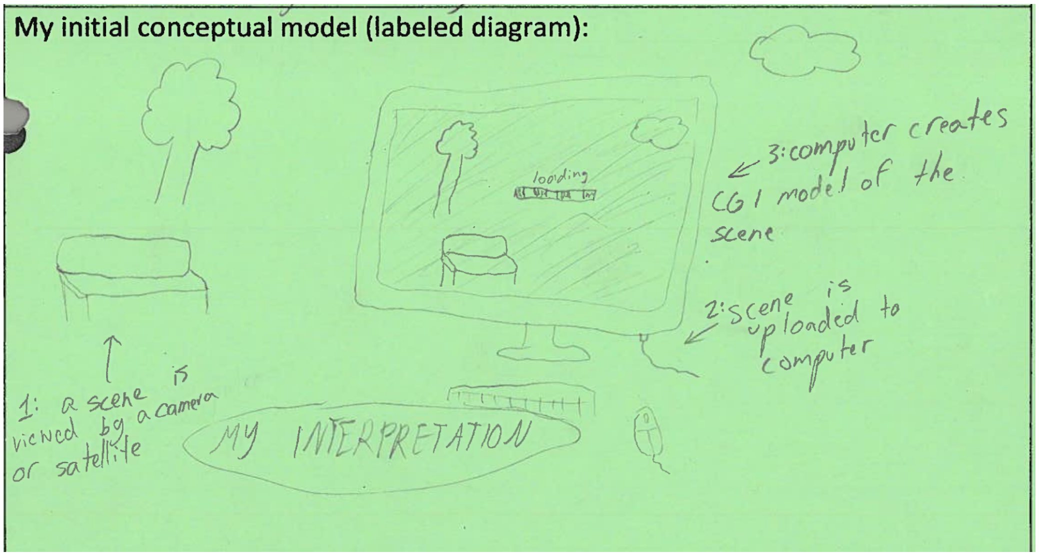
Feedback	• What are your general thoughts about this program? • Does this remind you of anything you've seen before? • Do you think you learned anything new by playing this model? • I was thinking of bringing this into a classroom, do you think I should? • How do you think this could help students working in a garden? • How could it help students learning science/ math? • What could make it more fun and interesting for you and your classmates?
Debrief	• I was trying to figure out what you knew about garden ecosystems before, and see what the model helped you understand even more. • Your ideas will help me figure out how to make this model better for students to use as they try to make experiments and predictions about the way the organisms in the garden interact. • Do you have any questions about anything we did, or about how the model works?
Closing	Thank you so much for your help! Please have some more snacks before you go.

For teachers, repeat above protocol but with additional questions below:

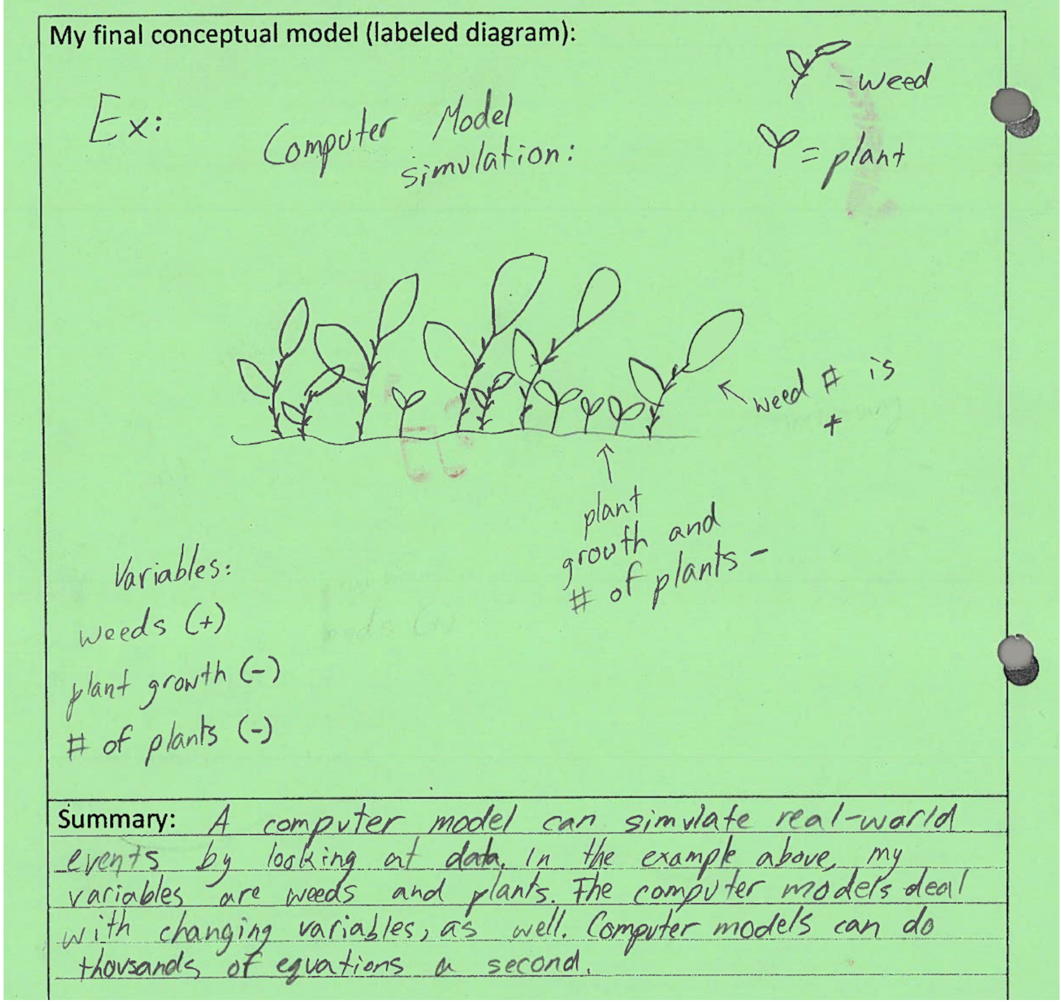
- What instructional goals could you foresee using this tool to reach?
- What do you anticipate being the most challenging part of using this program in your classroom?
- Have you used any similar technology platforms in your classroom before, and if so, how did they go?
- What are your thoughts on integrating technology and the garden to do experiential science?

Appendix D: Students' initial and final models from iteration 2 of DBR study

Figure D1: Lola



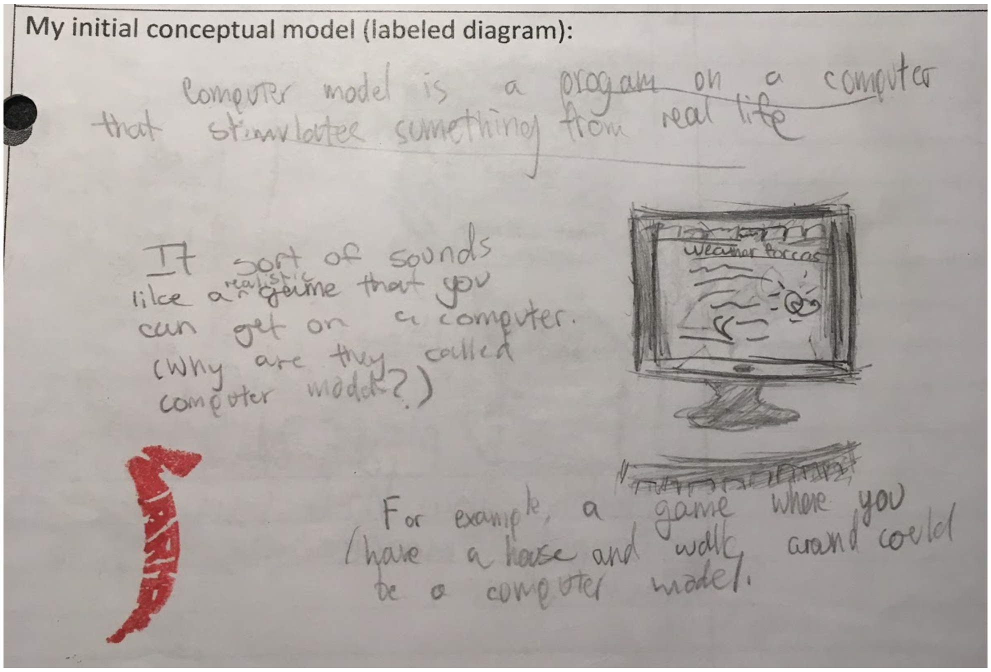
My initial conceptual model (labeled diagram):



My final conceptual model (labeled diagram):

Summary: A computer model can simulate real-world events by looking at data. In the example above, my variables are weeds and plants. The computer models deal with changing variables, as well. Computer models can do thousands of equations a second.

Figure D2: Cassidy

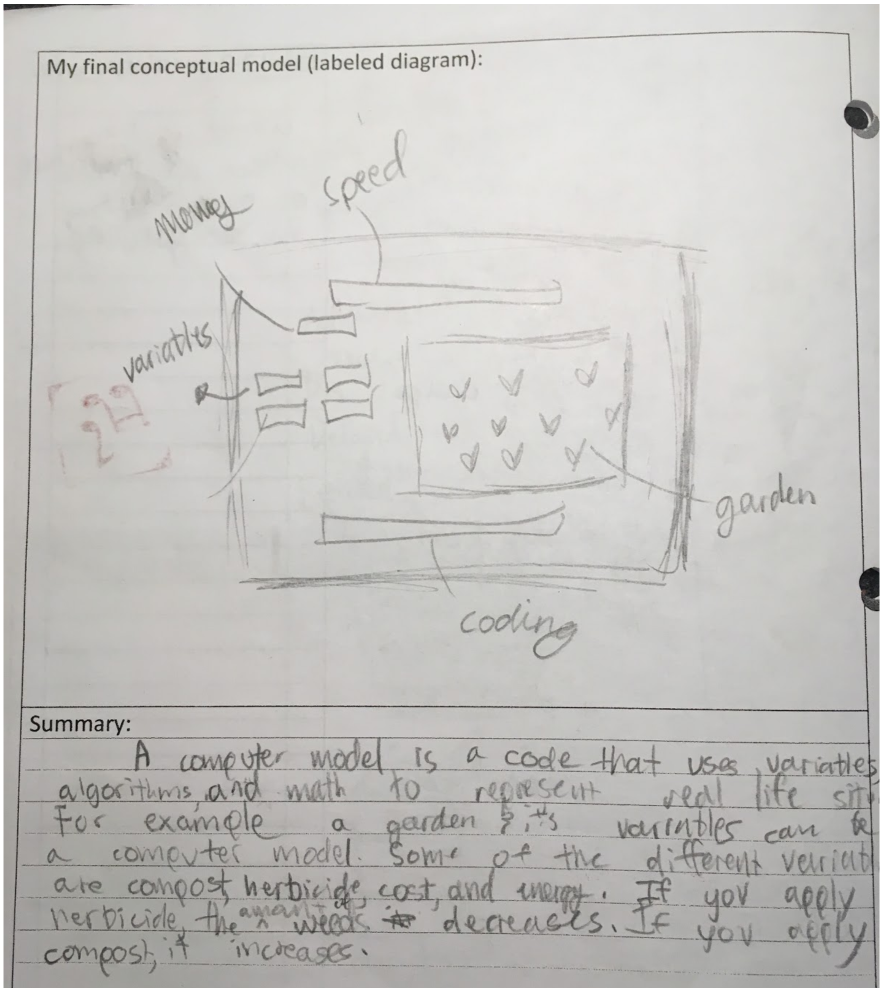


My initial conceptual model (labeled diagram):

Computer model is a progam on a computer that stimulates something from real life

It sort of sounds like a realistic game that you can get on a computer. (Why are they called computer model?)

For example, a game where you have a house and walk around could be a computer model.

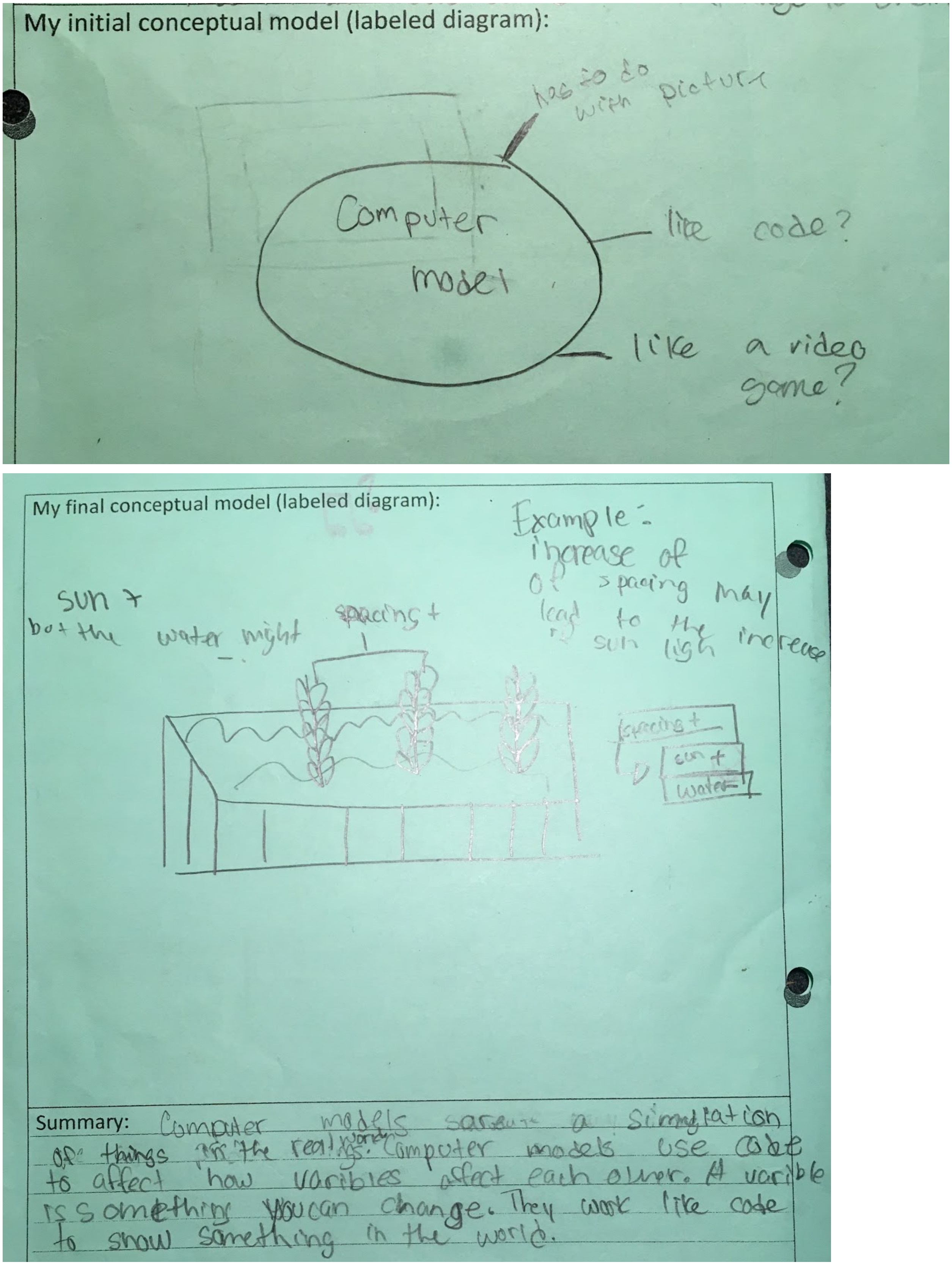


My final conceptual model (labeled diagram):

Summary:

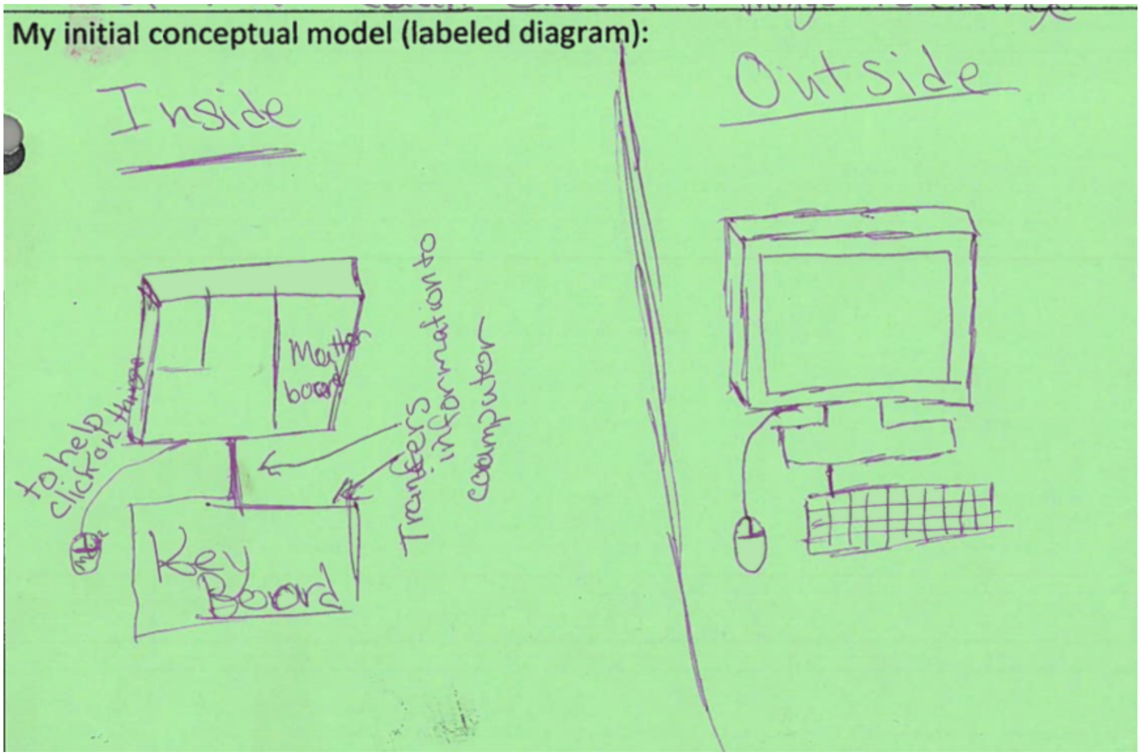
A computer model is a code that uses variables algorithms, and math to represent real life sit For example a garden & it's variables can be a computer model. Some of the different variat are compost, herbicide, cost, and energy. If you apply herbicide, the amount of weeds ~~it~~ decreases. If you apply compost, it increases.

Figure D3: Diana

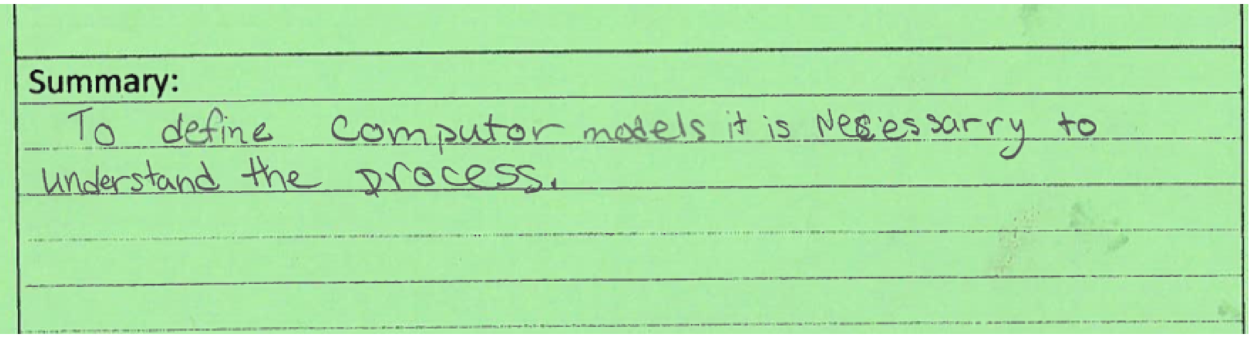


Summary: Computer models ~~sareute~~ a simmylation of things in the real world. Computer models use code to affect how varibles affect each other. A varible is something you can change. They work like code to show something in the world.

Figure D4: Nadia



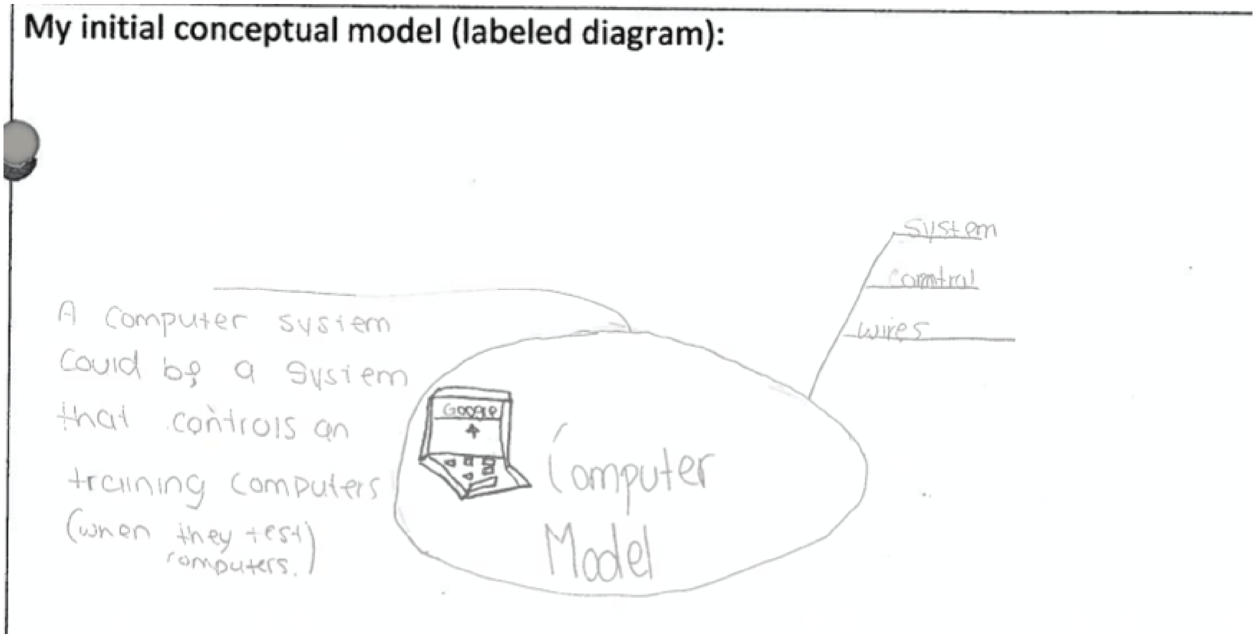
My initial conceptual model (labeled diagram):



Summary:

To define computor models it is Nessessarry to understand the process.

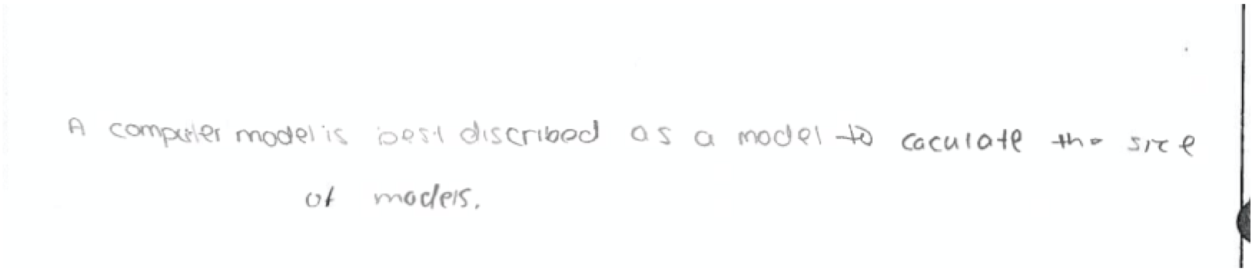
Figure D5: Yelena



My initial conceptual model (labeled diagram):

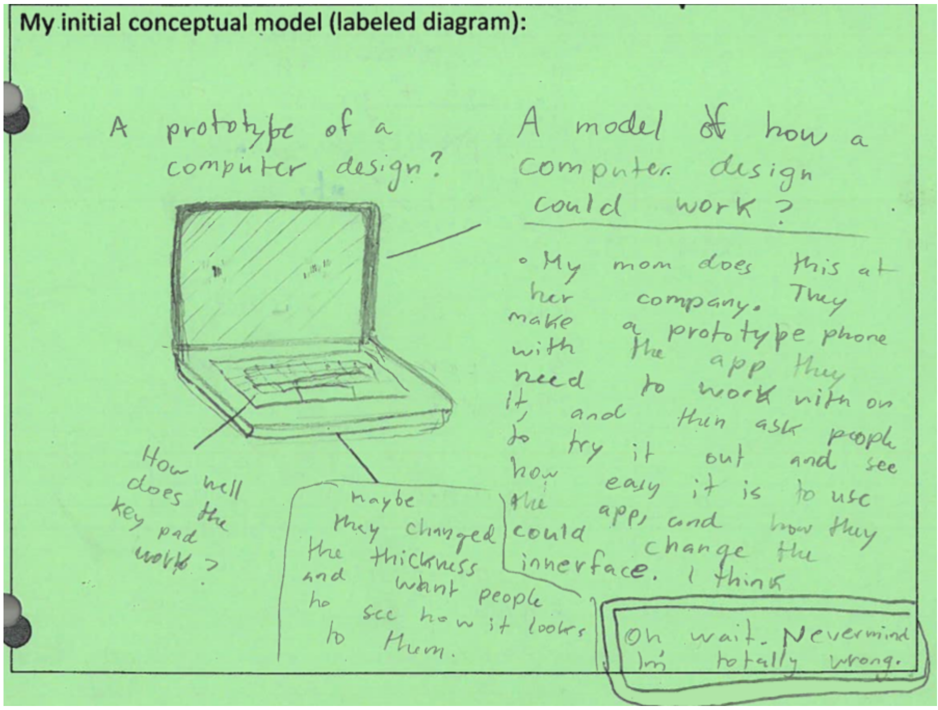
A computer system could be a system that controls an training computers (when they test computers.)

Final (no diagram)



A computer model is best discribed as a model to caculate the size of models.

Figure D6: Molly



My initial conceptual model (labeled diagram):

A prototype of a computer design?

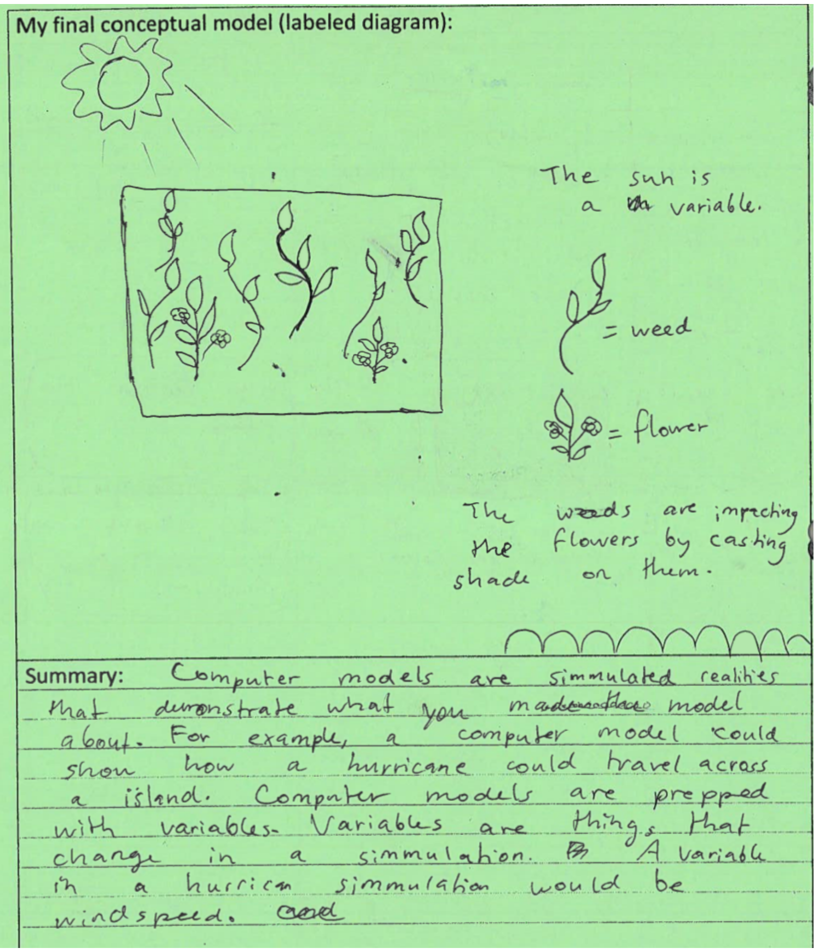
A model of how a computer design could work?

- My mom does this at her company. They make a prototype phone with the app they need to work with on it, and then ask people to try it out and see how easy it is to use the app, and how they could change the innerface. I think

How well does the key pad work?

maybe they changed the thickness and want people to see how it looks to them.

Oh wait. Nevermind I'm totally wrong.



My final conceptual model (labeled diagram):

The sun is a variable.

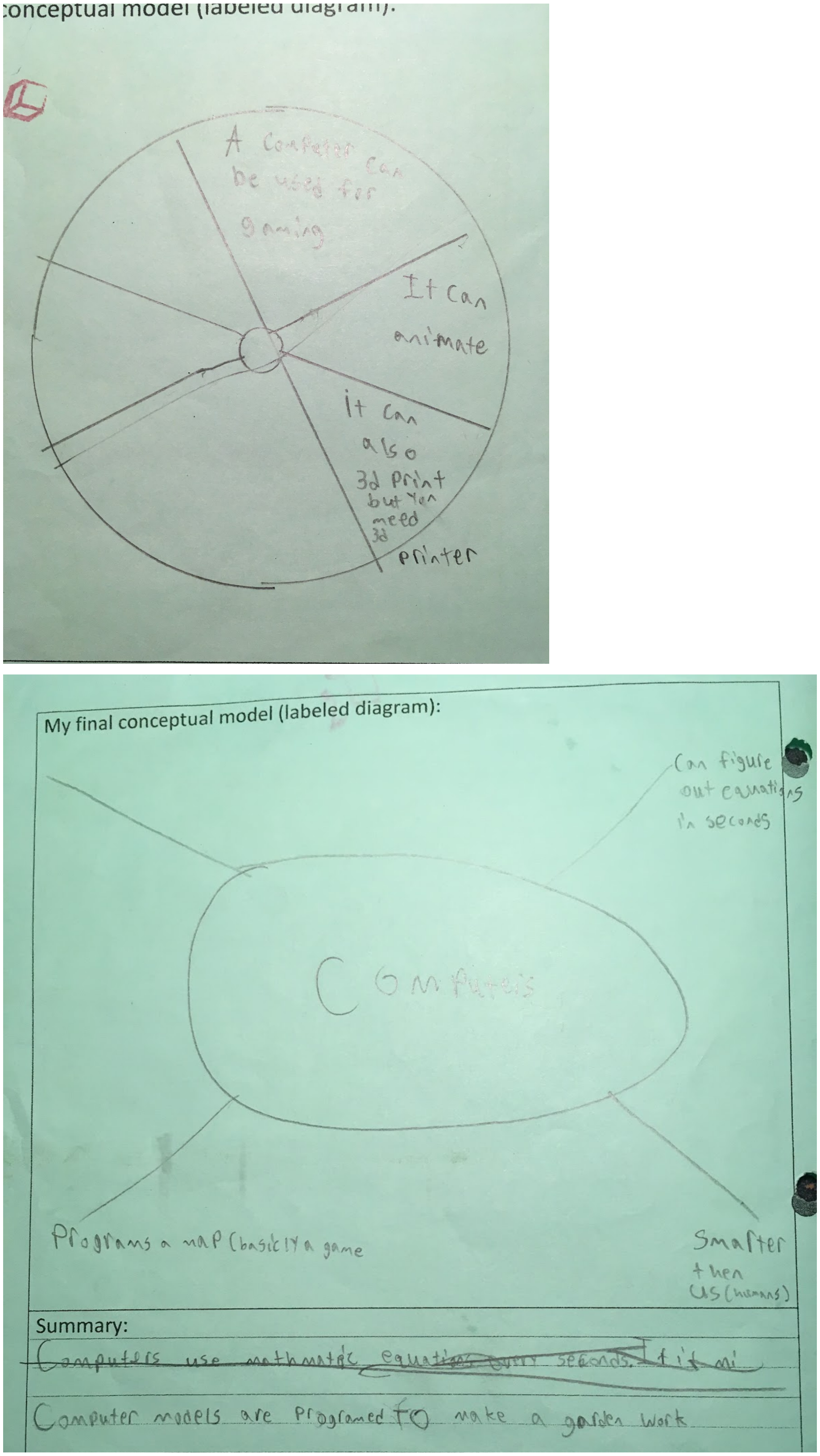
= weed

= flower

The weeds are impeching the flowers by casting shade on them.

Summary: Computer models are simmulated realities that demonstrate what you model about. For example, a computer model could show how a hurricane could travel across a island. Computer models are prepped with variables. Variables are things that change in a simmulation. A variable in a hurrican simmulation would be windspeed.

Figure D7 : Jaden



conceptual model (labeled diagram):

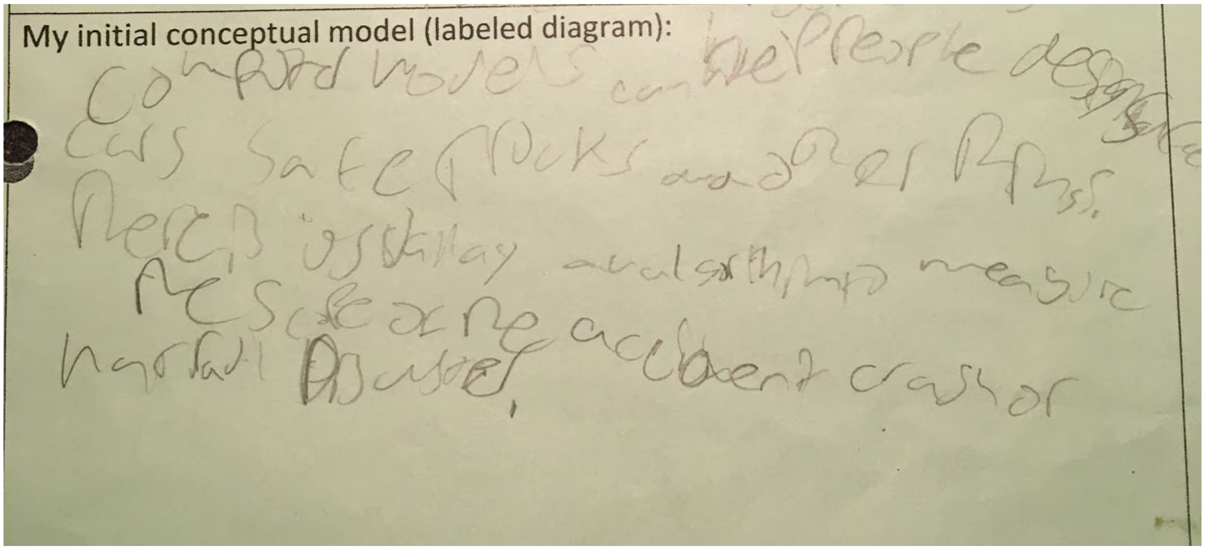
My final conceptual model (labeled diagram):

Summary:

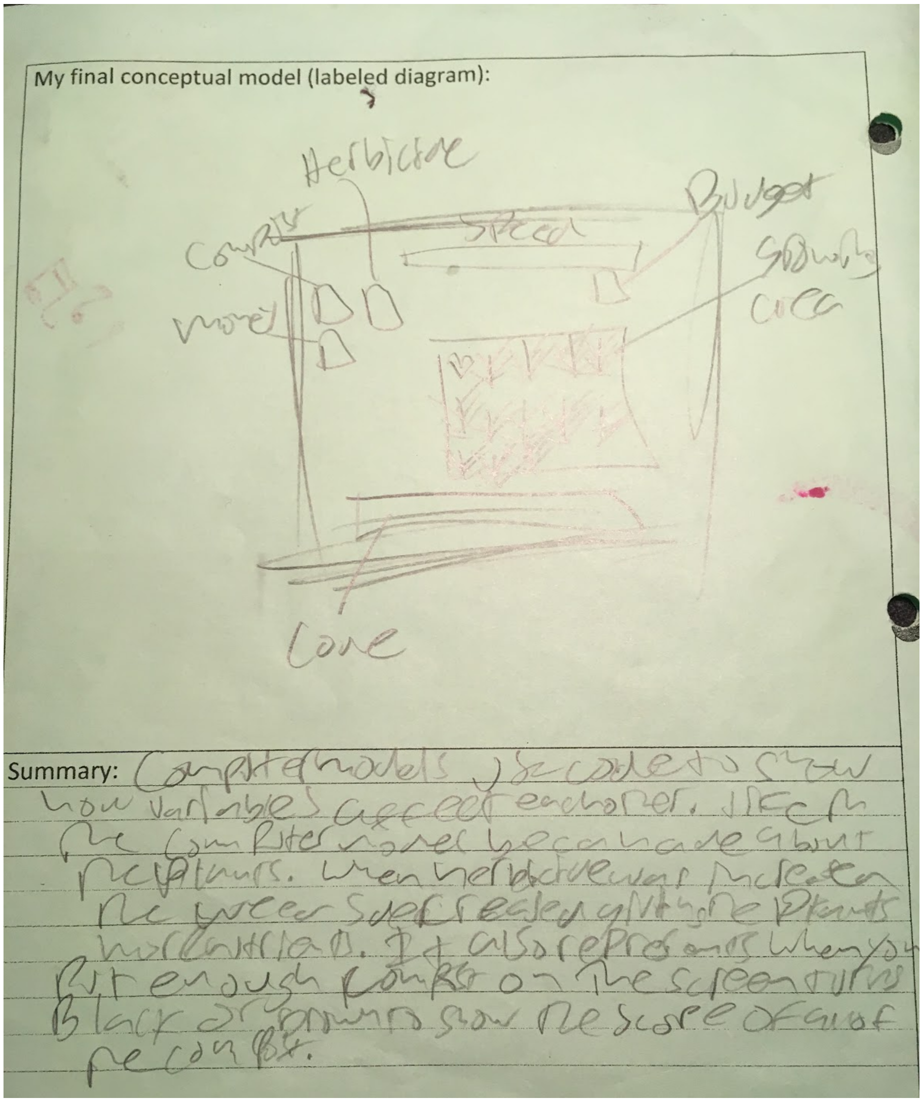
~~Computers use mathmatic equations every seconds. I it mi~~

Computer models are programed to make a garden work

Figure D8: Nico



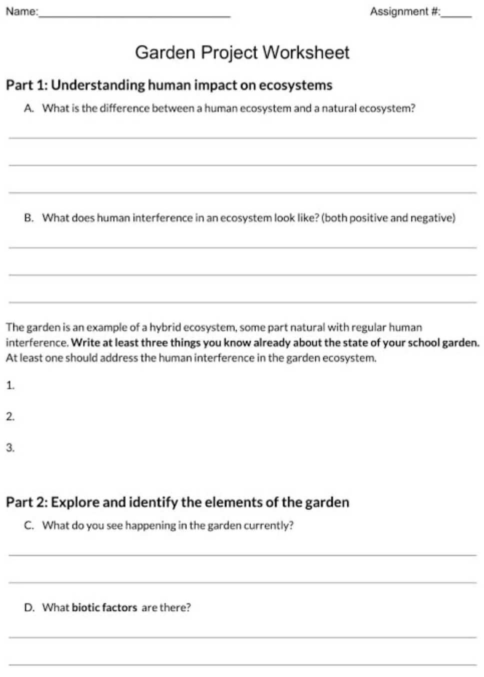
My initial conceptual model (labeled diagram): Computer models can help people design safe cars safe trucks and other things. Then usually analyz and something measure the scale of the accident crash or harmful Disaster.



My final conceptual model (labeled diagram):

Summary: Computer models use code to show how variables affect each other. I see in the computer model we can made about the plants. When herbicide was increased the weed speed reduced giving the plants more nutrition. It also represents when you put enough compost on the screen turns black and numbers show the score of all of the compost.

Appendix E: Worksheet packet from iteration 3 of DBR study



Name:______________________________ Assignment #:_____

Garden Project Worksheet

Part 1: Understanding human impact on ecosystems

A. What is the difference between a human ecosystem and a natural ecosystem?

B. What does human interference in an ecosystem look like? (both positive and negative)

The garden is an example of a hybrid ecosystem, some part natural with regular human interference. **Write at least three things you know already about the state of your school garden.** At least one should address the human interference in the garden ecosystem.

1.

2.

3.

Part 2: Explore and identify the elements of the garden

C. What do you see happening in the garden currently?

D. What **biotic factors** are there?

E. What **abiotic factors** impact the garden?

F. What are things that have changed since the last time you were in the garden?

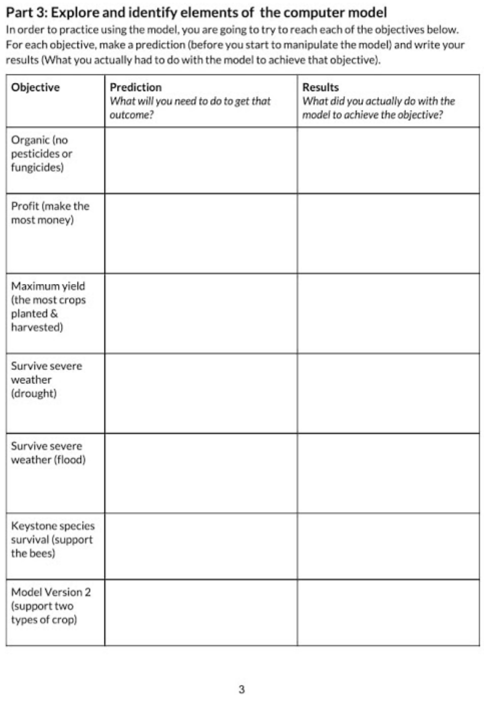
G. What can you see that demonstrates human interference in the garden?

H. What is something that you think is a problem in the garden, that might need solving?

I. What would make the garden more interesting to you?

J. Is the garden healthy? How can you tell?

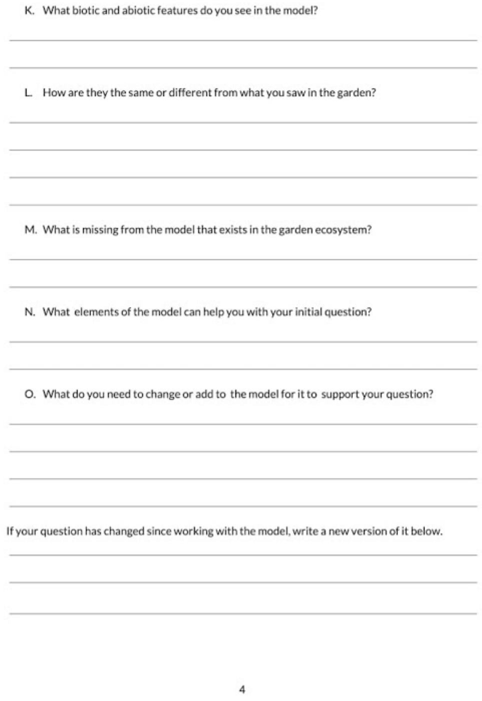
Write a testable question that you would like to spend the next few class periods investigating about the garden. It should include at least one living or non-living element.



Part 3: Explore and identify elements of the computer model

In order to practice using the model, you are going to try to reach each of the objectives below. For each objective, make a prediction (before you start to manipulate the model) and write your results (What you actually had to do with the model to achieve that objective).

Objective	**Prediction** *What will you need to do to get that outcome?*	**Results** *What did you actually do with the model to achieve the objective?*
Organic (no pesticides or fungicides)		
Profit (make the most money)		
Maximum yield (the most crops planted & harvested)		
Survive severe weather (drought)		
Survive severe weather (flood)		
Keystone species survival (support the bees)		
Model Version 2 (support two types of crop)		



K. What biotic and abiotic features do you see in the model?

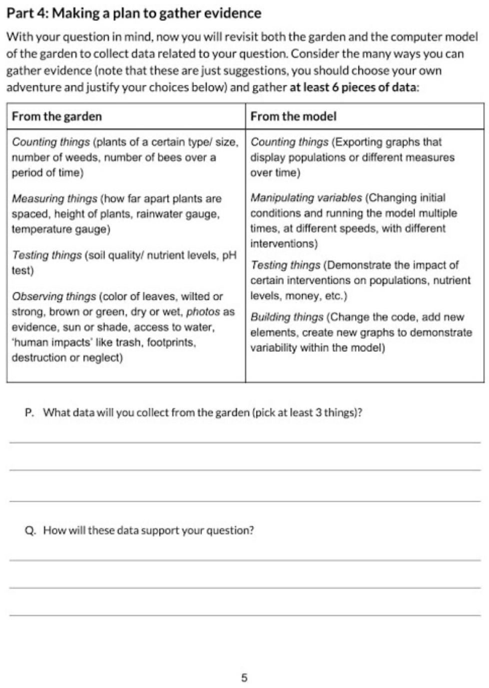
L. How are they the same or different from what you saw in the garden?

M. What is missing from the model that exists in the garden ecosystem?

N. What elements of the model can help you with your initial question?

O. What do you need to change or add to the model for it to support your question?

If your question has changed since working with the model, write a new version of it below.



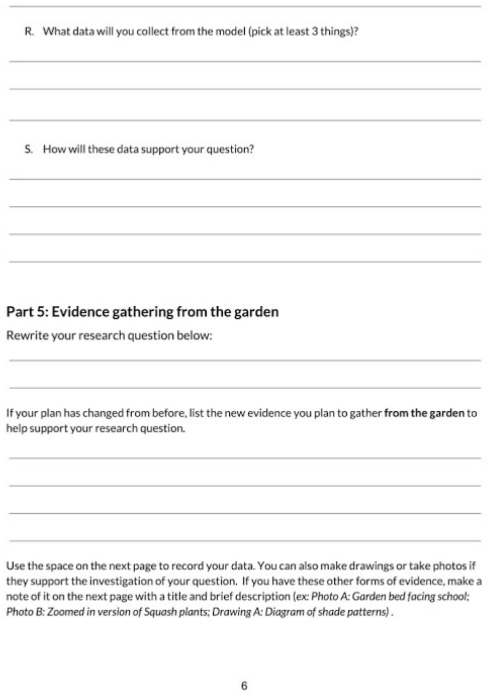
Part 4: Making a plan to gather evidence

With your question in mind, now you will revisit both the garden and the computer model of the garden to collect data related to your question. Consider the many ways you can gather evidence (note that these are just suggestions, you should choose your own adventure and justify your choices below) and gather **at least 6 pieces of data**:

From the garden	**From the model**
Counting things (plants of a certain type/ size, number of weeds, number of bees over a period of time) *Measuring things* (how far apart plants are spaced, height of plants, rainwater gauge, temperature gauge) *Testing things* (soil quality/ nutrient levels, pH test) *Observing things* (color of leaves, wilted or strong, brown or green, dry or wet, *photos* as evidence, sun or shade, access to water, ‘human impacts’ like trash, footprints, destruction or neglect)	*Counting things* (Exporting graphs that display populations or different measures over time) *Manipulating variables* (Changing initial conditions and running the model multiple times, at different speeds, with different interventions) *Testing things* (Demonstrate the impact of certain interventions on populations, nutrient levels, money, etc.) *Building things* (Change the code, add new elements, create new graphs to demonstrate variability within the model)

P. What data will you collect from the garden (pick at least 3 things)?

Q. How will these data support your question?



R. What data will you collect from the model (pick at least 3 things)?

S. How will these data support your question?

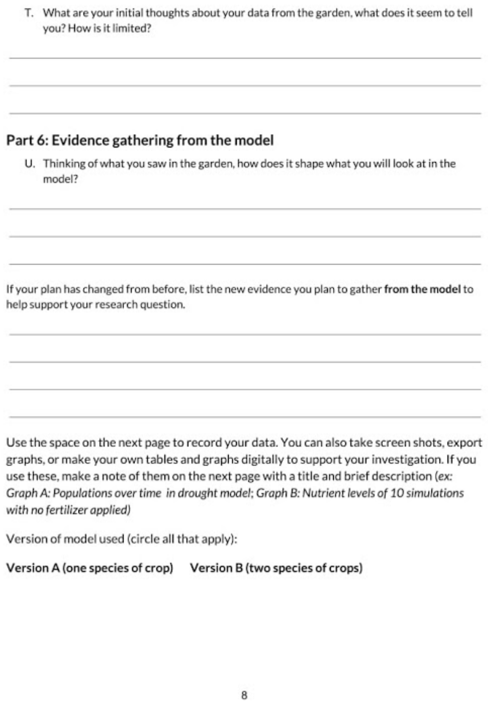
Part 5: Evidence gathering from the garden

Rewrite your research question below:

If your plan has changed from before, list the new evidence you plan to gather **from the garden** to help support your research question.

Use the space on the next page to record your data. You can also make drawings or take photos if they support the investigation of your question. If you have these other forms of evidence, make a note of it on the next page with a title and brief description (*ex: Photo A: Garden bed facing school; Photo B: Zoomed in version of Squash plants; Drawing A: Diagram of shade patterns*) .

Evidence from the garden



T. What are your initial thoughts about your data from the garden, what does it seem to tell you? How is it limited?

Part 6: Evidence gathering from the model

U. Thinking of what you saw in the garden, how does it shape what you will look at in the model?

If your plan has changed from before, list the new evidence you plan to gather **from the model** to help support your research question.

Use the space on the next page to record your data. You can also take screen shots, export graphs, or make your own tables and graphs digitally to support your investigation. If you use these, make a note of them on the next page with a title and brief description (*ex: Graph A: Populations over time in drought model!; Graph B: Nutrient levels of 10 simulations with no fertilizer applied)*

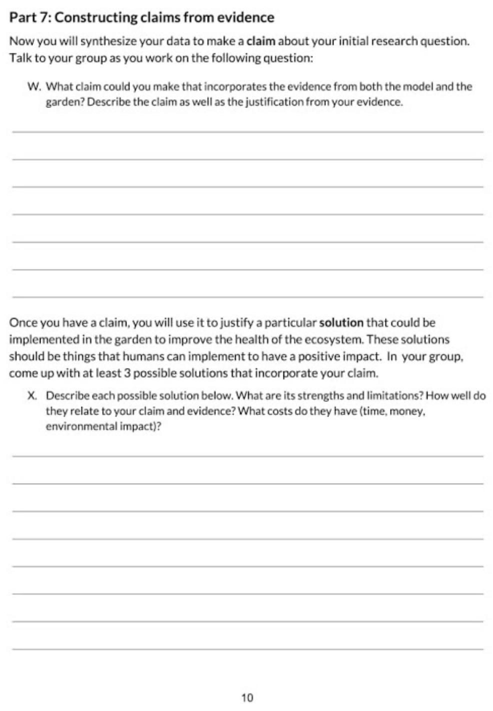
Version of model used (circle all that apply):

Version A (one species of crop) **Version B (two species of crops)**

Evidence from the model

Describe any changes you made to the model code or interface below.

V. What are your initial thoughts about your data from the model, what does it seem to tell you? How is it limited?



Part 7: Constructing claims from evidence

Now you will synthesize your data to make a **claim** about your initial research question. Talk to your group as you work on the following question:

W. What claim could you make that incorporates the evidence from both the model and the garden? Describe the claim as well as the justification from your evidence.

Once you have a claim, you will use it to justify a particular **solution** that could be implemented in the garden to improve the health of the ecosystem. These solutions should be things that humans can implement to have a positive impact. In your group, come up with at least 3 possible solutions that incorporate your claim.

X. Describe each possible solution below. What are its strengths and limitations? How well do they relate to your claim and evidence? What costs do they have (time, money, environmental impact)?

Y. Write what you believe is the best solution that will improve the health of the garden:

Z. Which evidence (from the garden and the model) will you use to justify your plan?

Use this template (bit.ly/garden_solution) to create a proposal for your solution that incorporates the evidence you have selected. The proposal will be due to Ms. O at the end of class on **Tuesday May 7th (2nd, 3rd, 7th period) or Wednesday May 8th (5th period).** The rubric for how you will be graded can be found here (bit.ly/garden_rubric)

Appendix F: Classroom data from iteration 3 of DBR study

ID	RQ fits for both contexts	Garden data relates to RQ	Model data relates to RQ	Model data builds off garden data	Pres incorporates model + garden data	M data in pres relates to claim	G data in pres relates to claim	Claim integrates model + garden data
1	1	1	1	0	1	1	0	0
2	0	1	1	1	1	1	0	0
3	1	1	1	1	1	1	1	1
*4	1	1	1	1	1	1	0	0
5	1	1	1	0	1	0	1	0
*6	1	1	1	1	1	0	1	0
7	1	0	1	0	1	1	0	0
*8	1	1	1	0	0	0	1	0
9	1	1	1	1	1	1	1	1
10	1	1	1	1	1	1	1	1
11	1	1	1	1	1	1	1	1
*12	0	1	1	1	1	1	1	1
13	1	1	1	1	1	1	1	1
14	1	1	1	1	1	1	1	1
15	1	1	1	1	1	1	0	1
16	1	1	1	1	1	1	1	0
17	1	1	1	1	1	1	0	1
18	1	1	1	1	1	1	1	1
19	0	1	1	1	1	1	1	1
20	1	1	1	1	1	1	1	1
21	1	1	1	1	1	1	1	1
22	1	1	0	0	0	0	1	0
23	1	1	1	1	1	1	1	0
24	1	1	1	1	1	0	1	0

Legend

Model > Garden	Other > Model	Garden > Model	Model = Garden

* indicates case examined in detail

Appendix G: Coding system for student transcript data

Code / sub-code		**Description**	**Example**
(P) Purposeful application		Students' references to the broader project components, the school garden space	
	GE	Garden evidence considered for collection, strategies	*Let's test three soil beds*
	G	Generic or value statement about the garden	*Does the garden have bees?*
	RQ	Reference to the project research question	*Our question is...*
	C	Reference to the project claim	*Our claim needs...*
	S	Reference to the project ecological solution	*What solution should we do?*
(I) Instrumented + situated negotiation		How students are connecting model to garden context, on their own or with support from pedagogical practices and activity design	
	WP	Worksheet prompt: questions or information	*Which evidence will you use?*
	IP	Instructor prompt	Teacher / researcher suggestion
	AF	Activity feature (structure of activity; presentation components)	Collecting evidence from model and garden; cost-benefit analysis
	MGI	Model/garden integration	*How can we use the model to look for soil nutrients too?*
(Q) Quantitative reasoning		What features of the model they're attending to, utilizing, and how they feel about the model	
	MC	Model component (design element, features)	*Nutrient graphs; Weeds*
	ME	Model evidence considered for collection, strategies	*Let's add water every 20 ticks*
	M	Generic or value statement about the model	*The model is glitchy; I don't know how to use the model.*