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A framework for pollination systems thinking and conservation

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ABSTRACT
We conducted interviews with 16 postsecondary students at a large public university on pollination systems knowledge. A semi-structured interview protocol was developed with open-ended prompts to elicit student explanations of pollination systems. Congruent themes were developed through coding of the interview transcripts into low, medium, and high sophistication of responses. From this, we developed a framework of pollination knowledge informed by systems thinking models that describe structures of plants and pollinators, conservation behaviors, and the function of pollination systems. The framework described can be used to explain students' understanding of pollination systems and identify strengths and gaps in this knowledge. We propose this framework may also be used as the basis for instrument development evaluating the impacts of educational programming designed to improve students' pollination knowledge.

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Pollination; systems thinking; knowledge framework; undergraduate conservation education; pollinator knowledge

1. Introduction

In the United States the public has become increasingly aware of the importance of insect pollinator protection, which has been manifested through wide-spread media attention, conservation, and education efforts. Pollinators are crucial for human food systems; nearly 1/3 of the food on US citizens' plate is the result of bee pollination through fruit and seed set of over 140 crop plants in the United States (USDA 2015). However, many pollinator populations are in decline, for example, mass die-offs of the European honey bee due to colony collapse disorder, and declines in the monarch butterfly due to reduction in milkweed plants and habitat fragmentation (Inamine et al. 2016). The importance and timeliness of this issue makes it a salient topic for K-12 and postsecondary science courses. However, few studies have documented students' current knowledge and understanding of pollination systems.

In a survey of entomologists, the idea that insects have economic value as pollinators of crops and animal feed was ranked as the top concept that every American should know (Pearson, Skinner, and Hoback 2007). Correspondingly, education efforts involving pollination systems have been widely developed in both formal and informal educational settings. In informal settings, there are several citizen science programs such as Monarch Watch (monarchwatch.org), Bumble Bee Watch (bumblebeewatch.org), and the Bumble Boosters Project (bumbleboosters.org), as well as organizations with pollination conservation educational missions such as the Xerces Society (xerces.org) and Pollinator Partnership (pollinatorpartnership.org). There are many publicly available lesson plans and activities for K-12 audiences on pollinator conservation. These lessons are often sponsored by national organizations (e.g. Smithsonian Institute and National Park Service) with topics ranging from pollinator plantings, conservation art, and field experiments. However, despite the importance of pollination systems and the

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widespread educational efforts, there is no coherent guidance on learning outcomes or frameworks for what educators should expect students to know in informal or formal settings at elementary, secondary or post-secondary levels. Further, the largest academic society for entomologists, the Entomological Society of America, does not have a formal stance on what students should know about pollinators and their conservation.

Students' knowledge of plants in general (Wood-Robinson 1991), as well as insects can be limited. Insects in particular have been studied in terms of life cycle and morphology understanding of K-12 students (Barrow 2002; Cinici 2013; Shepardson 1997), general insect characteristics (Shepardson 2002) or insect diversity (Snaddon and Turner 2007). There are few existing studies on students' knowledge of pollinators specifically, or documentation of potential misconceptions about pollination systems that exist among students at any educational level. Lewis and Wood-Robinson (Lewis and Wood-Robinson 2000) found that only 7% of 482 students (14–16 years old) knew about pollination, and still failed to link this process to sexual, rather than asexual reproduction. Hershey (2004) mentions observing confusion between pollination and fertilization in pre-college students.

A public with greater knowledge about pollination systems could facilitate the understanding of issues and contribute to community and individual informed decision-making. Arguably, some understanding of pollination systems and conservation techniques is important knowledge for citizens to enact pollinator conservation. Specific practices that an individual may take that have been shown to benefit pollinators include: planting a diversity of flowering plants that provide the proper pollen and nectar resources for pollinators, preservation of existing natural habitats and managed habitat such as hedge-rows to boost nest site availability for wild nesting bees, and pesticide reduction to reduce acute and chronic effects on pollinators (Lee-Mäder, 2011; Lee-Mäder et al. 2010). Conservation efforts to engage individuals in these practices may benefit from individuals who understand the nature of pollination systems and the connection between human food production and pollination systems.

We expect students to have some difficulty reasoning about pollination because of the complexity of the system that connects pollinating animals, plants and humans. Students also struggle to understand complex systems, and their mental representations of systems are often limited to nebulously defined relationships between macro-level structural components (Jordan et al. 2013). Complex systems in nature have multiple scales of organization, heterogeneous components that have interconnections, and invisible dynamic processes (Hmelo-Silver and Azevedo 2006; Wilensky and Resnick 1999). Pollination systems as a complex system can be illustrated in several ways. For example, the current conservation status of pollinating insects is a result of multiple interacting components including humans who impact the landscape therefore pollinator habitat, and an interaction of chemicals, disease, and parasites on pollinator health (Colony Collapse Disorder 2016). The reproductive processes of plants are invisible, and often the influence of insect pollinators is not easily observed without deliberate observation. For students to reason about pollinator conservation they need to connect these processes and relationships across temporal and spatial scales, which may not be obvious to students (Duncan and Reiser 2005). Additionally, the role of insect pollinators in human food systems is a result of the aggregate processes of plant reproduction on evolutionary time scales, as well as food chains, such as the reliance on pollinated crops like alfalfa for increased dairy milk production. In general, the ability of students to reason about pollination as part of a complex system relies on their connecting understanding of plant reproduction on one level, to the resulting food availability on a larger scale.

To truly evaluate the effectiveness of pollination education programs, to develop additional programs, and investigate the relationship between knowledge, awareness and action, a baseline for what people know about pollinators and conservation is needed. To meet this need, we sought to describe what post-secondary students know about pollination systems and conservation of pollinators. To inform our research we used literature on systems-thinking and complex systems as a theoretical construct (Hmelo-Silver 2004; Hmelo-Silver and Azevedo 2006; Wilensky and Resnick 1999). To structure our analysis of student reasoning around systems-thinking we used a structure-behavior-function (SBF) theoretical framework (Dauer et al. 2013; Goel and Stroulia 1996; Hmelo-Silver 2004). We collected post-secondary students' explanations of pollination systems and conservation of pollinators through structured interviews and described themes that emerged from these explanations. Our research objectives were to explore and describe postsecondary student knowledge about pollination and create a framework to characterize varying levels of understanding pollination concepts.

2. Methodology

2.1. Target population and sampling

We employed criterion sampling (Creswell 2012) to purposefully recruit and interview postsecondary students enrolled in a diversity of science courses (i.e. Introductory Life Science, Introduction to Entomology, Introduction to Forensic Science, Introductory Plant Science, and Introductory Agronomy) at a large Midwest university. Our sampling strategy operated under the assumption that students with a strong academic background in general biology, environmental science, or agriculture provided a range of specific knowledge and understanding of pollination, plants, insects and conservation. Participant backgrounds are described in Table 1, which illustrates student diversity in terms of gender, grade point average (GPA), major and nature identity. A total of 16 undergraduate students (10 females, 6 males) participated in this study. Each individual was assigned an alias. A selective sample size of 16 was chosen in accordance purposeful sampling approach allowing for in-depth analyses of individual cases (Patton 2002). All participants were 19 years of age or older with a mean of 20.4 years (SD ± 1.6). Participant GPAs ranged from 1.6 to 4.0 with a mean of 3.4 (SD ± 0.57). Most of the students were sophomores (50%). The remaining were freshman (6%), juniors (19%) and seniors (25%). The majority of students (88%) grew up in Nebraska. Half of the students considered themselves to be naturalists. Of those remaining, several students did not consider themselves to be naturalists (38%) or were unsure (13%). The majority of students (82%) had completed or were currently enrolled in undergraduate entomology, horticulture or ecology courses.

Interviews were conducted with 3 experts each holding advanced degrees and having well-established academic and research careers in the field of entomology. These interviews were used to evaluate interview questions and to provide expert understanding of pollination systems knowledge. All interviews were conducted by the authors.

2.2. The interviews

We used a structured, one-on-one interview approach to describe general patterns in understanding pollination systems and conservation of pollinators using open-ended questions and prompts (sub-questions). The interview protocol was developed with and informed by an SBF framework. In the SBF framework, systems and systems models are composed of structures (the physical components of a system), behaviors (the relationships or mechanism connecting structures with one another) and functions (the roles or outputs of the system) (Hmelo-Silver 2004; Hmelo-Silver, Marathe, and Liu 2007). We elicited student thinking about the physical components of the pollination system (plant and insect anatomy and function), the behaviors that connect pollinators and plants (pollinator survival, plant reproduction), and the overall function of the system, which we characterized as the resulting influence of pollinators on our food supply and the resulting influence of humans on pollinators through conservation policies (interview protocol in Appendix A). To further investigate student thinking about specific behaviors that influence pollinators, we presented students a list of five conservation actions on a card (Figure 1) during the interview. We asked students if they agreed or disagreed that these actions would benefit pollinators and to explain why they agreed or disagreed. Interviews were recorded and transcribed verbatim using a transcription service.

2.3. Interview analysis and framework construction

Interviews were analyzed using thematic qualitative text analysis and manual coding (Kuckartz 2014). All 4 authors independently carried out an initial coding phase to reduce the research participants'

Table 1. Interviewed student demographics.

Pseudonym	Age	Major	Class stand	GPA	Gender	Background	Do you consider yourself a naturalist?	Related coursework
Liam	21	Fisheries and Wildlife	Soph	1.6	M	Urb/Sub	'Yes, I am interested in and appreciate nature'	Ent, Eco
Maggie	25	Environmental Studies	Sr	3.3	F	Urb/Sub	'Yes, I look forward to the warm weather to collect insects, visit parks, and spend time outdoors'	Ent, Eco
Sue	20	Applied Science	Soph	3.5	F	Urb/Sub	'Yes, I am interested in nature and naturalism food sources, systems, how people relate to plants ethnobotony'	Ent, Hort, Eco
Tammy	20	Horticulture	Junior	4.0	F	Rural	'Yes, sustainable food production'	Ent, Hort
Jacob	20	Fisheries and Wildlife	J	3.5	M	Urb/Sub	'I don't know but I love nature and desire its protection'	Hort, Eco
Jimmy	21	Insect Sci	Junior	N.A.	M	Rural	'Yes, I study entomology'	Ent, Hort, Eco
York	21	Envr. Restoration Sci	Sr	3.6	M	Rural	'Yes, interested in natural resources conservation'	Ent, Eco
Kenny	22	Ag Business	Sr	3.7	M	Rural	'No'	Ent, Hort
Mike	19	Biochemistry	Soph	3.8	M	Urb/Sub	'Not necessarily – NO'	Eco
Sara	19	Forensic Science	Soph	3.2	F	Rural	'Not really'	Ent enrolled
Patricia	19	Anthropology	Soph	3.4	F	Urb/Sub	'Somewhat, probably not that much'	None
Lisa	20	Horticulture	Soph	3.5	F	Urb/Sub	'Yes'	Ent, Hort
Alexis	20	Biology/Psychology	Soph	3.3	F	Urb/Sub	'No, not huge fan of nature in general'	None
Winnie	22	Political Science and Global Studies	Sr	3.8	F	International/ Urban	'No, I do not particularly engage in activities that are nature oriented'	Ent
Mary	19	Undeclared	Fresh	3.1	F	Urb/Sub	'Yes, I love to observe nature more if I had more opportunities'	Ent enrolled
Kanika	19	Advertising and Public Relations	Soph	3.9	F	Urb/Sub	'No, because I am not very educated'	Ent enrolled

Note: Eco = Ecology, Ent = Entomology, Hort = Horticulture.

1) Plant flowers that bloom during different times of the year in your yard.

2) Spray pesticides at dusk only.

3) Water your yard so your lawn grass is healthy for pollinators to eat and live in.

4) Put a bee box or plant hedgerows in your yard for pollinators to nest in.

5) Plant less agricultural crops.

Figure 1. A card displayed during the interview with actions.

explanations into meaningful codes (Creswell 2012). Homogenous and related codes were used to develop several broader conceptual categories about pollination systems. After several iterations of coding and category discussions, a consensus among the authors was reached on a final framework of 10 conceptual categories. The resulting categories of complex pollination systems were informed by structures, behaviors and functions according to the SBF model (Hmelo-Silver, Marathe, and Liu 2007) related to plants, pollinators and conservation (Table 2).

Codes and transcript excerpts within each conceptual category were compared with each other to establish three levels of sophistication: high (3), medium (2) and low (1). This typology resulted from multiple iterations of independent coding based on draft frameworks, comparisons of research participants' understanding of the pollination system within each conceptual category, discussions of coding discrepancies and refining the framework to reach a consensus among authors. After agreement was reached on a refined framework, all interviews were recoded by at least two coders to assess the framework's applicability to the data. Further discussions of the codes and framework refinement occurred until ultimately all of the codes, conceptual categories and sophistication levels for each interview were reconciled.

We summed a 'Pollination Knowledge Score' for each research participant in our data-set (Tables 1 and 2) by adding up an individual's 10 sophistication level scores (high = 3, medium = 2 and low = 1). The maximum score possible was a 30 (high level of sophistication across all 10 conceptual categories), and the lowest possible score was a 10 (low level of sophistication across all 10 conceptual categories). In order to qualitatively examine relationships between different categories of our framework across all of the students in our data-set, we created a heat map to visually indicate patterns of high (green), medium (yellow), and low (orange) sophisticated responses (Table 2). We sorted students by Pollination Knowledge Score total and calculated an average score for each category across students (Table 2).

We also coded student responses for five insect pollinator conservation actions shown to them on a card into three categories based on level of correctness according to the expert opinion of the authors. Student responses were coded as: 2 = correct, 1 = mix of correct and incorrect concepts, and 0 = incorrect. Different scores were used for categorizing students' responses to these conservation practices as students were asked to agree or disagree with the actions on the cards and explain their answer, as opposed to the more open-ended nature of the other interview questions. Calculated mean level of correctness across all students for the five actions is found in (Table 3). These conservation actions responses were used in conjunction with other conservation questions conducted during interviews to determine *action-oriented conservation* knowledge levels.

3. Results

3.1. Description of the framework in context of systems-thinking

We developed a framework that describes students' thinking about plants and pollinators that we grouped into plant structures (Table 4), pollinator structures and behaviors (Table 5), and pollination systems functions (Table 6). The table includes example student responses that best represent high

Table 2. Pollination knowledge conceptual categories (scores by students).

Broad categories	Pollination knowledge related to plants structures			Pollination knowledge related to insect pollinators structures and behaviors			Pollination knowledge of systems functions and conservation				
Framework concepts	Types of plants	Plant structures	Purpose for plants	Types of pollinators	Pollinator structures	Purpose for pollinators	Pollinating insect survival needs and influencers	Relationship human/ pollinators	Role of pollinators in the environment	Action-oriented conservation	Pollination knowledge total score
Liam	3	3	3	3	3	3	3	3	3	3	30
Maggie	3	3	3	3	3	3	3	3	3	2	29
Sue	3	2	3	3	3	3	3	3	3	3	29
Tammy	3	3	3	3	2	3	3	3	3	3	29
Jacob	3	3	3	2	2	3	3	3	3	2	27
York	3	2	3	2	2	3	2	3	3	3	26
Jimmy	2	3	2	2	2	3	3	3	3	3	26
Kenny	3	3	2	2	1	3	3	2	2	2	23
Mike	2	2	2	2	2	3	2	2	2	3	22
Sara	2	2	2	2	2	3	2	2	1	2	20
Patricia	2	1	2	2	2	2	2	2	2	1	18
Lisa	1	2	1	2	2	3	2	2	1	1	17
Alexis	1	2	2	2	2	2	1	2	2	1	17
Winnie	1	1	1	1	2	2	2	2	1	1	14
Mary	1	1	1	2	1	2	2	1	1	1	13
Kanika	1	1	1	1	1	1	1	1	1	1	10
Mean rating	2.13	2.13	2.13	2.13	2.00	2.63	2.31	2.31	2.13	2.00	21.88

Table 3. Mean student scores for the correctness of their responses to agreeing or disagreeing with five potential actions to benefit pollinators.

Potential beneficial actions	*M*	SD
Plant flowers that bloom during different times of the year in your yard	1.2	.8
Spray pesticide at dusk only	1.2	.9
Water your yard so your lawn grass is healthy for pollinators to eat and live in	1.3	.9
Put a bee box or plant hedgerows in your yard for pollinators to nest in	1.0	.9
Plant less agricultural crops	.9	.9
Average of potential actions	5.6	3.4

Notes: Students were given a codes according to the following: 2 = correct response, 1 = mix of correct and incorrect response, 0 = incorrect response.

Table 4. Pollination knowledge framework related to plants structures.

Category	Level	Description/attributes	Example quotes from Interviews
Types of plants	1	Knowledge of plants requiring pollination very limited and omits plants that produce food	'Like, flowers, like specific ones? … dandelions … carnations … roses … sunflowers …' [Kanika]
	2	A limited variety of plants requiring pollination are given as examples	'Blueberries–Corn maybe? Not for sure, um, like any fruit.' I: 'Can you think of any plants that do not need pollination as part of their life cycle?' P: 'Probably a plant that doesn't flower like– A perennial or something?' [Patricia]
	3	Knowledge of a large diversity of plants requiring pollination	'… Nuts, like almonds and cashews, apples, pears, mangos … different kinds of beans … kiwis, blueberries, maybe strawberries … sunflowers … coneflower …' (Maggie) 'Almonds, pumpkins, cucumbers … most species within the Rosaceae family, so that's, like, the almonds and cherries, apples …' [Tammy]
Plant structures	1	Knowledge of plant structures limited to simple visible or observable structures	'Um, and like, usually flowers like in the middle, you see it's a different part of the flower. I don't know what it's called. Um, so this middle part–… Except for it's like the, um, the other parts of the plant I'd say. So I'd say like that would be, um, where it would be able to come in …' [Winnie] 'I have no idea. I never learned those. … It has petals–. The stem, these are obviously leaves, that's the pollen, um, that's probably it' [Patricia]
	2	Uses limited number of specific terms to describe structures	'From the top of the flower and they would mix with the female part or male part, I'm not really sure, and then go into the stem to reproduce' [Sara] '… I feel like an, like the egg would develop which is the seed and then the fruit would grow around it. That's all I know' [Alexis]
	3	Detailed description of plant structures involved in pollination with specific terminology used (i.e. egg or sperm, stigma, style, anthers)	'I'll start with the stem, and then you have some leaves, then you have your blossom … So it's got the, I think … the middle part. The ovaries are inside of it. Um, part of me wants to say stigma … and then petals are around it and they attract pollinators and sort of protect it from the elements and then you have your anthers that have the pollen on them. And then so this is the middle part again with the ovaries and um, inside of it you have the egg cells, the ovas clustered in there and then pollen goes down into there and fertilizes the eggs and then, so, and then that, that can happen through a vector, like a bumble bee or a honey bee, or by itself' [Liam]
Purpose of pollination for the plant	1	Does not describe the relationship between pollination and plant reproduction or stated relationship is incorrect	'You need the bees to carry some of these elements – whatever they are called – from a specific plant or flower to the other ones, and whatever it is that they bring to the other ones creates a reaction or something that's needed for better plants to grow somehow' (Winnie)
	2	Describes individual-scale reproductive success	'It's basically to help plants reproduce and, uh, make new offspring'(Kenny)
	3	Describes population-scale reproductive success resulting in genetic diversity for the plant	'[The purpose of pollination is] for genetic variation so all trees aren't copies of each other. The whole process of evolution is based on variance in, in species … over time the trees that get their pollen out there the best and fertilize the most trees, their genes [are] preferentially ah, replicated and reproduced and get more common' (Jacob)

Table 5. Pollination knowledge framework related to insect pollinators structures and behavior.

Category	Level	Description/attributes	Example quotes from interviews
Types of pollinators	1	Knowledge of pollinators is limited to bees and uncertainty is expressed about other insects	'Um, I don't, I don't even know. Dragonflies maybe? I basically just think of things that can fly … bees … butterflies … I wouldn't think moths … not flies' (Kanika)
	2	Knowledge of a limited variety of pollinating insects (bees, butterflies) are provided	'I guess bees is the one that comes to mind. I'd say most kinds of insects could pollinate plants just kind of indirectly by crawling over them and carrying some pollen, uh, across the plant with them dropping it off' [Kenny]
	3	Knowledge of a large diversity of insect pollinators, non-insects (bats, birds etc.), and may mention wind as a pollinator	'Um, fruit bats. There's some species of possum in Australia that does it. Um, probably other mammals, too. Butterflies, ants, bees, humming birds or other birds that feed on nectar. I mean, anything that comes in contact with a, that visits a variety of flowers could be a pollinator, I guess …' [Liam] 'All different kinds of bees … and bats, butterflies, some kinds of birds, like maybe, um, hummingbirds … Wind, uh, Asian people with paintbrushes [laughs]' [Sue]
Animal pollinator structures	1	Knowledge of animal pollinator structures limited to simple visible or observable structures for eating (mouth) and arriving at the plant (wings)	'Um, like their mouth and their legs like to gather it, I guess … maybe their antennas to like sense their surroundings.' [Mary]
	2	Uses limited number of specific terms to describe structures	'I know a lotta bugs have hairs on them. Um … I know that bees have – and I'm sure flies do, too, have – rakes on their hind legs that collect pollen' [Lisa]
	3	Detailed description of animal structures involved in pollination with specific terminology used including non-observable attributes of these structures (i.e. pollen baskets, UV-specific vision, proboscis length)	'They have long tongues in some different species, [a] proboscis that can reach into plants so they can gather the nectar … I believe they see differently than we do, so they can, like, focus on a plant and they'll see, like, in ultra-violet … so that kind of makes them more attracted to [flowers]' [Maggie]
Purpose of pollinator for the animal pollinator	1	Describes no or an incorrect relationship between pollination and food for the animal	'Um, does it have something to do with like creating CO_2? … Um, something with the bees collecting pollen and transmitting it into some other kind of like CO_2 or something into the air' (Kanika)
	2	Describes individual-scale direct needs (e.g. food, shelter)	'Because I think it probably benefits the insect as well or the animal like – . Um, maybe for food or um, something that benefits them'(Mary)
	3	Describes systems-level understanding including the acquisition of the food for the animal and the unintentional aspect of pollination	'I think it's just happenstance. I don't think there are any animals that are going around saying, ok, I'm going to pollinate, except for people, obviously, that are saying I'm going to take this pollen and put it over here. It's just like, the pollen gets on it in the course of it's life and you know, moves somewhere else as they are moving around' (Jacob)
Pollinating insect survival needs and influencers	1	Unable to describe specific or accurate needs of pollinators	'Um, [pollinators need] food source and a home, so I think like obviously the flower provides both of those because it takes the nectar back to make like honey for like honey bees I think … Not pollen specifically, no' (Alexis)
	2	Describes various general factors of pollinator survival needs at an individual level (e.g. food, water, shelter)	'Mm, well, they probably need a food source … And some type of habitat that they can make somewhere. I'm sure they have to have water … probably a good climate where they can survive – I don't know if insects have to drink water … I don't know that much about insects but I'm sure they need it for something' (Patricia)
	3	Describes various factors of pollinator survival at a population level, as well as detailed descriptions of specific needs (e.g. various blooming periods for food, nesting and foraging and hibernation for habitat)	'A single bee needs food and shelter, warmth obviously. Food, water, shelter which is provided for that bee by the rest of the colony. Um, they forage for nectar. They stockpile it. Turn it into honey, which is used as food and also the rest of the bees know where the nectar is through communication like the dances they do–and the pheromones. They also need a queen because the queen bee is the only one that lays eggs and can lay eggs and therefore repro–, like you know, maintain the, the colonies numbers but the queen herself needs special bees that can tend to her. The bees need the colony to survive because that is how they get all of the, food shelter and water and so there! (Liam)

Table 6. Pollination knowledge framework related to pollination systems function and conservation.

Category	Level	Description/attributes	Example quotes from interviews
Relationship between humans and animal pollinators	1	Individual – centric view that is purely based on direct impacts of individual people and vice versa (e.g. stings, allergies)	'I know that like a lot of people have allergies to pollen and maybe you know, like that would have an effect on humans because like I said if there's like too much pollen, or like too little then people would have certain reactions to it' (Mary)
	2	A general sense of interconnectedness between humans and pollinators, but the connections are very limited, vague or indirect	'Well, certainly, certainly bees do since they produce honey. Um, butterflies I imagine there's the probably the biggest thing for butterflies is people like to look at them. There's an aesthetic value to butterflies and some moths' (York)
	3	The entire pollination system is connected with multiple relationships involved. Explains human reliance on pollinators for large-scale food systems	'… without bees, we wouldn't have X number of billions of dollars of crop revenue every year … But it does relate to our food systems, so without bees we wouldn't have, supposedly, like, 1 in every 3 bites of food, and we would be surviving on mostly meat and grains … We wouldn't have any of the luxurious and really evolved vegetables that we love. And they provide a lot of biodiversity. They just provide a lot of genetic variation that wouldn't happen otherwise' (Sue)
Role of pollination in environmental systems	1	The role of pollination is focused on reproduction and does not go beyond basic mentions of reproduction for the plant	'They help a majority of organisms reproduce … Plants, trees, fruit trees. Um, other than reproduction, no' (Sara)
	2	The role of pollination is discusses in regards to plant genetic diversity or simple food chains	'Um, well they help you know, keep the ecosystem going by helping other plants survive so in turn that does a lot for other animals in the environment because if one thing goes, everything else kind of gets destructed' (Patricia)
	3	The role of pollination includes impact on ecosystems (including wildlife and abiotic aspects) and human food systems	'Yeah, I mean, because pollinating insects, influence the production of plants … we need plants, we need trees … that's a big part of our, our food production is apples so if we don't have pollination of apple trees then there'll going to be less apples. And that could affect the environment. For one, any flowering trees … if they're not getting pollinated and not growing … that would affect the environment for more, more CO_2 in the air, less oxygen for us. And there's tons of other ways, for example, maybe there's some flowers on the stream bed … they're necessary to keep some erosion from happening … Without the pollinators to keep them living there could be environmental problems, definitely' (Yulie)
Action-oriented conservation	1	Only describes *individual* actions that directly affect pollinators	'Preserving the insects maybe. That's all I can think of just like leaving them be instead of … I feel like humans like to interact a lot and like pick the flowers, or like kill the bees, and just like letting them be and do their job' (Kanika)
	2	Describes how *communities* can indirectly impact food, water, shelter needed by pollinators for survival (e.g. reducing monoculture, community garden planting)	'You can put out little feeders for things or plant flowers or plant whatever to, [help] certain pollinators, you can help preserve or create environments for them, I guess' (Jacob)
	3	In addition to individual and community level action, includes actions that *society* can take to preserve pollinators (legislation, agricultural practices, labeling, etc.)	'CRP for example is kind of a policy decision; having grass as opposed to a wheat field. You know, there could be some wildflowers in there and that would indirectly affect pollinators … I don't think that the CRP program was implemented to help pollinators, but I think it can indirectly affect them for sure' (York)

(Level 3), medium (Level 2) and low (Level 1) levels of sophistication of thinking about pollinators and conservation. Below we describe the framework in terms of how systems thinking informed our levels of sophistication of student responses.

3.2. Pollination systems structures

The coding categories 'Types of plants' (Table 4) and 'Types of pollinators' (Table 5) were characterized by the level of student knowledge about the diversity of plants that require pollination, and the diversity of organisms that pollinate plants. Our most proficient level for each category is parallel to recognizing heterogeneous structures, an important characteristic of complex systems (Hmelo-Silver and Azevedo 2006; Wilensky and Resnick 1999) (Tables 4 and 5).

Students who gave Level 1 type explanations for the coding category 'Plant structures' and 'Animal pollinator structures' were only able to discuss visible or observable structures of plants and animals that were involved in pollination (Tables 4 and 5). This is consistent with other studies where novices focus on visible structures (Hmelo-Silver 2004; Hmelo-Silver, Marathe, and Liu 2007). In order to elicit more specific students' knowledge of plant structures related to pollination, we asked students to draw a diagram of a flower that shows how pollination happens and to explain what plant parts are involved. When asked to describe plant parts involved in pollination, Mary responded, 'just like the center of the flower' and could not be more specific (Figure 2). In contrast, Liam drew invisible structures that are important to reproduction (Figure 2) and used correct scientific terminology including stigma, anther, pollen, ovaries, eggs, and ova. Level 3 student responses about 'Animal pollinator structures' included structures that are not visible to the naked eye and would take specific scientific knowledge to explain, for example pollen baskets and ultraviolet vision in bees (Table 5). Most students' descriptions involved structures related to insects flying or eating. Many students could additionally describe more specific features, usually eyes or hair that collected pollen, achieving a Level 2.

3.3. Pollination systems behaviors

For the categories 'Purpose of pollination for plants,' and 'Purpose of pollination for animals' we grouped students by their ability to discuss relationships between components in pollination systems, as has been observed to be difficult for novices in other complex system settings (Hmelo-Silver, Marathe, and Liu 2007) and students' ability to give an explanation at larger spatial and temporal scales. Both of these categories describe students that are unable to describe correct relationships between structures (Level

Figure 2. Comparison between a Level 1 response from Mary and a Level 3 response from Liam to the interview prompt to 'draw a diagram of how pollination happens.' Level 1 responses revealed that students' knowledge was limited to simple visible or observable structures, whereas Level 3 responses were characterized with detailed description with specific terminology used.

1), students who give explanations that are at individual organism scales (Level 2) and students who are able to talk about population scale process such as genetic diversity in a population and evolutionary relationships between organisms (Level 3).

For 'Pollinating insect survival needs and influences' we focused specifically on the needs of bees as pollinators since they are the target of many conservation programs, and knowledge of these needs may be important for conservation actions. The levels of sophistication for this category followed a similar pattern of lack of understanding of relationships (Level 1), individual organism centric (Level 2) and systems thinking with specific needs described that link pollinators to the environment (Level 3).

3.4. Pollinator conservation: system function

We investigated student understanding of pollinator conservation from three different perspectives, the relationship between humans and animal pollinators, the role of pollinators in biotic and abiotic environmental systems, and actions humans make to influence pollinators. We developed levels of sophistication in responses based on previous research that indicated that novices are more likely to focus on local, concrete explanations rather than more global, dynamic relationships in a system (Hmelo-Silver, Marathe, and Liu 2007). Each of our categories ranged from Level 1 responses that focused on individual-centric actions or needs of humans or animal pollinators, to Level 2 responses that were characterized by limited or vague connections between system actors (pollinators, plants, humans for example), to Level 3 responses that were integrated connection between multiple features of pollination systems.

In order to elicit more specific understanding of pollination conservation, we asked students to agree or disagree with statements about actions that may or may not help insect pollinators and to explain why. All of the statements we provided were actions that benefit pollinators except for 'water your yard so your lawn grass is healthy for pollinators to eat and live in.' Overall students varied in the correctness of their response to whether or not each of these statements could benefit pollinators (Table 3). The average correctness was highest (1.3 ± 0.9 SD) for 'water your yard …' as many of the students recognized that lawn is not the best habitat, nor does it typically contain food sources for insect pollinators. Students had the most difficulty with their agreement with strategy of planting more agricultural crops (0.9 ± 0.9 SD). One student stated that he agreed, 'Agricultural crops are just as good as wild flowers and things like that.' Another countered the statement, saying,

> That doesn't mean anything … if I could change this statement, I would say, 'Plant less monocultures instead of agricultural crops.' because that is a really broad definition. But, there's nothing wrong with agricultural crops; it's monocultures that are harmful to many species, and to just the earth in general.

4. Discussion

4.1. Observations about student knowledge of pollination systems

A general pattern that we observed across students that emerged as a result of our coding was that students struggle to understand pollinator structures and specific conservation practices. Students performed lowest in the 'Pollinator structures' category and the 'Action-oriented conservation' category (2.00, Table 2) than in any of the other categories (Table 2). The coding category 'Pollinator structures' may have low scores because Level 3 student responses required describing structures that are not visible to the naked eye and would take specific scientific knowledge to explain, for example pollen baskets (pollen carrying structures on honey bees and bumble bees) and ultraviolet vision (Table 5). Few students had this knowledge, whereas most students' descriptions primarily involved structures related to insects flying or eating. It was surprising to us that students scored more poorly on aspects of pollination systems that were related to conservation. This is particularly interesting in light of the large number of educational programs aimed at informing students and citizens about the conservation needs of pollinators. Additionally, students generally did not score well on the correctness of their agreement or disagreement about particular actions that benefit pollinators (Table 6). It may be that pollinator instruction is focused on biological processes related to plants and pollinators, but less frequently ties the biological system to human needs and conservation practices.

Next we discuss four observations that we thought were particularly striking or interesting that may be useful in identifying student misconceptions. Our first observation is that students had difficulty connecting pollination to the process of reproduction for plants. Three of the students we interviewed (Winnie, Mary and Kanika) could not link pollination and plant reproduction at all throughout the interview. They talked vaguely about a process that might help plants 'grow.' Other students could link the process of pollination and reproduction when asked directly about the purpose of pollination, but struggled in the context of a real world phenomenon. Five students (Kanika, Lisa, Winnie, Mary and Mike) did not connect pollination or fertilization as key to the development of a food product like an apple. For example, Lisa was asked to describe how an apple tree produces an apple, and she was unable to identify pollination as a critical step in that process. Instead she said, 'The seed will grow roots and eventually have a stem and, um, once the stem grows large enough, it'll have extremities that carry nutrients from the soil, it will be able to hold fruit and produce an apple.' When asked, 'Some people say that pollination is needed for an apple tree to make an apple. Do you think it is?' She replied,

> Um, I don't think so. I guess I just associate pollination with flowers and flowering plants, which I guess apples are flowering, but I don't associate it so much with trees having to be pollinated to produce fruit. I would more associate it with just, uh, like, the flowers on the tree or in the plants nearby rather than the fruit itself.

To Lisa, the purpose of pollination has to do more with *flowers*, than with the plant producing seeds.

Second, we noticed that many students' understanding of plants involved in pollination was focused on flowers. We speculate that students' responses to these questions are heavily reliant on their personal experiences noticing flowers and pollen rather than what they have learned in the classroom. For example, one student, Lisa, mentioned flowers that a roommate received during Valentine's Day that shed pollen all over the counter, and her extrapolation that, '… most flowers have pollen and need pollination.' Another student Winnie responded, '… it's flowers, really,' then reasoned about flowers that need (dandelions) and don't need (roses, tulips) pollination. When asked why she thought some flowers do not need pollination she responded that 'That's only from observation, because I don't recall seeing bees on them.' Most often it seems that personal experience is dominated by plants with well-known, showy flowers rather than plants with less obvious flowers, like on trees for example, which is crucial to developing an understanding of the diversity of food plants that rely on pollinators. Overall, most students included plants that are insect pollinated for human food production in their list of plants that require pollination. Only two students, Mary and Kanika never mentioned food plants, and four students, Jacob, Lisa, Winnie and Mike, only mention insect pollinated food plants after asked, 'Do pollinators do anything useful for humans?'

Third, students had difficulty identifying kinds of creatures that pollinate plants. Students who gave Level 1 responses about 'Types of pollinators' were not specific about types of pollinators, and were limited primarily to talking about bees (Table 5). For example, Mary was asked to list the kinds of creatures that pollinate plants and responded, 'Besides bees? Um, I'm not sure if there is really. And that's only from what I think I've seen around.' Some students also seemingly arbitrarily excluded some types of insects. This type of thinking may, again, be a product of the student relying on their observational experiences of pollination, which may be limited, or may be influenced by media which is heavily skewed towards insects that are bees or look like bees. In a Google Images search (on 8 July 2016) using the search term 'pollinators,' of the first 150 images, 143 images included a pollinator. Of those pictured, 39% were bees, 26% were butterflies and moths, 16% were other insects (flies, beetles and wasps), 11% were birds, 6% were bats, and 2% were toads, lizards, and other small mammals. Additionally, Schussler (2008) examined 69 children's books and found that few of the books (n = 16) included reference to an insect pollinator although the role of the pollinator in these books was infer rather than stated, and fertilization was not mentioned. In general, she found that often portrayals of plant reproduction did not include details about mechanisms or supported misconceptions about pollination.

Fourth, we found several students whose conception of animals involved in pollination were very broad, and three explicitly said that *any* animal could be a pollinator if they brushed up against a plant.

For example, Jacob mentioned that '… probably small mammals climbing around or large ones that happen to get pollen on them.' could pollinate plants. When asked what kind of mammals he was thinking of he responded, 'I mean, I can imagine some, some large, like, say like a wolf is frolicking through a field of flowers and it gets some pollen on it and then that pollen, you know, goes, happens upon another flower in the course of that frolicking.' Examples of large mammals (cows, dogs, deer, bear or wolves) were mentioned by 5 of students. It may be that these students are conflating pollination and dispersal, which we saw evidence of among 8 students at some point in the interview. Sometimes there was an obvious conflation of these two processes, for example, when Alexis was asked what creatures pollinate plants she mentioned sparrows, cats, dogs and cows and said '… so it's like cows, when they eat something they poop out the seeds, that's their food source but they're also helping the plant by dispersing the seeds again.' Others students were more subtly confusing the two processes, for example, Mary when talking about the purpose of pollination said

> I don't know if it has anything to do with when it spreads in the air, like, if it reaches another area and then that certain plant of flower or something can grow there too. Like, if it just spreads the growth of what it's coming from … And then the wind blows and takes that pollen somewhere else, like whether it be across the state or something, and then that flower could grow where the pollen ends up.

We speculate that these students may not have a clear understanding of specific plant processes involved in fertilization and dispersal to begin with that contributed to the confusion. Or, additionally, students may not have a strong understanding of the specialized evolutionary relationship that develop between animal pollinators and plant species, and instead may have a view that pollination may occur during chance encounters between animals and plants.

5. Summary and implications

This theoretical framework is a first step in understanding what students know about pollinators. It may be useful in developing validated assessments of individuals' understanding of pollination systems, and is also a useful tool for discussing gaps in pollination system understanding and which areas of student knowledge could be better emphasized in both formal and informal instruction. In this study, we focused on asking questions that represented both broad and specific concepts that we felt most directly tied knowledge about pollinator conservation and recognize this framework may not capture all pollination knowledge domains. We believe it is helpful for everyone to have some understanding of the relationship between pollinator and plants, how pollination impacts humans and the environment, and the roles and practices of humans, communities, and society on pollinator health to make informed decisions impacting pollinator health. Future studies could explore the relationship between pollination knowledge and conservation actions.

The lowest level of knowledge sophistication represented by interviewees was in the action-oriented conservation category (see Table 2). We feel this is troublesome for promoting conservation efforts, as postsecondary students (the focus of this study) will soon join the workforce and take on roles like homeowners, farmers and ranchers, green industry workers, and public servants. In these roles they will face both transparent and non-transparent decisions that affect pollinator health. Thus, we feel promoting the knowledge of action-oriented pollinator conservation practices is especially needed and timely in postsecondary education.

While study participants were from a breadth of majors, races, and backgrounds, they were recruited from a single university. In our participants, 38% reported growing up in a rural location with many of these giving responses indicative of some understanding of agricultural systems (e.g. that in Midwest corn dominates agriculture and general awareness of pesticide application in agriculture), and 60% of the students identify themselves as a 'naturalist' or interested in nature. As a result, there could be biases in our study participants towards conservation knowledge practices and human impacts, not indicative of students from other regions or with other identities. Future studies looking at pollinator knowledge domains should consider expanding to include participants from other locations and cultural backgrounds.

This framework represents a baseline of pollination systems knowledge that may aid postsecondary teachers, pollinator conservation outreach programs, and pollination researchers in developing more targeted educational tools, outreach materials, and media. Also, the SBF model was useful in exploring and organizing student knowledge of pollination systems. Student created SBF models may be a useful instruction tool and a way for instructors to assess student knowledge in a classroom. We suggest that educational researchers can use this framework as a foundation to develop assessment tools for measuring pollination systems knowledge gains of learners as a result of educational interventions.

Disclosure statement

No potential conflict of interest was reported by the authors.

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Appendix A

Interview protocol
(1) How does an apple tree produce an apple? (2) You mentioned pollination. Can you describe that process? OR [only if pollination not mentioned] Some people say that pollination is needed for an apple tree to make an apple. Do you think it is? (3) What do you think the purpose of pollination is? (4) List some of the kinds of plants that need pollination. [Make a list as they talk so you can pick some of the student's responses that represent a range of pollination methods.] For ______, how does that get pollinated? For ______, how does that get pollinated? For ______, how does that get pollinated? (5) Can you think of any plants that *do not* need pollination as part of their life cycle? (6) Can you draw a diagram of a flower that shows how pollination happens? [Ask the student to explain out loud as they are drawing. And be sure to have either them or you speak what they are pointing to in their diagram if possible.] What plant parts are involved? Can you think of any other terms a scientist would use to describe plant parts? What is the purpose of different plant parts? (7) List some of the kinds of creatures that pollinate plants. [If they don't mention bats, other mammals or birds ask: Can you think of any creatures besides insects that pollinate plants?] Why would an animal (or insect or creature) pollinate a plant? What features do the animals (like _____) have to facilitate their relationship with plants? What features do the plants have to facilitate their relationship with animals (like _____)? (8) What do bees need to survive? [Make a list as they talk so you can refer to it later.] How does a bee use ____ to survive? How does a bee use ____ to survive? [If not mentioned] Does a bee need water to survive? [If not mentioned] Does a bee need pollen to survive? Can you think of anything that would hurt bees survival? (9) Do pollinating insects do anything useful for humans? Can you think of any ways that having *less* pollinating insects might influence humans? (10) Do pollinators have an impact on the environment? If so, can you describe their impact? [This question may be repetitious, if so, skip.] (11) Is there anything that you could do to help pollinators? [Display card below and read list of student ideas] Some students suggest that to help pollinators you should: (1) Plant flowers that bloom during different times of the year in your yard (2) Spray pesticides at dusk only (3) Water your yard so your lawn grass is healthy for pollinators to eat and live in. (4) Put a bee box or plant hedgerows in your yard for pollinators to nest in (5) Plant less agricultural crops Do you agree with each of these? [For each question have the student explain why they agree or don't agree.] (12) Do you know of any policies or laws that involve pollinators?