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A Review of the Research Literature on Teaching about Interdependent Relationships in Ecosystems to Elementary Students

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INTRODUCTION

Elementary teachers face formidable obstacles when planning and implementing science instruction, including inadequate preparation opportunities, lack of resources, and accountability pressures. Data from the 2012 National Survey of Science and Mathematics Education bear this out (Banilower et al., 2013). Further, the expectations for elementary science instruction were raised to a new level with the release of the Next Generation Science Standards (NGSS Lead States, 2013),the latest in a series of college and career-ready standards. Together with the Common Core State Standards in Reading and Mathematics (National Governors Association Center for Best Practices & Council of Chief State School Officers, 2010a, 2010b), they put forth an ambitious vision of what students should know and be able to do in these fields as a result of K–12 education. To realize the vision of excellent science education for all students portrayed in the NGSS, elementary teachers will need to draw on varied domains of knowledge. Prominent educators and researchers have proposed the existence of a professional knowledge base for teaching, similar to the specialized knowledge bases for medicine and law (Grossman, 1990; Hiebert, Gallimore, & Stigler, 2002; Hill, Rowan, & Ball, 2005; Shulman, 1986). Efforts to articulate the components of such a knowledge base have been underway for over two decades.

Some constituent knowledge forms, such as disciplinary content knowledge, are fairly well understood and widely accepted as necessary, but not sufficient, for effective teaching (e.g., Heller, Daehler, Wong, Shinohara, & Miratrix, 2012). Perhaps the most widely recognized form of specialized knowledge for teaching—and arguably the one with the most potential for helping teachers overcome knowledge-related obstacles—is "pedagogical content knowledge" (PCK), which Shulman (1986) described as an amalgam of pedagogical knowledge (general teaching knowledge) and content knowledge (knowledge of a specific discipline). An oft-cited example is knowledge of an effective strategy for teaching a particular concept; for example, having students slide an object on progressively smoother surfaces to construct an understanding of the idea that an object in motion tends to remain in motion in a straight line unless a force acts on it. Magnusson, Krajcik, and Borko (1999) developed a model of PCK that has strongly influenced conceptualizations of what constitutes PCK in science as well as other disciplines. Recently, a new model of PCK emerged, one that acknowledges both collective and personal aspects of PCK (Gess-Newsome, 2015). In this model, shared or collective PCK is referred to as topic-specific professional knowledge (TSPK). Hypothesized relationships among these and other forms of knowledge are shown in Figure 1.

As illustrated in the model, discrete professional knowledge bases—disciplinary content knowledge chief among them—are the foundation for TSPK. Examples of TSPK include an instructional strategy that has been found through empirical studies to be effective for teaching a specific idea, or recognition of a conceptual difficulty found through assessment studies to be prominent among elementary students. This knowledge can be applied by teachers to their own unique settings and for their own purposes. As teachers take up TSPK—e.g., through reading, professional development experiences, discussions with colleagues, reflecting on their practice—and use it in their teaching, it becomes personal PCK.

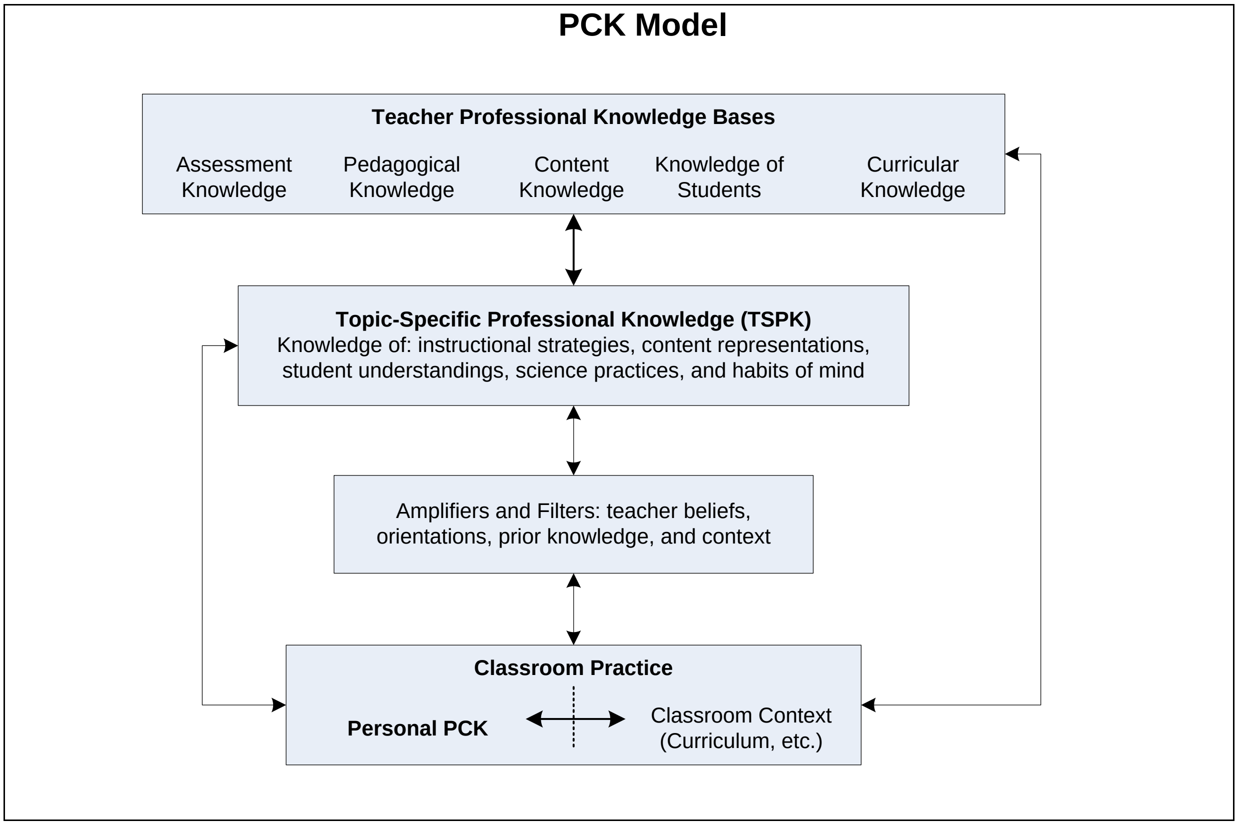

Figure 1

TSPK can help elementary teachers overcome knowledge-related obstacles to science teaching in several ways. Most importantly, TSPK provides a rich resource for helping teachers incorporate what is known about effective teaching of a topic into their instruction (see Figure 2). For example, TSPK can be a valuable instructional planning resource or the focus of discussion in a teacher study group or professional learning community. Another high-leverage use of TSPK is in instructional materials development (Banilower, Nelson, Trygstad, Smith, & Smith, 2013). Similarly, teacher educators and professional development providers can use TSPK to craft and provide topic-specific support for pre-service and in-service teachers.

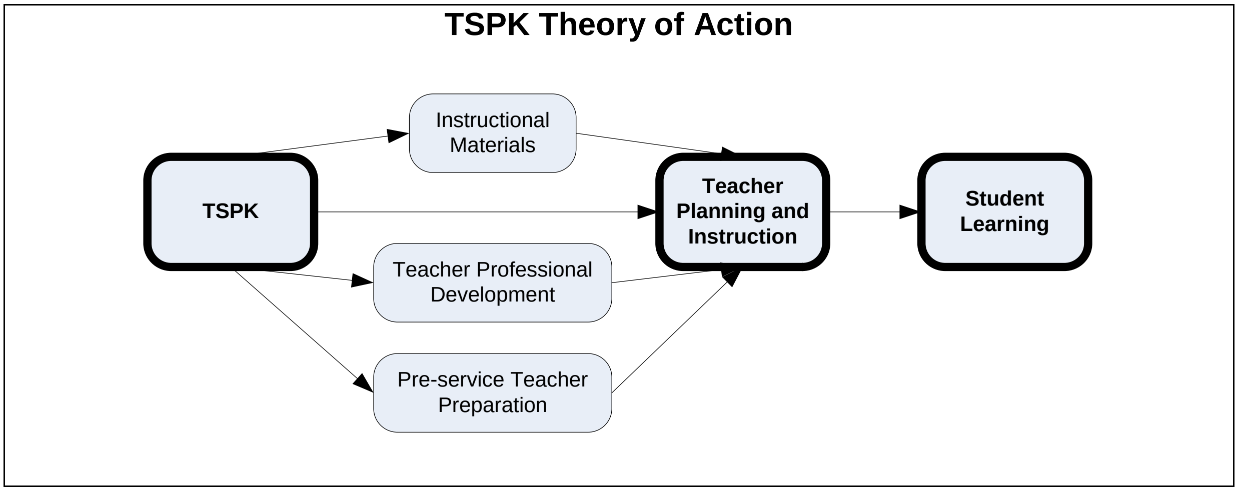

Figure 2

There is a common perception that TSPK is widely available. Although TSPK does exist and has been compiled in a few topic areas (e.g., empirical research abounds for student thinking about force and motion), most science topics are not yet well researched. Even a brief search of the literature illustrates the lack of easily accessible TSPK in many topics. In addition, the literature that does exist is not organized for use by teachers.

With support from the National Science Foundation, Horizon Research, Inc. (HRI) is testing a method for collecting and synthesizing PCK from multiple sources, with the ultimate goal of making the resulting TSPK available to teachers as a support for implementing the NGSS. The method draws on empirical research literature, practice-based literature (e.g., professional journals for classroom teachers), and expert wisdom of practice (collected by surveying and/or interviewing expert practitioners).

In this report, we describe the results of a review of empirical research literature related to teaching one topic from the NGSS. Our goal was to determine how much PCK for teaching interdependent relationships in ecosystems at the upper elementary level could be "extracted" from the empirical literature. Subsequent reports will describe efforts to synthesize PCK from the combination of this source, the practice-based literature, and expert wisdom of practice.

METHODOLOGY

The literature review focused on one NGSS disciplinary core idea (DCI) related to Interdependent Relationships in Ecosystems at the fifth grade: 5-LS2.A. The NGSS state the ideas related to interdependence as:

> The food of almost any kind of animal can be traced back to plants. Organisms are related in food webs in which some animals eat plants for food and other animals eat the animals that eat plants. Some organisms, such as fungi and bacteria, break down dead organisms (both plants or plants parts and animals) and therefore operate as "decomposers." Decomposition eventually restores (recycles) some materials back to the soil. Organisms can survive only in environments in which their particular needs are met. A healthy ecosystem is one in which multiple species of different types are each able to meet their needs in a relatively stable web of life. Newly introduced species can damage the balance of an ecosystem (NGSS Lead States, 2013, p. 48).

We rearranged and unpacked some of the ideas in a way that would more easily allow us to organize findings from the literature:

1. The food of almost any kind of organism can be traced back to producers such as plants and algae.
    a. Food provides organisms the materials and energy they need to grow and function.
    b. Producers make their own food *inside themselves* using energy from the sun, and matter from air and water.

2. Organisms in ecosystems are related in food webs
    a. Consumers get their food by eating other organisms. Some consumers eat producers. Some consumers eat other consumers.
    b. Decomposers, such as bacteria, fungi and earthworms, are consumers that break down dead organisms (or parts of organisms).
    c. Decomposition eventually restores (recycles) some materials back to the environment, making necessary resources available to producers.

3. Organisms can survive only in environments in which their particular needs are met. Environmental conditions include, but are not limited to, light, temperature, moisture, amount of oxygen, nutrient availability, and salinity.

4. A healthy ecosystem is one in which the needs of multiple types of organisms are met in a relatively stable web of life.

5. Natural events and human activity can change the balance or stability of an ecosystem. When the balance, or stability, of an ecosystem changes, the opportunities for different types of organisms to meet their needs can increase or decrease.

We began the literature search by identifying a list of key search terms, such as "ecosystem(s)," "food web," and "student knowledge." The full list of key terms can be found in Table 1. Individually, these terms returned a broad spectrum of results from several search engines (ERIC and Google Scholar among them); therefore, many of the terms were used in combination in order to narrow the literature to articles that relate to teaching interdependence in ecosystems at the elementary school level. Two examples include, "ecosystems AND elementary students" and "food web AND misconceptions[1] AND elementary education." For search terms more likely to yield instruction guidance (e.g., lesson plans, instruction), phrases such as "elementary/secondary education" and "elementary/secondary science" were used to narrow the search. To be included in the review, a study had to meet the following criteria:

- Reported in a peer-reviewed journal, peer-reviewed conference proceedings, or an edited book;
- Included K–8 students in the study sample;
- Was a systematic empirical study (strictly theoretical pieces were not included); and
- Could not be a literature review only (however, the bibliographies of these articles were used to identify primary sources).

Table 1
Key Search Terms

Activities	Ecology misconceptions	Elementary student	Predator
Concepts	Ecosystem interdependence (ies)	Food web	Prey
Curriculum	Ecosystem misconceptions	Instruction	Producer
Decomposer	Ecosystem(s)	Learning	Student knowledge
Decomposition	Elementary	Lesson plans	Student thinking
Ecology	Elementary education	Lesson(s)	Understanding

Articles were initially screened by reading only the abstract. Those that appeared to meet the review criteria (N = 110) were saved in a reference management program.

The project team created a list of tags to be applied as the articles were read more carefully, and the tags were used to filter the collection. For example, articles that were found to focus on high school students, pre-service teachers, or in-service teachers (but not K–8 students) were excluded from the final collection of literature. Because we were most interested in finding PCK related

[1] In this report, "misconception" is used to denote any idea that conflicts with accepted scientific ideas about a phenomenon, acknowledging that such ideas are neither good nor bad and may represent a productive step in a student's learning progression.

to targeted ideas about interdependent relationships in ecosystems, we also excluded articles focused on:

- Specific types of ecosystems (e.g., longleaf pine, watershed, coral reef) when connections to general ecosystem concepts were not evident;
- A particular set of organisms (e.g., insects, shrimp, polar bear) when connections to general ecosystem concepts were not evident;
- Misconceptions or concept development at a level broader than ecosystems (e.g., biology, 5^{th} grade science); or
- Photosynthesis in the absence of its role in ecosystem.

Although the initially screened articles spanned a wider range of dates, the final pool included 38 studies, with publication years from 1982 to 2014 (median = 1998).

Once the literature pool was finalized, researchers began coding the kinds of PCK in each study. The coding scheme was both *a priori*, based on the Magnusson et al. (1999) model of PCK, and emergent. Magnusson et al. describe discrete forms of PCK, including knowledge of instructional strategies, knowledge of students' understanding of science, and knowledge of science curriculum. In some cases, we elaborated on these forms, for example adding *misconceptions* and *learning progressions* as categories of knowledge of student understanding.

Because the articles in the pool varied in the quality of the research designs, the project team added a confidence rating for each piece of PCK coded. The codebook is included in the Appendix. This rating was intended to reflect the reliability and generalizability of the PCK. For example, if an article claimed that upper elementary students are likely to have a particular misconception, the rating conveys how confident we are that the claim is true. To determine the confidence rating, we used an adapted version of the Standards of Evidence (SoE) review process (Heck & Minner, 2009). The SoE review assesses the extent to which key components of the research are documented and judges support for findings considering each question that the publication addresses. Key in the assessment of rigor is the consideration of multiple aspects of internal validity. We selected a subset of indicators in order to create an abbreviated review process, focusing on five factors:

1. Sample size;
2. Appropriateness of analyses;
3. Validity and reliability of research instruments;
4. Appropriateness of generalizations; and
5. Potential for investigator bias.

Additionally, we looked at the alignment of the purpose of the research and the coded PCK when determining the confidence rating. For example, if a study was not designed to identify student misconceptions, but student misconceptions were identified incidentally, each coded misconception received a low confidence rating. However, if the same item of PCK was extracted from many articles in the literature pool, even if it received a low confidence rating each time, the item ultimately received a high rating overall based on the accumulation of evidence.

A codebook (included in the Appendix) was developed to provide descriptions of each code, rules for when a code should be applied, and explanations of how to determine confidence ratings. The project team iteratively reviewed 10 articles, applied the coding scheme (comparing codes and confidence ratings), and refined the codebook. This process was continued until the project team reached a consensus understanding of the codes and applied them consistently. Following modifications to the codebook, two project researchers applied the coding scheme to the remaining articles in the pool.

Although traces of all PCK types were found in the literature, our findings reported here focus exclusively on student thinking and prompts because these two areas were by far the most prevalent across the studies. We define prompts as questions or tasks that teachers would pose to their students in order to elicit their thinking in writing or orally to use for formative purposes. Although we identify many prompts in the empirical literature, some that are appropriate for research purposes (e.g., one-on-one interviews) are not appropriate for classroom use. For this reason, we extracted prompts from the literature that the reviewer could envision a teacher using with students as is—that is, without substantive changes to the language used.

In the next section, we summarize the substantive findings from the studies.

FINDINGS

As mentioned previously, the search and screening processes yielded 38 studies, shown in Table 2. An expanded version of the table, including a brief description of each study, appears in the Appendix.

Table 2
Article Summaries

Author (Year)	Where the study occurred	Number	Age/Grade of subjects
1. Adeniyi (1985)	Nigeria	232 tested; subset of 26 students interviewed	Ages 13–15
2. Alao & Guthrie (1999)	U.S.	72	5th grade
3. Bailey & Watson (1998)	England	~100	Ages 7–11
4. Barman, Stein, McNair, & Barman (2006)	U.S. & Canada	~2400	K–8th grade
5. Bell-Basca, Grotzer, Donis, & Shaw (2000)	U.S.	60	3rd grade
6. Brody (1993)	U.S.	316	4th, 8th, and 11th grade
7. Brody (1994)	U.S.	467	4th, 8th, and 11th grade
8. Brody & Koch (1990)	U.S.	187	4th, 8th, and 11th grade
9. Çetin (2007)	England & Turkey	96	Ages 14–15 (7th grade)
10. Demetriou et al. (2009)	Cyprus	46	Ages 9–10 (4th grade)
11. Ero-Tolliver, Lucas, & Schauble (2013)	U.S.	23	1st grade
12. Evagorou, Korfiatis, Nicolaou, & Constantinou (2009)	Cyprus	13	5th and 6th grade (Ages 11–12)
13. Gallegos, Jerezano, & Flores (1994)	Mexico	506	4th–6th grade
14. Gotwals & Songer (2010)	U.S.	318	6th grade
15. Grotzer (2009)	U.S.	99	6th grade
16. Grotzer & Basca (2003)	U.S.	60	3rd grade
17. Helldén (1998)	Sweden	~25	2nd–8th grade
18. Hmelo-Silver, Eberbach, & Jordan (2014)	U.S.	311	Middle school
19. Hogan (2000)	U.S.	52; 16 focal students	6th grade
20. Hogan (2002)	U.S.	24	8th grade
21. Hogan & Fisherkeller (1996)	U.S.	Curriculum piloted in 12 classrooms; 8 students interviewed	5th and 6th grade
22. Jordan, Brooks, Hmelo-Silver, Eberbach, & Sinha (2014)	U.S.	66; data analyzed from 35 students who completed all tasks	7th grade
23. Jordan, Gray, Brooks, Honwad, & Hmelo-Silver (2013)	U.S.	40	7th grade
24. Jordan, Gray, Demeter, Lui, & Hmelo-Silver (2009)	U.S.	45	7th grade
25. Jordan, Hmelo-Silver, Liu, & Gray (2013)	U.S.	138	7th–8th grade
26. Leach, Driver, Scott, & Wood-Robinson (1992)	England	~200	Ages 5–16
27. Leach, Driver, Scott, & Wood-Robinson (1995)	England	~200	Ages 5–16
28. Leach, Driver, Scott, & Wood-Robinson (1996a)	England	~200	Ages 5–16
29. Leach, Driver, Scott, & Wood-Robinson (1996b)	England	~200	Ages 5–16
30. Magntorn & Helldén (2007a)	Sweden	23	Ages 10–11
31. Magntorn & Helldén (2007b)	Sweden	15	Ages 13–14
32. Myers, Jr., Saunders, & Garrett (2003)	U.S.	171	Ages 4–14
33. Özkan, Tekkaya, & Geban (2004)	Turkey	58; 10 students interviewed	7th and 8th grade

34. Palmer (1997)	Australia	123	Ages 12 and 16
35. Papaevripidou, Constantinou, & Zacharia (2007)	Cyprus	16	5th grade
36. Simpson & Arnold (1982a)	Scotland	578	Ages 11–16
37. Simpson & Arnold (1982b)	Scotland	Varied based on task and age range	Ages 11–16
38. Smith & Anderson (1984)	U.S.	1 class	5th grade
39. Tsoi (2011)	China	140	Ages 8–10

In attempting to code PCK from these articles, it became clear that the literature is heavily focused on aspects of student thinking, and within student thinking, primarily on misconceptions. Some studies also included prompts used to elicit student thinking; however, these studies typically concentrated on examining student thinking rather than the efficacy of particular instructional strategies. Nonetheless, these questions and tasks may offer guidance for first steps towards uncovering students' initial ideas. Below, we summarize our findings organized by five fundamental ideas related to interdependent relationships in ecosystems.

Producers make food for their growth using light, carbon dioxide from air, and water.

Several studies examined student thinking related to the concept of producers. Study results often indicated that students are unaware of producers making their own food (Demetriou et al., 2009; Leach et al., 1992). The notion that producers take in food, or nutrients, from their surroundings (e.g., the soil), as opposed to making food, is pervasive in student thinking (Adeniyi, 1985; Barman et al., 2006; Brody, 1993; Çetin, 2007; Helldén, 1998; Hogan & Fisherkeller, 1996; Leach et al., 1992, 1996a; Özkan et al., 2004; Simpson & Arnold, 1982b; Smith & Anderson, 1984). For example:

> *When considering what plants need in order to grow, students tended to portray plants as requiring what humans need in order to grow. For example, the ideas that plants "eat," "drink," and "breathe" occurred frequently. The students observe plants as being provided sunlight, water, and food externally, much like their idea of how they themselves take in food and water to grow, or stand in the sun to be warmer.* (Barman et al., 2006, p. 75)

> *Plants get energy from their food. This food is obtained from the soil, through the roots.* (Simpson & Arnold, 1982b, p. 177)

Other studies reported that some students do acknowledge that producers make food for their growth; however, they tend to hold an incomplete understanding of the process (Barman et al., 2006; Helldén, 1998; Simpson & Arnold, 1982b; Smith & Anderson, 1984). These incomplete understandings often result from a combination of missing conceptions or misinformation, including students' omission of one or more of the essential components (i.e., light, carbon dioxide, and water) needed to produce food. Incomplete understandings also arise from confusion surrounding the source of these components. Helldén reported instances of such confusion in his longitudinal study:

> *[The student] suggested for example at [age] 11 that the carbon dioxide came from the worms in the soil.* (1998, p. 10)

Smith and Anderson (1984) found that students thought of light as something to enhance plant health rather than a requirement for food production and survival. Interestingly, a classroom investigation designed to examine plants' needs inadvertently introduced this misconception. The class carried out an investigation where they grew grass in the light and in a dark closet:

> *When the students observed that grass began to grow in the dark, their view that plants need light to live and grow was shaken. After observing specimens of grass from the closet…the students nearly unanimously asserted that plants do not need light. The observation that the grass in the dark was actually taller than that in the light probably contributed to this belief. As the students continued to observe the plants…they used such words as "dark green," and "stronger," and "straight" to describe those in the light, while those in the dark they labelled "light green" or "yellow," "weaker," and growing "in all directions." This was consistent with the view that plants need light to be healthy, and more students appeared to develop this conception.* (Smith & Anderson, 1984, pp. 689–690)

Additionally, students' unfamiliarity with aquatic vegetation makes it difficult for them to fully understand the needs of producers in aquatic environments (Adeniyi, 1985; Brody, 1993, 1994; Brody & Koch, 1990):

> *For most students, the apparent lack of vegetation in large bodies of water led to the misconception that plants do not live in water.* (Adeniyi, 1985, p. 314)

Matter and energy flow through ecosystems. Matter provides organisms the materials and energy necessary to function and grow.

Several studies examined student thinking about trophic relationships and the flow of matter in ecosystems (Adeniyi, 1985; Gallegos, Jerezano, & Flores, 1994; Gotwals & Songer, 2010; Grotzer, 2009; Hogan, 2000; Hogan & Fisherkeller, 1996; Magntorn & Helldén, 2007; Özkan et al., 2004; Tsoi, 2011). Tasks involving the construction and interpretation of food webs or a particular ecosystem were common approaches for exploring students' ideas related to understanding and illustrating relationships. Illustrative examples of the prompts found to target the concept of relationships within ecosystems follow.

Grotzer reported use of the following in student interviews:

> *Here is a picture of the forest. Here are some plants and animals from the forest. What are some ways that they are important to each other?* (2009, p. 26)

Demetriou et al. asked students to respond in writing to the following questions, based on their interpretation of a provided food web:

> *a) What do snakes eat?*
> *b) Which species' population will be affected if the sparrows disappear?*
> *c) What will happen if the corn disappears?* (2009, p. 183)

Researchers found that some students conceptualize food web relationships at the individual level (i.e., a single predator and a single prey), as opposed to the population level (Bell-Basca et al., 2000; Leach et al., 1996b). For example:

> *In this study many pupils, particularly between the ages of five and 11, were likely to talk about organisms in the singular, suggesting a relationship between one predator and one prey organism as opposed to relationships between populations. Pupils between five and seven did not show any evidence of conceptualizing groups of interdependent organisms in ecosystems; their only experience of organisms (and particularly mammals as represented in this task) was in the context of zoos, farms, storybooks and pets.* (Leach et al., 1996b, 136)

Additionally, young students often associated organisms' eating habits with their size, strength, or perceived ferocity (Adeniyi, 1985; Gallegos et al., 1994; Grotzer, 2009). Related to this point, Gallegos et al. identified two commonly held student views:

1. *Animals are carnivorous if they are big and ferocious.*
2. *Animals are herbivorous if they are passive or, frequently, smaller than the carnivorous animals.* (1994, p. 268)

Similarly, researchers found that students tended to believe that organisms eat all others below them in a food web (Grotzer, 2009; Hogan, 2000; Özkan et al., 2004). A top-level consumer, for example, would be seen as having all other organisms in the ecosystem as a food source. Additionally, Grotzer characterized students as having "a tendency to focus on menu-driven as opposed to opportunity-driven feeding relationships" (2009, p. 16). That is, animals choose from among many options in selecting their prey. Similar trends appeared to exist in student ideas about organisms easily changing their diet based on food availability (Grotzer, 2009; Hogan, 2002; Leach et al., 1992; Tsoi, 2011).

> *There were a number of instances, where it was clear that either experiences that students had or didn't have, influenced how they reasoned about the concepts. If one does not have the opportunity to see how certain plants, seeds, and berries are seasonal in the woods and can be bought every day of the year in the local supermarket, the opportunistic nature of a food web is unlikely to come across without explicit attention to it.* (Grotzer, 2009, p. 16)

Some students appear to believe that organisms generally depend on humans to supply their needs (Demetriou et al., 2009; Leach et al., 1992, 1996b)**:**

> *Specifically, most [students] considered that ducks, fish and geese were human-dependent, declaring that they fed on bread that humans threw to them.* (Demetriou et al., 2009, p. 185)

> *Many pupils…thought that mice eat cheese that is given to them by people, and that rabbits eat carrots that are given to them, by people or taken from people's vegetable gardens.* (Leach et al., 1992, p. 97)

The NGSS introduce the concept that organisms need food in grades K–2; however, in grades 3–5, the expectation deepens to students understanding that food provides animals with the materials and energy they need for body repair, growth, warmth, and motion. One study's findings illustrate student thinking related to this progression:

> *From the age of about eight, a growing number of pupils appreciated that food is an essential requirement for the growth of living things. However, the scientific explanation that the body matter of all organisms is "chemically transformed food" posed huge problems to learners.* (Leach et al., 1996a, p. 31)

Helldén found that students were inclined to view organisms as "the 'end station' for matter flowing through the ecosystem," (1998, p. 8). Others also found this to be the case, particularly with the process of decay (Hogan, 2000; Leach et al., 1996a). Students appear to think in ways that run counter to the concept that decomposition eventually restores (recycles) some materials back to the environment. For example:

> *The vast majority of pupils up to the age of 16 did not see any need to explain where all the matter goes during the process of decay* (Leach et al., 1996a, p. 29)

> *[The student] said that salt can get into freshwater, kill freshwater fish, snail and plants, then wash up onto land and get into soil where it harms grass and mustard plants, then goes into the crickets that eat the plants, and finally is excreted as animal waste. He*

stopped short however, of tracing the excreted salt back into the ecosystem. (Hogan, 2000, p. 26)

Decomposition is the chemical breakdown of dead organisms (or organism parts) performed by some consumers, and is essential to a healthy ecosystem.

Several studies found evidence that elementary-age students view decomposition as a process that occurs in the absence of decomposers (Çetin, 2007; Ero-Tolliver, Lucas, & Schauble, 2013; Grotzer, 2009; Helldén, 1998; Hogan & Fisherkeller, 1996; Leach et al., 1992, 1995). Within a subset of these studies, students conceptualized decomposition as either the physical disintegration (e.g., leaves being ground up into smaller parts, as opposed to chemical decomposition) or removal of a dead organism or its parts by humans (Ero-Tolliver, Lucas, & Schauble, 2013; Grotzer, 2009; Helldén, 1998; Hogan & Fisherkeller, 1996). Ero-Tolliver et al. suggested how students' environments may influence their thinking::

> *Students said that the leaves "disappeared," "died," were "blown away," or were taken away by trash collectors, all reasonable replies, given the experiences of these urban children.* (2013, p. 2141)

Other studies highlighted students' uncertainty about what organisms perform decomposition in an ecosystem and particularly students' tendency to not associate microbes with decomposition (Çetin, 2007; Grotzer, 2009; Leach et al., 1992). For example:

> *On their pretests, students missed non-obvious, microbial causes of decay. Students talked about processes such as aging, weathering, [and] erosion as factors in the structural change of the things that decay. Or they referred to more obvious decomposers such as worms, animals or kids stepping on it, etc.* (Grotzer, 2009, p. 14)

Researchers suggest that limited exposure to decomposition, may contribute to students' unfamiliarity with the phenomenon and the idea of decomposers as living organisms (Grotzer, 2009; Leach et al., 1992):

> *The pupils did not think that [mold] was alive...they thought that [mold] came from within decaying material as it decayed.* (Leach et al., 1992, p. 174)

> *Unless students have experiences witnessing decay, they do not necessarily have ways of realizing that decay does occur even if no children are around to step on the piles of leaves that they see on city sidewalks. The city sidewalks eventually get swept clean so students do not have the experience over time of witnessing the process. Time delays are difficult enough to deal with because we often stop attending to such processes, however, in this case, many of the students don't have the experiences to support an understanding*

> *of what happens over time. This complicates their opportunity to witness what happens and to realize that tiny microbes play a role.* (Grotzer, 2009, p. 14)

Ultimately, these alternate conceptions of decomposition may lead to students discounting the important function of decomposers in an ecosystem (Leach et al., 1992; Özkan et al., 2004) and an incomplete understanding of the cycling of matter.

Although the aforementioned studies found students to lack a complete understanding of decomposition and the role of decomposers, Leach mentioned leveraging a common student experience when trying to elicit student thinking about these ideas:

> *"[The study] used decaying fruit as a stimulus because children in the trials of the probes seemed familiar with decay in this context. It may be that children would offer different explanations about the causation of decay in different contexts such as a decaying animal body."* (1992, p. 114)

Others also drew on everyday experiences in order to ask students to make predictions or explain phenomena that they may not have considered otherwise. For example:

> *What do you think will happen to the leaves on the ground in the autumn?* (Helldén, 1998, p. 6)

> *What happens over time after a tree in the forest dies?* (Grotzer, 2009, p. 6)

> *John put four apples in a glass bowl, but then he forgot to eat them for two weeks. He noticed that they have a bad smell and have lost their original shape. Explain briefly why they can smell and lost their original shape.* (Çetin, 2007, p. 7)

Research indicated that pictures or time-lapse videos can also be useful stimuli for eliciting student ideas related to decomposition (Grotzer & Basca, 2003; Helldén, 1998; Leach et al., 1995). One study utilized ongoing observation:

> *First, the teacher put a single banana on each table where four students sat. The easy accessibility of the banana to sight (as well as smell and touch via occasional poking) encouraged students to notice gradual changes in its appearance from day to day, and the children drew and wrote descriptions of change in their notebooks.* (Ero-Tolliver et al., 2013, p. 2143)

Abiotic factors impact organisms' ability to function and survive.

Across several studies, students appeared to hold naïve conceptions related to abiotic factors. These environmental conditions include, but are not limited to, light, temperature, moisture, amount of oxygen, nutrient availability, and salinity. Students often either do not recognize nonliving factors as part of an ecosystem (Brody, 1993, 1994; Magntorn & Helldén, 2007b; Özkan et al., 2004), or commonly believe that organisms are not affected by these abiotic factors (Adeniyi, 1985; Brody, 1994; Leach et al., 1996a). Hogan documented differences in how students understand the effects of abiotic factors. In some instances, students overlook indirect effects on organisms, such as the extended impacts of pollutants on an ecosystem; in others, students suggest that abiotic factors affect all organisms equally (Hogan, 2000). The tendency to overgeneralize also appeared in students' understandings of particular abiotic factors. For example, Hogan (2000) found that students often viewed fertilizer as universally toxic. In contrast, Brody (1994) shared examples that demonstrate students' inclination to disregard natural, biodegradable, or non-visible entities as pollutants. Brody also found that some students, although they recognized abiotic factors, viewed these factors as unchanging:

> *[Students] were missing knowledge of how salinity and temperature may differ seasonally and in different parts of the marine environment.* (1993, p. 13)

The vast majority of the prompts found to address abiotic environmental conditions focused on producers' survival and growth in varied conditions. As mentioned previously, prompts of this nature typically asked students to make predictions about what would happen to the plant (Helldén, 1998; Smith & Anderson, 1984), rather than focusing on the process of making food.

All populations within an ecosystem are interdependent.

Students' uncertainty about the range of connections existing in food webs appeared in varied forms throughout the literature. Students' thinking about food web disturbances appears similar to their conceptions of abiotic factor impacts. Several studies found that students think populations are affected *only* by those *directly* linked in a food web (Bell-Basca et al., 2000; Grotzer, 2009; Hogan, 2000, 2002; Hogan & Fisherkeller, 1996; Magntorn & Helldén, 2007b; Özkan et al., 2004; Tsoi, 2011). One study noted:

> *A main result was that 11 year old students tend to focus on local rather than extended effects within an ecological system.* (Hogan, 2000, p. 27)

Grotzer reported instances of this pattern in student thinking related to producers:

> *In the pre-interviews and at the outset of the unit, students typically missed indirect effects—they didn't realize that if all the green plants disappeared, it would affect just about everything in the food web, not only the things that directly eat green plants.* (2009, p. 7)

Additionally, Grotzer and Basca discussed the difficulty that elementary-age students face when trying to understand "underlying causal patterns":

> *Non-obvious causes make it difficult for students to analyze interdependencies. Hidden agents may disguise a causal relationship or contribute to processes in unexpected ways. For example, the causal actions of microorganisms are not easily available to students without special tools and there is no particular reason they would assume that there is a causal mechanism they cannot see. When effects are removed in time and space from their causes, students have difficulty recognizing them as connected to the precipitating event (e.g., extended domino-like relationships in food web).* (2003, p. 18)

Similarly, students' understandings also appear somewhat limited when examining the directionality of effects (Gotwals & Songer, 2010; Hogan, 2002; Leach et al., 1996b):

> *Pupils are more likely to trace effects up through trophic levels than down through trophic levels. For example, pupils were likely to think that the removal of mountain lions would not affect the population sizes of other organisms, but that the removal of grass and crops would affect most other organisms. When primary consumers were manipulated, pupils were more likely to trace the effects up through the trophic levels to predators than down to producers.* (Leach et al., 1996b, p. 137)

Prompts focused on the interdependent nature of ecosystems most often posed hypothetical scenarios to elicit initial ideas, or referred to a previous investigation to assess understanding; in both cases, the provided context was typically the decline of a particular population or the introduction of pollutants. For example:

> *The snakes in this place are all hit by an illness, so that they all die. The illness only affects snakes. What do you think might happen as a result of this? Explain as clearly as you can.* (Leach et al., 1992, p. 93)

> *For the pollutant effects task, students were given three cards labeled Fertilizer, Acid Rain, and Salt - the three pollutants they had used during their Eco-Column experiments. They were told to show all of the places that the pollutant would go within their web, what it would do there, and what would happen within the web as a result.* (Hogan, 2000, p. 24)

Research also suggests that students differ in their grasp of how a decline in producers would have adverse effects on other organisms. Some researchers pointed to students' missing conceptions about the role of producers and their importance to other organisms in an ecosystem (Brody, 1994; Brody & Koch, 1990; Grotzer, 2009; Hogan, 2002). In their discussion of statewide science assessment results, Brody and Koch (1990) noted the following responses to one multiple-choice item:

> *…only 25% of 4th graders, 50% of 8th graders and 62% of 11th graders knew that green plants are important to animals because they make food and give off oxygen.* (p. 24)

Others found that students viewed ecosystems as universally fragile, believing that a food web disturbance would affect all populations similarly (Grotzer, 2009; Özkan et al., 2004):

> *However, one of the issues that arose was extending the concept of connectedness too far. Once students got the idea of the connectedness in the food web, some of them applied it indiscriminately and thought that if any animal died, the whole web would collapse.* (Grotzer, 2009, p. 13)

> *If the size of one population in a food web is altered, all other populations in the web will be altered in the same way.* (Özkan et al., 2004, p. 98)

CONCLUSION

Our review suggests that the majority of the empirical literature about interdependence in ecosystems at the upper elementary level is focused on student thinking. Although a subset of studies focused on changes in student thinking as a result of a particular instructional approach or instructional unit, very few studies included enough detail for a teacher to implement the instruction studied. Therefore, the PCK we synthesized, like the literature itself, largely focused on student thinking.

Patterns emerged across the aspects of student thinking discussed in the literature. In addition, we noticed even broader themes in student thinking that run across the targeted ideas. The first of these overarching themes is anthropomorphic thinking—that is, considering nonhuman entities to possess humanlike traits or motivations. An example includes thinking that producers take in food (like humans), rather than needing materials to make food. Anthropomorphism also emerges in student conceptions of trophic relationships, as students may apply their own experiences of selecting food at a grocery store or restaurant to the feeding behavior of organisms in an ecosystem.

Upper elementary students also appear to view organisms as dependent on humans. The idea that organisms and processes rely on humans may result from students' everyday experiences, particularly those in a garden, home, or zoo setting, which may reinforce this notion that organisms could not survive without human intervention. Similarly, students may attribute the disappearance of decaying parts of organisms to humans rather than decomposers.

A third theme focuses on students' incomplete understandings of the abstract—in the case of ecosystems, entities or processes that cannot be seen. For example, abiotic factors often go unrecognized; Brody (1994) found that elementary-age students need to sense something physically in order to acknowledge its existence resulted in a limited understanding of pollutants. Similar patterns of unawareness and uncertainty exist in student thinking about the concepts of decomposition and producers making their own food.

An additional, yet related, theme cutting across these concepts involves students' tendency to focus on immediate interactions and effects. In feeding relationships, students often focus *only* on direct connections. When causes and effects are separated by time or space, students may find it difficult to pinpoint the connection. One example is that students tend to consider effects of abiotic resources only as they relate to the directly interacting population. Similarly, when students consider the flow of matter, few integrate the recycling of matter back to the environment and through the food web. Additionally, students tend to generalize their impressions of the familiar to all instances. For example, Hogan (2000) found some students to assume that all fertilizers are toxic based on their experiences.

In summary, much of the student thinking discussed in this review is rooted in students' everyday experiences, including both what they observe in the natural world and hear in conversation. The following section outlines associated implications, as well as broader considerations for teaching about interdependent relationships in ecosystems.

IMPLICATIONS FOR INSTRUCTION

As previously mentioned, students' experiences observing and conversing about the natural world often shape the way they approach ideas about interdependence in ecosystems. For this reason, the use of precise language is particularly important when working to move students toward scientifically accurate understandings. For example, conveying producers' needs by saying, "The plant *wants* light," or "The plant is *happy* because it was watered," both anthropomorphizes producers and treats these required materials for survival and growth as mere enhancements. Modeling evidence-based explanations and pressing for them can serve as a helpful practice in encouraging precise and scientifically accurate language use.

The literature suggests that students need explicit opportunities to consider the effect of factors they cannot see or sense in other ways—for example, the effect of soil nutrients or pollutants on plant health. Such experiences could take the form of observing several model systems with varied conditions, or using an online simulation to manipulate an ecosystem and observe gradual changes in populations. In either case, instruction should clearly tie changes to underlying factors, with the goal of helping students see these factors as less abstract.

Closely related, students likely need opportunities to consider the role of decomposers in recycling matter. Observing a plant in a sealed terrarium can be a powerful discrepant event for students, as they may predict that the plant will die (Helldén, 1998). Seeing the plant survive creates a need for students to consider the sources of the materials that the plant is using to make food. Investigating these sources (e.g., decaying plant and animal matter) naturally leads to the question of how the materials are transformed into resources the plant can use to make food. Time-lapse videos of decay enable students to examine changes that would be more difficult to observe in a natural setting or a modeled system (Grotzer & Basca, 2003; Leach et al., 1992).

Our review also has implications for broad concepts that might be emphasized in instruction. Each of the themes we identified encompasses student thinking that addresses multiple concepts related to interdependence. The NGSS envision three-dimensional learning that interweaves disciplinary core ideas, science practices, and crosscutting concepts. It is not surprising that the NGSS align the content unpacked in this review with the crosscutting concept of "Systems and System Models" (NGSS Lead States, 2013, p. 48). However, the themes presented in this review suggest that instruction focused on interdependent relationships in ecosystems could support students' development of additional crosscutting concepts such as: (1) Cause and effect: Mechanism and explanation, and (2) Energy and matter: Flows, cycles, and conservation (National Research Council, 2012, p. 84).

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Appendix

Table A-1
Article Summaries

Author (Year)	Where the study occurred	N	Age/Grade of subjects	Summary
1. Adeniyi (1985)	Nigeria	232 tested; subset of 26 students interviewed	Ages 13–15	Used data collected from classroom observation, open-ended assessment responses, and clinical interviews to examine student misconceptions.
2. Alao & Guthrie (1999)	U.S.	72	5th grade	Administered cognitive and motivational measures to examine predictors of conceptual understanding.
3. Bailey & Watson (1998)	England	~100	Ages 7–11	Administered questionnaires to examine students' attitudes toward drama/role play, as well as students' understanding of ecological concepts.
4. Barman, Stein, McNair, & Barman (2006)	U.S. & Canada	~2400	K–8th grade	Used data collected from teacher-conducted interviews to study student thinking about plants and plant growth.
5. Bell-Basca, Grotzer, Donis, & Shaw (2000)	U.S.	60	3rd grade	Interviewed students to examine the effects of an instructional unit and interventions on student thinking.
6. Brody (1993)	U.S.	316	4th, 8th, and 11th grade	Conducted interviews in order to make comparisons of student understanding in various areas.
7. Brody (1994)	U.S.	467	4th, 8th, and 11th grade	Conducted interviews to assess student knowledge of science and natural resource concepts in relation to ecological crises.
8. Brody & Koch (1990)	U.S.	187	4th, 8th, and 11th grade	Conducted interviews to assess student knowledge of marine ecosystems.
9. Çetin (2007)	England & Turkey	96	Ages 14–15 (7th grade)	Administered questionnaires to examine and make comparisons of student understanding of decomposition.
10. Demetriou et al. (2009)	Cyprus	46	Ages 9–10 (4th grade)	Administered pre- and post-tests to examine the efficacy of a curriculum focused on trophic relationships.

11. Ero-Tolliver, Lucas, & Schauble (2013)	U.S.	23	1st grade	Administered pre- and post-instructional written assessment to examine students' reasoning about the process of decomposition.
12. Evagorou, Korfiatis, Nicolaou, & Constantinou (2009)	Cyprus	13	5th and 6th grade (Ages 11–12)	Administered assessment tasks pre- and post-instruction to evaluate the impacts of using simulations on students' development of seven discrete system thinking skills.
13. Gallegos, Jerezano, & Flores (1994)	Mexico	506	4th–6th grade	Administered a three-task questionnaire to students to explore their thinking about trophic relationships.
14. Gotwals & Songer (2010)	U.S.	318	6th grade	Collected data using written assessments and cognitive interviews to examine student reasoning related to food web disturbance.
15. Grotzer (2009)	U.S.	99	6th grade	Conducted qualitative research in classrooms implemented a specified unit about causality in ecosystems.
16. Grotzer & Basca (2003)	U.S.	60	3rd grade	Conducted interviews to examine the impacts of an intervention on student understanding of ecosystem concepts.
17. Helldén (1998)	Sweden	~25	2nd–8th grade	Conducted a longitudinal study; interviewed students to examine changes in their thinking.
18. Hmelo-Silver, Eberbach, & Jordan (2014)	U.S.	311	Middle school	Administered assessments pre- and post-instruction to examine the effects of a technology-infused curriculum on students' understanding of relationships in an aquarium ecosystem.
19. Hogan (2000)	U.S.	52; 16 focal students	6th grade	Analyzed written tasks as well as interview tasks to examine student thinking before and after engagement in a unit centered on mini-ecosystems.
20. Hogan (2002)	U.S.	24	8th grade	Conducted one-on-one interviews and administered a group task to explore students' reasoning about an environmental management decision.

21. Hogan & Fisherkeller (1996)	U.S.	Curriculum piloted in 12 classrooms; 8 students interviewed	5th and 6th grade	Conducted interviews in order to develop a coding scheme for analyzing student ideas.
22. Jordan, Brooks, Hmelo-Silver, Eberbach, & Sinha (2014)	U.S.	66; data analyzed from 35 students who completed all tasks	7th grade	Analyzed student-drawn models and written responses to examine student understanding of ecosystem processes.
23. Jordan, Gray, Brooks, Honwad, & Hmelo-Silver (2013)	U.S.	40	7th grade	Coded and analyzed students' drawn models of ecosystems to examine the effects of an intervention involving the use of an aquarium on student thinking.
24. Jordan, Gray, Demeter, Lui, & Hmelo-Silver (2009)	U.S.	45	7th grade	Analyzed student work samples focused on model aquaria to assess student understanding of ecological processes.
25. (R. C. Jordan, Hmelo-Silver, et al., 2013)	U.S.	138	7th–8th grade	Conducted classroom observations and administered assessments pre- and post-instruction to examine the efficacy of instruction focused on aquatic ecosystems.
26. (Leach et al., 1992)	England	~200	Ages 5–16	Interviews, written tasks, and observations were used to examine student ideas about various ecosystem concepts.
27. (Leach et al., 1995)	England	~200	Ages 5–16	Provides information related to the theoretical background, design, and methodology of the study.
28. Leach, Driver, Scott, & Wood-Robinson (1996a)	England	~200	Ages 5–16	Provides findings from the study related to student ideas about the cycling of matter.
29. Leach, Driver, Scott, & Wood-Robinson (1996b)	England	~200	Ages 5–16	Provides findings from the study related to student ideas about interdependence.
30. Magntorn & Helldén (2007a)	Sweden	23	Ages 10–11	Conducted interviews to examine how student understanding of ecosystems developed over the course of instruction.
31. Magntorn & Helldén (2007b)	Sweden	15	Ages 13–14	Conducted observations and interviews to examine students' ability to transfer conceptual understanding across ecosystems following a multi-phase instructional unit.

32. Myers Jr., Saunders, & Garrett (2003)	U.S.	171	Ages 4–14	Conducted interviews to collect data about students' understanding of animals' needs.
33. Özkan, Tekkaya, & Geban (2004)	Turkey	58; 10 students interviewed	7th and 8th grade	Conducted interviews and administered assessments to examine the effects of using conceptual-change texts in instruction.
34. Palmer (1997)	Australia	123	Ages 12 and 16	Conducted interviews to study the ways in which students apply the concept of interdependence.
35. Papaevripidou, Constantinou, & Zacharia (2007)	Cyprus	16	5th grade	Used pre-test results to guide the development of instructional materials, and administered a post-test to look for changes in student understanding.
36. Simpson & Arnold (1982a)	Scotland	578	Ages 11–16	Conducted interviews and administered assessments to examine student thinking related to concepts considered to be requisite knowledge for learning about photosynthesis.
37. Simpson & Arnold (1982b)	Scotland	Varied based on task and age range	Ages 11–16	Conducted interviews and administered assessments to gather student ideas' about photosynthesis and related biological processes.
38. Smith & Anderson (1984)	U.S.	1 class	5th grade	Conducted a case study using data collected from observations of instruction and planning, teacher interviews, and assessments administered pre- and post-instruction.
39. Tsoi (2011)	China	140	Ages 8–10	Administered questionnaires to gather data about students' perceptions of sharks and related ecosystems ideas.

† All connected to the same research project designed to study student thinking related to ecological concepts.

Table A-2
PCK Extraction Codebook

Code	Description	Extraction Rules	Confidence Rating
Misconception	Misconceptions are student ideas that are in conflict with accepted scientific ideas. Misconceptions typically arise from students' interaction with the physical world around them. A common misconception is that plants get their food from soil. Misconceptions are neither good nor bad, but they do tend to be deeply ingrained in students' thinking. Some are part of a learning progression for a topic, suggesting that many students will have the misconception at some point as they develop full understanding.	Extract all misconceptions from an article, even if identifying misconceptions was not the intent of the study. Can modify or paraphrase article text for clarity, brevity. For now, lump missing conceptions with misconceptions. Capture related misconceptions separately when possible. When present, capture the cognitive source along with the misconception.	The confidence rating is about how confident we are that this misconception is widespread among 5th grade students based on the study in the article. If the point of a study was to identify student misconceptions and the article fares well in the rapid SoE review, the misconception gets a high confidence rating. All other misconceptions get a low confidence rating. NOTE: when we synthesize across studies, a misconception that shows up several times with a low rating may receive a high rating based on the accumulation of evidence.
Misinformation	In contrast to misconceptions, misinformation is an incorrect fact not derived from every day experience with the physical world. For example, students might think that an organism must occupy only one level (e.g., primary consumer) in a food web. Students' misinformation is probably not as deeply ingrained in their thinking as misconceptions are.	Extract all misinformation from an article, even if identifying misinformation was not the intent of the study.	The confidence rating is about how confident we are that this misinformation is widespread among 5th grade students based on the study in the article. If the point of a study was to identify student misinformation and the article fares well in the rapid SoE review, the misinformation gets a high confidence rating. All other misinformation gets a low confidence rating. NOTE: when we synthesize across studies, misinformation that shows up several times with a low rating may receive a high rating based on the accumulation of evidence.

Code	Description	Extraction Rules	Confidence Rating
Idea-level Consideration	Teaching tips are pieces of advice for teachers and are bigger than an individual activity, things that can be useful for teachers to know when teaching the topic. For example, teachers may need to consider whether students think of organisms in food webs as individuals rather than representing populations. NOTE: If a tip can be associated with all big ideas in the topic, it should be coded as a unit-level consideration instead (see below).	Extract all idea-level considerations from an article, even if identifying tips was not the intent of the study.	If the point of a study was to identify teaching tips and the article fares well in the rapid SoE review, the tip gets a high confidence rating. All other tips get a low confidence rating. NOTE: when we synthesize across studies, a tip that shows up several times with a low rating may receive a high rating based on the accumulation of evidence.
Unit-level Consideration	Unit-level considerations (ULCs) are broader than teaching tips and apply to the entire unit, but they should not be broader than the unit (the latter might actually be pedagogical knowledge instead of PCK). For example, students tend to focus on local impacts and have difficulty reasoning about an ecosystem on a larger scale. Code a ULC to all big ideas in the topic.	Extract all ULCs from an article, even if identifying ULCs was not the intent of the study.	If the point of a study was to identify ULCs and the article fares well in the rapid SoE review, the ULC gets a high confidence rating. All other ULCs get a low confidence rating. NOTE: when we synthesize across studies, a ULC that shows up several times with a low rating may receive a high rating based on the accumulation of evidence.
Prompt	Prompts are questions or tasks that teachers would pose to their students in order to elicit their thinking in writing or orally to use for formative purposes. (Some prompts that are appropriate for research purposes (used in interviews, etc.) may be inappropriate for classroom use.)	Extract a prompt if the reviewer can envision a teacher using it with students as is. The "bar" for modifying prompts from article text is higher than that for misconceptions. If prompts that accompany activities or activity seeds can stand independently, capture as prompts. If not, don't.	The confidence in a prompt is based entirely on the content of the prompt (e.g., how well aligned it is with the idea, how "usable" it is by a teacher), as judged by the reviewer. For example, a prompt that contains wording that may be inaccessible for students would receive a low confidence rating.

Code	Description	Extraction Rules	Confidence Rating
Instructional Activity	Instructional activities are stand-alone, ready-to-use activities that teachers can use in their instruction “as is” with no additional written materials or training. Their purpose is to develop understanding of a big idea. That is, the article should provide enough information so that teachers are able to implement the activity in their classrooms. The learning goal should be explicit or easily inferred. NOTE: Eventually, we will categorize the activities into more general instructional strategies, such as lab experiments, simulations, readings.	Extract an instructional activity if a teacher can use it as is—i.e., it has sufficient context and instructions.	If the point of the article was to investigate the impact of an instructional activity, the confidence rating will be based on the findings of the article and a rapid SoE. If the instructional activity was incidental, the confidence rating will be low. If the article explicitly investigates the efficacy of an entire unit and uses an individual activity to illustrate the material, the activity would receive a low rating.
Activity Seed	Not a ready-to-use instructional activity, but a fleshed out idea for an activity. The seed must have enough description to determine that it fits some big idea(s) and to give a reasonable expectation that teachers could develop it into an activity.	Do not capture if seed is unsuccessful in implementation or in need of substantial modifications in order to be helpful	In order to have a high confidence rating, an activity seed must meet all three of the following criteria: • Is it explained in a way that is clear and accessible to teachers? • Are students likely to learn targeted content from it? • Is it feasible? (time required, materials required)
Summative Assessment Activity	Summative assessment activities are stand-alone, ready-to-use activities that teachers can use in their instruction to evaluate students.	Extract an assessment if a teacher can use it as is--i.e., it has sufficient context and instructions. Briefly summarize the form and substance of the assessment, and if there's a rubric, describe how it's structured, what kinds of factors it takes into account.	1. If the assessment does not have reliability and validity info, it should receive a LOW rating. (NOTE: if the reliability and validity info are in another article, the assessment should be extracted from that article.) 2. If the assessment does have reliability and validity info, the rating should be based on that information. Reliability should be above 0.7, and there should be at least one form of validity evidence.

Code	Description	Extraction Rules	Confidence Rating
Common Student Experiences	Common student experiences are things that a teacher can capitalize on in instruction, knowing that there is a good chance that most students have similar experiences. For example, most students have observed decaying fruit. Common student experiences may be keyed to one big idea or more than one.	Extract a common student experience if there is evidence in the article that most students come to instruction with the experience. An article that describes what just one student has experienced is not sufficient. Do not include previous instruction experiences.	The confidence rating is based on a rapid SoE review.
Developmental Challenge	Developmental challenges are things that students struggle with that are broader than misconceptions. For example, 5th grade students and younger may struggle to accept the existence of decomposers that are too small to see. Developmental challenges may be keyed to one big idea or more than one. Some developmental challenges may have associated ULCs. For example, we think that kids do not apply explanatory frameworks consistently, but rather that it is context specific (e.g., students may understand the particle model in the context of boiling water, but will not apply it to condensation on a cold drink can). The unit-level consideration is that teachers can't assume that just because kids use the particle model appropriately in one context, they will use it appropriately in another.	Extract a developmental challenge if there is evidence in the article that most students come to instruction with the challenge.	The confidence rating is based on a rapid SoE review.

Code	Description	Extraction Rules	Confidence Rating
Learning Progression	A learning progression will probably be identified explicitly in an article. A learning progression is at the topic level, so we do not need to code to individual big ideas. All misconceptions in a learning progression can be coded with the progression.	Extract a learning progression if the article describes a sequence of increasingly sophisticated and scientifically accurate understandings and skills within a domain that learners develop over several years.	The confidence rating is based on a rapid SoE review.