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Marijke Hecht & Kevin Crowley

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Unpacking the Learning Ecosystems Framework: Lessons from the Adaptive Management of Biological Ecosystems

Marijke Hecht and Kevin Crowley
School of Education
University of Pittsburgh

An ecological framework is often used to describe the context for learning in educational research and practice. However, there is often a focus on descriptive aspects that frame the ecosystem as a complicated set of interconnected elements —but not a true complex problem. Acknowledging connections between ecosystem elements is not enough to affect the systemic change that the wicked problem of education requires. In this paper, we argue for moving toward a more robust framework that takes seriously the notion of learning happening via relational processes between system elements, and looks more deeply at the ways in which those dynamic elements are interacting in complex, multiscalar ways. We promote drawing more heavily from ecologists' understanding of biological systems, particularly the application of concepts drawn from adaptive management strategies used in the field of restoration ecology. We present an argument to decentre our field's typical focus on individual youth, just as ecologists have moved biology away from an emphasis on individual organisms. We postulate that decentring youth enables new ways of thinking about learning ecosystem design and management. We then explore three specific concepts used in adaptive management in ecology: ecotones, keystone and indicator species, and disturbance and resilience.

An ecological framework is often used to describe the context for youth learning and development in educational research (Akiva, Kehoe, & Schunn, 2016; Bevan, 2016) and educational practice (Krishnamurthi, 2014; Poon, 2017). The framework is grounded in an understanding that learning relies on what

Correspondence should be addressed to Marijke Hecht, Learning Research Development Center, University of Pittsburgh, 3939 O'Hara Street, Room 820, Pittsburgh, PA 15260. E-mail: meh183@pitt.edu

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Barron (2006) called 'critical interdependencies across contexts' (p. 195). It is important to recognize the idea that learning experiences are best seen as connected across place and time, and that education can happen in a range of contexts in and out of schools. The idea of the ecosystem, which has often been used as an analogy, has been instrumental in helping to spread and shape these ideas.

In this paper, we argue for moving toward the use of a more robust framework that takes seriously the notion of learning happening via relational processes between system elements, and looks more deeply at the ways in which those dynamic elements are interacting in complex ways. By relational we mean that these processes reflect interactions between and among various elements of the learning ecosystem. Specifically, we promote the use of a learning ecosystem framework that draws more heavily from ecologists' understanding of biological systems, particularly the application of concepts drawn from adaptive management strategies used in the field of restoration ecology. This expanded framework could help inform the management of learning ecosystems that create interrelated elements that support overall learning ecosystem health and resilience (Falk et al., 2015). Our goal in writing this paper is not to unpack every potential concept from restoration ecology that might be used for learning ecosystem management. Instead, we are focused on a subset of ideas that we think resonate most strongly with current work on learning ecosystems. We propose enriching the concept of learning ecosystems by examining the vocabulary we use for elements of the system, reconsidering how we think about relationships between elements of the system, and refining approaches for describing and interpreting learning ecosystem function at different scales.

This paper is divided into two sections. The first section examines how the learning ecosystem framework is currently applied across a variety of learning settings, and proposes two conceptual moves to make further use of the framework: viewing learning ecosystems as complex systems rather than merely complicated and using scalar thinking as a tool for approaching this complexity. The second section focuses on extending the learning ecosystem framework by drawing upon ideas of adaptive management from the field of restoration ecology. We open with an explanation for why using the language and concepts of adaptive management might be a fruitful approach. We present an argument to decentre our field's typical focus on individual youth, just as ecologists have moved biology away from an emphasis on individual organisms toward a truly systemic view. We postulate that decentring youth enables new ways of thinking about learning ecosystem design and management. We then explore three specific concepts used in adaptive management in ecology:

- How might attention to ecosystem boundaries and ecotones support learning?
- How might we identify where to monitor and invest resources by considering "indicator species" and "keystone species" in a learning ecosystem?
- How might we better support resilience of systems by accepting constant change and preparing for natural disturbance?

LEARNING ECOSYSTEMS AS A LENS

Current Application of the Framework

Efforts to explain the complexity of interactions between home, school, and community have been popularized by Bronfenbrenner's model of human ecology (1979). Bronfenbrenner's work brought about an important shift in psychology, drawing attention to the idea that individuals do not exist in isolation and instead are influenced by nearby elements, such as the home, and farther away elements, such as societal factors. The notion of how human ecology influences learning and development was refined over subsequent decades to explore learning that occurs outside of traditional classroom spaces.

Barron (2006) refined this framework by defining a *learning ecology* as "the set of contexts found in physical or virtual spaces that provide opportunities for learning." (p. 195). The National Research Council (2015) defines a learning ecosystem as: "the dynamic interaction among individual learners, diverse settings where learning occurs, and the community and culture in which they are embedded." (p. 5). Elements of this learning ecosystem include people (youth, family, educators, funders, etc.); places (schools, libraries, community centres, museums, hospitals, etc.); activities/resources (internships, programs, curricula, books, internet); and intangibles (politics, social services, the history of education in a community, culture). Note that in this paper, we will use the phrase learning ecosystem instead of learning ecology in order to emphasize our focus on systems. The idea of a learning ecosystem helps to frame the multilayered complexity of how learning occurs across different participants, settings, and times.

The learning ecosystem framework is now used ubiquitously across many different learning settings. It has been used to frame the impact of the physical space on learning, including the need for purposeful design (Herzog, 2007) and the need to consider places other than schools as learning spaces, such as libraries (Rettig, 2009), museums (Salazar-Porzio, 2015), and other community-based and informal learning settings (Russell, Knutson, & Crowley, 2013). The ecosystem framework has also been used to help characterize the kinds of virtual spaces that learners engage in (Berglund, 2009; Folkestad & Banning, 2010), as well as how those virtual spaces connected with bricks and mortar classrooms (Herro, 2016; Lin, 2011). Use of an ecological framework can be seen in writings about the practice of distance learning (Miller & Husmann, 1996), and the need to be attentive to "digital divides" (Henning, Van der Westhuizen, & Diseko, 2005). The importance of connecting learning opportunities for youth is also an application of learning ecosystem analogies (Corin, Jones, Andre, Childers, & Stevens, 2017). The ecosystem framework has been used to draw connections between traditional classrooms and their communities in both preK-12 (Cekaite & Evaldsson, 2017) and higher education (Damsa & Jornet, 2016) settings. Recognizing this connection across the formal/informal educational sectors can surface issues of equity and justice in education by highlighting the ways in which home and community culture offer unique perspectives that can support learning (Gutiérrez, Bien, Selland, & Pierce, 2011), but may also reveal contextual challenges facing some youth as they engage in academic pursuits (Lee, 2017).

However, even when there is a strong emphasis on the complexity of learning environments, as in Barron's foundational work and myriad other pieces that use an ecosystem lens—including those focused on equity, such as Carol D. Lee's powerful call in her AERA 2010 address to look at interdependence across contexts (2010)—many authors, including ourselves, have often reverted to a less complex focus on individual learning experiences within the ecosystem, rather than exploring systemic, relational patterns. The current use of learning ecosystems is often by analogy and often portrayed in static, simple terms, rather than with the dynamic, complexity of biological systems (Falk & Dierking, 2018).

Not Just Complicated, but Complex

Educational improvement is a "wicked problem"—it is chronic, complex, unlikely to be solved via linear solutions, and may benefit from collaborative and iterative refinement (Gomez, Russell, Bryk, Lemahieu, & Mejia, 2016). Recognizing this complexity means that we must accept that simple causal explanations for challenges in the educational system will not suffice (Jacobson, Levin, & Kapur, 2019). Problems like this require attention to the "collective impact" of multiple players within the learning ecosystem (Kania & Kramer, 2011). Lemke and Sabelli (2008) called for educational research that draws on models of complex dynamic systems. The field of restoration ecology, which uses adaptive management approaches, can provide one such model.

Currently, the descriptive aspects of the learning ecosystem framework often point to a view of the ecosystem as a *complicated* set of interconnected elements —but not a true *complex* system. However, if educational systems were merely *complicated* then surely policymakers, researchers, and practitioners would have been able to identify replicable approaches to solving educational challenges. The reason these challenges persist is because learning ecosystems are complex—by which we mean they are dynamic, non-linear, and unpredictable (Yoon, 2011); they are continually undergoing changes that amount to more than the sum of their parts (Johnson, 2008). Therefore, we cannot expect, as we might with a complicated problem, to come up with a set of instructions to solve educational problems and expect them to remain solved, nor can we easily replicate these efforts across space and time effectively (Snyder, 2013). The *complexity* of learning ecosystems is why merely acknowledging connections between ecosystem elements is not enough to affect the kind of systemic change that the wicked problem of education requires. Given this complexity, we do not believe the ecosystem framework is doing all the work that it could do for the field.

By taking a deeper look and exploring the dynamic processes of learning ecosystems, we may be better able to manage systems that offer more equitable lifelong and lifewide learning opportunities (Falk & Dierking, 2018). In particular, we propose using dynamic relational processes as the unit of analysis. By relational processes, we mean interactions between and among elements of the learning ecosystem including but not limited to youth, educators, families, and the material elements they engage with, such as classroom spaces or nonhuman nature. These relational processes can be observed as robust episodes of interaction, such as the verbal exchange of ideas between students in a classroom or a learner's connection to scientific content through the physical manifestation of phenomena, such as stormwater flow in a rainstorm. The ecosystem actor that we call "learner" or "student" necessarily exists only in relation to these other elements of the system; without these elements, there is no nameable entity of "learner". Therefore, we propose focusing on those relational processes and shifting the unit of analysis from learning as an individual outcome to learning as a process that exists because of the interactions between learning ecosystem actors.

The concept of relational processes is used in a number of fields. They are the focus of new materialist philosophy which draws upon physics to illustrate how even at the atomic and subatomic levels, relational processes inform action and agency (Barad, 2007; Fox & Alldred, 2018). A rejection of the distinction between subject and object in favor of an emphasis on relational processes between entities is also used in practice theory (Spaargaren, Weenink, & Lamers, 2016) and network theory, where the concept of relationality is described as one where "entities have no essence in themselves, but their properties and boundaries are formed and shaped through their relations to other elements" (Vicsek, Király, & Kónya, 2016, p. 79).

Applying the lens of relational processes to learning ecosystems requires moving away from thinking of the ecosystem as a complicated set of interconnected pieces and toward thinking of the ecosystem as a complex with elements that exist through their relationship with each other. This way of thinking is at the essence of ecology, which moved the biological sciences away from a focus on individual organisms and toward exploration of the interactions of living and nonliving components within systems (Horton, 2018). Applying this conceptual lens to learning mirrors how sociocultural theories acknowledge the importance of culture on individual learning (Gutiérrez & Rogoff, 2003). It extends this frame by considering the relational processes between a greater range of elements in the system, including nonhuman nature and place (McKenzie & Tuck, 2015). Using ecological thinking changes the way we see the ecosystem itself: it is no longer a collection of participants and learning places with separate essences that need to be connected for individual children. Instead, the learning ecosystem emerges as a constellation of intertwined and entangled elements, where learning happens through dynamic relational processes among the people, places, and stuff we find across/within/between school and out-of-school places.

Not Just Scaling Up, but Thinking across Scales

In an article examining the intersection of educational research and design, Penuel, Fishman, Haugan Cheng, and Sabelli (2011) reflect that: "An enduring goal of research in education has been to identify programs that can reliably work in a wide variety of settings so that such programs can be scaled up to improve system-level outcomes." (p. 331). Often, when we talk about scale in the field of education, scale is raised in reference to improvement—to take what we see working in one program, one classroom, and bring it *to scale*. However, we know from policy analysis, that scaling up educational interventions is often less effective than the original application of the idea. Part of what is missing from the notion of scaling is that the focus can be on the unidimensional aspect of simply increasing numbers, when in fact a multidimensional approach would be more effective given the complex nature of the system (Coburn, 2003).

Scaling up in educational systems gets even more troubled when we acknowledge that only a small portion of our days are spent within formal, school-based learning environments. Even during the years of formal schooling, children have something like 80% of their potential learning time outside of classroom settings (Banks et al., 2007). This expansion of the scale of learning opportunities across an individual's life makes replication more complicated. Is success in a maker program at a library tied to the place "library"? Or is the success due to the relationship between educator and youth, which might allow the program to be replicated at a faith-based institution where equally strong relationships are fostered? The franchise model for replication, which struggles to be effective in schools, completely falls apart within the complexity of out-of-school learning and a broader learning ecosystem. Cohen and Garcia (2014) write, "Nearly all interventions that affect important outcomes are faced with the question 'How can it be disseminated on a wide scale?' … Instead one should ask ‘Who can it help, and when and where can it help them?’” (p. 17). Reframing dissemination in this way recognizes the complex nature of educational interventions and the need for more localized and adaptive approaches.

Here is where applying ecological thinking to the notion of scaling can help. Ecology is a science of case studies—and the complexity of systems means that no two cases will ever be the same (Code, 2006). Therefore, the notion of replication with high fidelity to the original must be put to the side. Instead, we ought to accept local variation and pursue adaptive strategies, which are commonly used in restoration ecology and rely on ongoing monitoring and iterative changes (Society for Ecological Restoration, 2016). This type of approach can be seen in some educational work. For example, some Networked Improvement Communities have begun looking at the adaptive integration of ideas from one setting to another (Bryk, 2015; Cannata, Cohen-Vogel, & Sorum, 2017). Moving these approaches beyond school systems to learning ecosystems that include the full range of learning settings is an important next step toward building equity. However, even with adaptive approaches, we can be lured into thinking of scale as trying to make things bigger. But the scale is about a shift in perspective, rather than just a shift in size.

We know from biology that form, function, and size are inextricably linked. The early evolutionary biologist and scientist, JBS Haldane, addressed the challenge of scalar shifts in his essay “On Being the Right Size”. In the essay, Haldane (1926) contends that an animal’s size proffers different specific forms that allow for different functions. This *structural scale variance*, or the difference in functionality across scales (Roberts, 2016), is important to attend to. Biological ecosystems exist at multiple scales—from microscopic systems in the soil to forests that extend for hundreds of miles. They are also nested, with smaller ecosystems situated “inside” of larger ecosystems. The analog of this is when we consider a school classroom or an out-of-school program as a learning ecosystem unto itself that is nested within a larger regional learning ecosystem. The youth we are hoping to reach move across these nested ecosystems—from their classroom to their community to the regional network of learning opportunities. At each scale, there are elements that interact, supporting the flow of energy and ideas and opportunities for learning.

What does this mean for applying a learning ecosystem framework to education? Importantly, the relative sizes of nested systems do not require subordination of the smaller to the larger. While each system interacts with other systems, the smaller system may actually influence the larger system as much as the reverse occurrence[1] For example, a microbial soil ecosystem is not

[1]Here we use *smaller* and *larger* to designate the perceived spatial relationship between say a classroom and a school. However, we also recognize that these relative terms serve to conceptually obscure the scalar differences of these different components of a system..

subordinate to a massive forest ecosystem. In fact, in many ways soil drives the health of the forest system that it is nested within. We might also find that each system operates independently of systems that it is nested within or that are nested within it (Simon, 1996).

When we view a classroom or program in this light, perhaps that changes how we approach educational management. We might open up ways to consider multilateral interactions across scales and how these influence management techniques at the systems' level, instead of focusing on how larger systems impact individuals within the system. While researchers must draw system boundaries to aid in understanding, these boundaries are naturally porous and relational process and interactions work across scales in ways that can be difficult to parse out (Horton, 2018). To understand learning ecosystems, then, we need to push ourselves to think in multiscalar ways because the very nature of ecosystems is that they exist at both micro and macro scales in nested, but nonhierarchical, structures.

FROM ANALOGY TO FRAMEWORK

Drawing on Adaptive Management

Barron (2006) has suggested the potential for using the learning ecosystem framework as a design tool. The intentional design and management of robust learning ecosystems, in partnership with communities and both formal and informal educational institutions, is critical for fostering connected in- and out-of-school learning experiences. These experiences are too often only possible for more affluent members of our society because they often require fees or transportation that may be barriers for some (Falk & Dierking, 2018; Penuel, Lee, & Bevan, 2014). A next step in extending the learning ecosystem framework is to look beyond mere identification of elements of the system and toward the analysis of both structure and function of learning ecosystems (Falk & Dierking, 2018; Falk et al., 2015).

We argue that to effectively use this ecological framework for design and management, we might look more closely at the ways that ecologists have attempted to exert influence on biological ecosystems through the adaptive management strategies used in the field of restoration ecology. Ecologists use their ever-developing understanding of ecosystem forms and functions as tools for ecological management, from urban green spaces to national parks. We have chosen to focus on these overtly human-influenced ecosystems rather than on so-called “wild” ecosystems because we recognize that humans are constituent parts of all ecosystems—whether biological or learning. We therefore inevitably influence ecosystem health, sometimes purposefully, oftentimes inadvertently.

What might we learn from adaptive management strategies in restoration ecology that could be applied to the management of learning ecosystems in ways that could support healthier and more equitable ecosystem function? First, we begin by considering a fundamental element of ecosystems: they are defined by interrelationships between elements rather than individual actions. We then turn to the potential application of three concepts drawn from the adaptive management of landscapes: first we explore the role of boundaries and ecotones; then we consider measures of ecosystem health and suggest the use of keystone and indicator species; and finally, we consider the significance of disturbance and resilience.

Decentring Individual Learners

From Bronfenbrenner on, models of human ecology and learning ecosystems have often been represented visually with an individual at the center of the system, where impacts from the environmental context exert force on the individual, often depicted as a child (see Figure 1). This representation of learning ecosystems can be found in educational literature that connects school

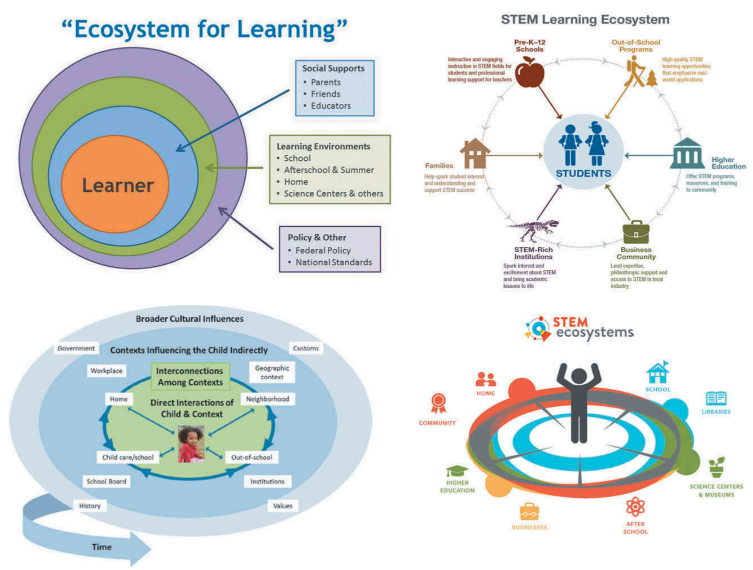

FIGURE 1 Images, clockwise, taken from websites for Afterschool Alliance (2014), U.S. Department of Education (2015), STEM Ecosystems (n.d.), and National Research Council of the National Academies (2015).

systems with informal, out-of-school learning (Bevan, 2016), and has also been used to describe domain-specific learning, such as STEM education (National Research Council of the National Academies, 2015). These diagrams work in the sense that they convey that no single influence accounts for learning and development. However, this persistent focus on youth as the center of the learning ecosystem undermines the potency of the ecosystem framework. It perpetuates the idea that learning happens at the individual level and that systemic inequity can be addressed by supporting opportunities for individuals.

Unlike in these diagrams, an ecosystem has no center. All elements of a system are influencers of and are influenced by their context; elements of an ecosystem can never be fully teased apart. For example, it is widely accepted in ecology that trees have important functional relationships with fungi, called mycorrhizae, which grow on tree roots. These fungi have been used to help characterize the expansive nature of complex systems (Engeström, 2007). In forest ecology, the relationship between mycorrhizae and trees is thought to support more than just the individual tree, and instead supports ecosystem function across multiple plants and mycorrhizal species (Ferlian et al., 2018).

In fact, the very existence of individual organisms and "essential identity" has been called into question by ecofeminist theorists such as Haraway (2016) and by biologists, some of whom are using the term "holobiont" to describe the complex and persistent interrelationships between species (Gilbert, Sapp, & Tauber, 2012). This integration occurs across kingdoms, where bacteria and eukaryotes, including plants and animals, exist together in functional units. This has been shown to occur in humans, wherein bacteria inform critical functions and are part of an ecosystem housed within the human body. This emerging understanding suggests that we not only currently coexist with bacteria but have actually evolved in response to our connection with them (McFall-Ngai et al., 2013). We and the hundreds of species of bacteria in our gut are long-term partners; we are holobionts (Gilbert et al., 2012).

Similarly, individual children are not only influenced by elements of the learning ecosystem—they are inextricably connected to and part of those elements in ways that we are only beginning to understand. What might a decentring of the individual—a rejection of the notion of an individual learner as a unit of analysis—open up in terms of learning ecosystem management strategies? Sociocultural views on human learning and behavior have long argued that an exclusive focus on individuals, or even groups of individuals, fail to recognize and account for larger cultural practices that co-evolve with and co-create learning and development (Gutiérrez & Rogoff, 2003). The learning ecosystem framework, when tied more closely to ecological concepts, supports this approach to thinking about educational experiences in the context of a complex, integrated system. The functional unit for learning could, therefore, be made up of the relational processes between youth, parents, and educators in both schools and out-of-school settings, as well as the material elements of these spaces, ranging from pencils in classrooms to trees in landscapes. These forces do not revolve around an individual child as a learner—they are part of the child and the child is part of them because the child as a "learner" can only exist in relation to other learning ecosystem elements.

Attending to Boundary Crossings and Ecotones

Recognizing that functional units of learning ecosystems operate within and across scales pushes us to consider how the boundaries between scales are crossed by energy, ideas, etc. For example, interest in science may be initiated in an out-of-school learning experience at a museum, be supported by a family member's parallel interest in the subject, and then get deepened through exposure to content in a school classroom (Crowley & Jacobs, 2002). Each of these learning moments is linked through the individual youth that is experiencing them, but they are typically depicted as distinct from one another in the learning ecosystem itself, with specific boundaries that are crossed by the youth.

However, we know from biological ecosystems that boundaries between different elements of the system can be fluid transition spaces, called ecotones, that have their own form and function. Transition spaces like this can be important spaces to monitor and manage because of the role they can play in supporting the health of adjacent systems. For example, the ecotone between a woodland and a river is a transition space that is called a riparian zone. The riparian zone provides an important buffer during rain events, filtering excess nutrients and pollution from water that is draining down and across the land; riparian areas also absorb rising waters from the river itself (Ricklefs & Miller, 2000). This ecotone's position between the two systems helps to support them both—it helps regulate water quality and quantity in the river and it reduces erosion and degradation on the land. Therefore, the riparian zone can become a tool for ecosystem management that can help to improve other systems that are adjacent to it.

What do transitional boundary zones in a learning ecosystem look like? One example of an ecotone at the scale of a school or program is the space just outside of a school or program building. Although youth may not be engaged in a formal learning activity in this space, the space still serves as both the introduction and coda for learning during the school day or program experience. How does passage through this ecotone inform a learner's engagement with education once they enter the building? How might it reinforce what has already been learned?

An ecotone like this also interacts with the social geographies that youth move through. For example, a youth may be interested in participating in a museum summer program. Even if transportation or cost are eliminated as barriers to participation, there may still be sociocultural factors, such as a museum's location in a neighborhood that may be unwelcoming for youth or a youth's perception that the museum itself is not welcoming (Dawson, 2014). This kind of transition—from one cultural space to another—is also an ecotone that should be considered in learning ecosystems.

Attending to ecotones could help promote successful learning pathways, which have been shown to be an important component for long-term interest and identity development (Azevedo, 2013; Crowley, Barron, Knutson, & Martin, 2015; Hecht, Knutson, & Crowley, 2019). For example, what is the ecotone between school and out of school? Is it home? Peer groups? Community? All of these? How might care and attention to ecotones support healthier elements that enable learning throughout a regional learning ecosystem? Opportunities for learning moments should not be reserved for the classroom or program. Educators could be trained and supported to encourage ecotone interactions across and between school/out of school experiences. And deliberate management of ecotone spaces could help support learning goals.

Managing and Monitoring for Ecosystem Health

We propose using the ecological concept of keystone species as a management tool. Keystone species are identified by their strong impact on the flow of energy and matter (the trophic cascade) of an ecosystem. They are drivers of ecosystem health, potentially impacting many other species across the system. Examples of keystone species in biological systems vary in size, but top predators such as wolves in Yellowstone are often used as common examples. By reintroducing this keystone species into the ecosystem, the wolf helps to stabilize the system overall by hunting and eating grazers, which thereby reduces pressure on plant material. Of course, the keystone also relies on other ecosystem elements, but overall, their presence has a strong influence on improving habitat and health for species throughout the system, sometimes directly and sometimes indirectly (Ripple & Beschta, 2004).

We hypothesize that, at the program scale, well-trained, caring, knowledgeable, and connected educators can function as a keystone. When we invest in the development and professionalization of educators and educational leaders, benefits for youth learning radiate through the system. Here, we mean more than just teachers; we mean the full range of adults, in and out of school, who interact with youth as part of the larger system. While school-based teachers may struggle to receive fair compensation and meaningful professional development, out of school educators are even less professionalized and have fewer training opportunities (Yohalem & Pittman, 2006). To support a healthy ecosystem, we must make investments in educators working throughout the system.

By using the concept of keystones as the focus for resource allocation, we ought to be able to attend to the elements are that are driving the flow of energy and matter through the learning ecosystem. At the regional scale, we might think of intermediary organizations as the keystones of the learning ecosystem. When these organizations are well supported, they are key to building capacity in learning ecosystems (Penuel et al., 2011). This kind of "trophic cascade" of energy from the intermediaries to the program providers to the youth means that we can make focused investments of time and energy in intermediaries and should see benefits at relatively distal points.

So where does that leave youth? Maybe we consider youth as indicators which tell us something about the health of an ecosystem. For example, in biological ecosystems, some species, such as the mayfly, are only found when there is little pollution. Therefore, the presence or absence of mayflies in small streams can be used by ecologists as indicators of healthy water quality (Hodkinson & Jackson, 2005). However, an ecologist who is working to achieve healthy water quality is more likely to focus on preventing pollution at the watershed scale than on specific micro-interventions for improving mayfly habitat. They understand that the reduction of pollution is an indirect but effective tool for habitat improvement overall and will look to the mayfly as a sign that their intervention upstream is working.

Just like with the mayfly in a small stream, when youth are thriving, interested, and learning in a classroom, neighborhood, or informal learning program, we know the system is healthy. When they are struggling, we know the system is not healthy. Seeing learners as indicators could allow educational researchers to focus on youth as critical barometers of ecosystem health, while shifting energy away from creating interventions that target youth outcomes. The reorientation could promote more "upstream" approaches to improving a learning ecosystem, such as creating more opportunities for young children to develop interest during informal learning activities, stronger brokering of opportunities by educators and parents, and greater alignment between in and out of school experiences.

The idea of indicator species can be applied at a larger scale as well. At a regional scale, we might view educational organizations, e.g., schools, community groups, museums, as indicator species. The presence of well-functioning educational organizations can provide a good measure of the health of the regional learning ecosystem overall. However, overemphasis on investing in individual organizational success can undermine resource allocation across the system. Instead, we could look upstream for other points of intervention that allow for strategic resource allocation—of human, social, and financial capital—that can effectively support the health of the ecosystem overall. In a learning ecosystem, therefore, we might use keystones to guide resource allocation and indicators to help measure impacts.

Disturbance and Resilience

Ecosystems are constantly changing and shifting, whether they are biological ecosystems or learning ecosystems. As with other complex management endeavors, we must avoid prescriptive outcomes that do not account for the system's dynamic nature (Simon, 1996). Instead, when working with learning ecosystems, we could adhere to the notion of adaptive management, which is both flexible and responsive (Groom, Meffe, & Carroll, 2006; Society for Ecological Restoration, 2016). Adaptive management recognizes that there while there may be constant elements within the system (e.g., students go to school from kindergarten through 12th grade) there is also abundant and constant change within the system that cannot be controlled (Spillane, Gomez, & Mesler, 2009).

One of the forces for dynamic change in a biological ecosystem is natural disturbance. While these disturbances seem destructive on the surface, they also serve to open up opportunities. Natural disturbances may be relatively small, such as a mature tree that falls and thereby opens up space in the forest canopy letting in light and allowing new plants to grow and thrive. There are also large natural disturbances, such as a hurricane or wildfire, that may do extensive damage to a system, completely reshaping major landscape features such as landforms and river pathways. Whether large or small, a biological ecosystem's ability to rebound from natural disturbance and maintain overall health is often a measure of what is called its resilience (Society for Ecological Restoration, 2016). So, what do we know about natural disturbance and resilience in biological ecosystems that we might apply to learning ecosystems?

For one—disturbance is not bad. In fact, it is a necessary force in dynamic systems, allowing for new species to find space for growth. In a learning ecosystem, we might see new ideas flourishing after the natural disturbance of a leadership change. A natural disturbance like this might also reveal weaknesses in the system. If the school or organization does not rebound, or is not resilient, what is fundamentally problematic in the system? Using an ecological frame forces us to look beyond the individual leader—again, we are decentring individuals here—and toward systemic reasons why the natural disturbance may have been problematic. In the case of leadership change, the challenge for resilience maybe that support staff within the organization werenot empowered to make decisions and therefore are not able to function when the leader shifts. An organization that has spread responsibility and control to actors throughout is more likely to be resilient when leadership changes (Hargreaves & Fink, 2004).

Secondly, local distinctions matter. Each type of biological ecosystem has its own type of natural disturbance. For example, fire is a primary natural disturbance in forests in the Western US, whereas wind burst might be more typical for a forest in the Appalachian region. Species and ecosystems adapt to these specific disturbances. When ecologists recognize what the natural disturbance is, they can use that to inform management decisions that can support resilience in the system when the disturbance inevitably comes. For example, if a hurricane is a likely disturbance, an ecologist might recommend building up and supporting dunes that help to protect the land from storm surges. Similarly, we might define different types of learning ecosystems, such as a STEM ecosystem or an out-of-school arts ecosystem. These different systems are also likely to have different potential disturbances. For example, a STEM ecosystem is likely to include schools, which are affected by the disturbance of governmental policy changes. In contrast, an out-of-school arts ecosystem may be more likely to need to weather a change in philanthropic funding as a disturbance.

Understanding local conditions, and the likely coincident natural disturbance, is critical for supporting the resilience of learning ecosystems. Learning ecosystems are shaped by the capacity of local actors, sociocultural history of the community, and more. Therefore, management of local learning ecosystems must take local conditions into account. This can help education leaders to better anticipate the specific types of natural disturbance that may occur and support efforts for planning and responsiveness. If you know that a hurricane is coming, you might choose to evacuate. If you know that you have a shortage of well-trained out-of-school educators, you might work to improve systems for recruitment, training, and retention. Defining what a thriving, resilient learning ecosystem looks like holds implications for adaptive management of that system. Two key components for supporting resilient learning ecosystems, therefore, are (1) accepting that natural disturbance will occur and (2) being attuned to the ways that these disturbances are locally contingent.

CONCLUSION

When we recently asked a program officer from a large regional foundation about their goals for educational funding in the coming years, they responded that they wanted to support a "more networked ecosystem" for learning. This vision of a high functioning ecosystem that supports and connects learning across formal and informal spaces has become a kind of holy grail for what it will take to manage more effective and equitable educational experiences for youth. In fact, the phrase *learning ecosystem* has become so embedded in talk amongst educational funders, providers, and researchers that the program officer provided no explanation of what they meant by a "more networked ecosystem", and we nodded in assent—of course, this should be a goal.

However, unpacking the learning ecosystem framework reveals ever-deepening layers of complexity. In this article, we began by arguing for the importance of considering learning ecosystems as complex and multiscalar. We also called for decentring and recasting youth from lead actors to players in an interactive system. We believe this shift could help us manage learning ecosystems in ways that move beyond creating opportunities for individuals and toward supporting the relational process that supports overall learning ecosystem health and resilience. By emphasizing these relational processes, the learning ecosystem framework can support efforts to shift away from policies and practices that rely on the myth of individual meritocracy and toward those policies and practices that can begin to address more systemic causes of inequity and injustice.

For practitioners and policymakers, the decentring of individual learners opens up a dialogue about how learners are interconnected with the people, places, and stuff that they interact with in learning ecosystems. Moving our focus away from individual learners (currently treated like individual organisms) to learners as groups (analogous to a species) connected with other ecosystem elements (as holobionts) gives us tools to think about how to undertake educational management as a systems problem and how to use an adaptive management approach. A richer use of the learning ecosystem framework might help us achieve a deeper understanding of system structures and interrelationships between entities (Falk et al., 2015). It may lead to more nuanced attention to scalar shifts between different levels of learning ecosystems and force us to accept recurring and sometimes dramatic disturbances to local systems. If we accept disturbance as a fundamental and necessary part of learning ecosystems, how might policymakers and funders support the management of systems that can be more resilient to these changes? And how might practitioners rethink how to support connected learning pathways, how to train educators, and, importantly, how communities and stakeholders can collectively work toward and invest in healthy regional ecosystems that are equitable, accessible, and effective?

For educational researchers, using the learning ecosystem framework more robustly with a focus on relational processes is a potential tool to support calls to decolonize educational research and embrace what Patel (2015) has called "a research stance that used holistic ecologies as the default form." (p. 36). This is not to say that research should never attend to how people learn at the individual level, but rather that for the larger goal of sustainable, just, and equitable educational improvements, our approaches need to be sensitive to systems that are more complex and multiscalar than we have been thinking about. One difficulty will be how to home in on what tools can be used for conceiving of and monitoring relational processes within complex systems. For example, how might relational processes be observed and measured both qualitatively and quantitatively? How might the field understand the limits and potential of natural disturbances? In Barron's (2006) foundational piece on learning ecologies, she rightly points out that designing studies that are able to address this complexity is a key challenge. If we want to assess the health of learning ecosystems, we still have some work to do to develop the appropriate research tools for this.

We also recognize the potential pitfalls of leaning too heavily on an ecosystem framework. One reflective reviewer perceptively asked if relying too greatly on concepts from biological systems might actually undermine our goal of attending to equity, since biological systems do not have inequities the way cultural systems do. But both biological and learning ecosystems can be healthy or unhealthy, highly functional or less so. In our view, an unjust and inequitable learning ecosystem is an unhealthy one. An ecological frame offers the benefit of purposeful and adaptive intervention to address those inequities.

Finally, we ought not to believe that we can control this setting, any more than we ought to believe we can control a biological ecosystem. In fact, intervention as a design approach may not make sense when we are thinking about learning ecosystems. Perhaps we need to recast how we think about learning ecosystem design altogether, focusing instead on adaptive response to chaos. As the early ecologist, Egler (1977), noted: “nature is not more complex than we think, it is more complex than we can think.” (p. 2) The complexity of learning is what makes the ecosystem framework so powerful; both biological and learning ecosystems are equally more complex that we can think. Consider the layers of human experience, emotion, capacity, the natural and built environment that we learn in, the cultural and personal histories that impact every learning experience. Given this complexity, letting go of control and being responsive to chaos and emergent phenomena is key. While this prospect may feel difficult and humbling, we believe that using an expanded learning ecosystem framework can help us make better use of the tools at our disposal.

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ORCID

Marijke Hecht http://orcid.org/0000-0003-2299-6534

REFERENCES

Akiva, T., Kehoe, S. S., & Schunn, C. D. (2016). Are we ready for citywide learning? Examining the nature of within- and between-program pathways in a community-wide learning initiative. *Journal of Community Psychology*, 1–13. doi:10.1002/jcop.21856

Azevedo, F. S. (2013). The tailored practice of hobbies and its implication for the design of interest-driven learning environments. *Journal of the Learning Sciences*, *22*(3), 462–510. doi:10.1080/10508406.2012.730082

Banks, J. A., Au, K. H., Ball, A. F., Bell, P., Gordon, E. W., Gutiérrez, K. D., … Zhou, M. (2007). *Learning in and out of school in diverse environments*. Seattle, WA: The LIFE Center.

Barad, K. (2007). *Meeting the universe halfway: Quantum physics and the entanglement of matter and meaning*. Durham, NC: Duke University Press.

Barron, B. (2006). Interest and self-sustained learning as catalysts of development: A learning ecology perspective. *Human Development*, *49*(4), 193–224. doi:10.1159/000094368

Berglund, T. O. (2009). Multimodal student interaction online: An ecological perspective. *ReCALL*, *21*(2), 186–205. doi:10.1017/S0958344009000184

Bevan, B. (2016). *STEM learning ecologies: Relevant, responsive, and connected*. Retrieved from http://csl.nsta.org/2016/03/stem-learning-ecologies/

Bronfenbrenner, U. (1979). *The ecology of human development: Experiment by nature and design*. Cambridge, MA: Harvard University Press.

Bryk, A. S. (2015). 2014 AERA distinguished lecture. *Educational Researcher*, *44*(9), 467–477. doi:10.3102/0013189X15621543

Cannata, M., Cohen-Vogel, L., & Sorum, M. (2017). Partnering for improvement: Improvement communities and their role in scale up. *Peabody Journal of Education*, *92*(5), 569–588. doi:10.1080/0161956X.2017.1368633

Cekaite, A., & Evaldsson, A.-C. (2017). Language policies in play: Learning ecologies in multilingual preschool interactions among peers and teachers. *Multilingua: Journal of Cross-Cultural and Interlanguage Communication*, *36*(4), 451–475. doi:10.1515/multi-2016-0020

Coburn, C. E. (2003). Rethinking scale: Moving beyond numbers to deep and lasting change. *Educational Researcher*, *32*(6), 3–12. doi:10.3102/0013189x032006003

Code, L. (2006). *Ecological thinking: The politics of epistemic location*. Oxford, UK: Oxford University Press.

Cohen, G. L., & Garcia, J. (2014). Educational theory, practice, and policy and the wisdom of social psychology. *Policy Insights from the Behavioral and Brain Sciences*, *1*(1), 13–20. doi:10.1177/2372732214551559

Corin, E. N., Jones, M. G., Andre, T., Childers, G. M., & Stevens, V. (2017). Science hobbyists: Active users of the science-learning ecosystem. *International Journal of Science Education, Part B: Communication and Public Engagement*, *7*(2), 161–180. doi:10.1080/21548455.2015.1118664

Crowley, K., Barron, B., Knutson, K., & Martin, C. K. (2015). Interest and the development of pathways to science. In K. A. Renninger, M. Nieswandt, & S. Hidi (Eds.), *Interest in mathematics and science learning* (pp. 297–314). Washington, DC: American Educational Research Association.

Crowley, K., & Jacobs, M. (2002). Building islands of expertise in everyday family activity. In G. Leinhardt, K. Crowley, & K. Knutson (Eds.), *Learning Conversations in Museums* (pp. 333–356). Mahwah, NJ: Lawrence Erlbaum Associates, Inc.

Damsa, C., & Jornet, A. (2016). Revisiting learning in higher education-Framing notions redefined through an ecological perspective. *Frontline Learning Research*, *4*(4), 39–47. doi:10.14786/flr.v4i4.208

Dawson, E. (2014). "Not designed for us": How science museums and science centers socially exclude low-income, minority ethnic groups. *Science Education*, *98*(6), 981–1008. doi:10.1002/sce.21133

Egler, F. E. (1977). *The nature of vegetation, its management and mismanagement. An introduction to vegetation science*. Norfolk, CT: Alton Forest Publishers.

Engeström, Y. (2007). From communities of practice to mycorrhizae. In J. Hughes, N. Jewson, & L. Unwin (Eds.), *Communities of practice: Critical perspectives* (pp. 41–54). London, UK: Routledge.

Falk, J. H., & Dierking, L. D. (2018). Viewing science learning through an ecosystem lens: A story in two parts. In D. Corrigan, C. Buntting, A. Jones, & J. Loughran (Eds.), *Navigating the changing landscape of formal and informal science learning opportunities* (pp. 9–29). New York, NY: Springer International Publishing.

Falk, J. H., Dierking, L. D., Osborne, J., Wenger, M., Dawson, E., & Wong, B. (2015). Analyzing science education in the United Kingdom: Taking a system-wide approach. *Science Education*, *99*(1), 145–173. doi:10.1002/sce.21140

Ferlian, O., Cesarz, S., Craven, D., Hines, J., Barry, K. E., Bruelheide, H., … Eisenhauer, N. (2018). Mycorrhiza in tree diversity-ecosystem function relationships: Conceptual framework and experimental implementation. *Ecosphere*, *9*(5), e02226. doi:10.1002/ecs2.2226

Folkestad, J. E., & Banning, J. (2010). The ecology model of learning: Evaluating digital media applications (DMAs) using established ecological subsystems of learning. *Journal of Educational Technology*, *7*(2), 41–51.

Fox, N. J., & Alldred, P. (2018). New materialism. In P. A. Atkinson, S. Delamont, M. A. Hardy, & M. Williams (Eds.), *The SAGE encyclopedia of research methods.* London, UK: Sage. doi:10.1215/9780822392996-001Save

Gilbert, S. F., Sapp, J., & Tauber, A. I. (2012). A symbiotic view of life : We have never been individuals. *The Quarterly Review of Biology*, *87*(4), 325–341. doi:10.1086/668166

Gomez, L. M., Russell, J. L., Bryk, A. S., Lemahieu, P. G., & Mejia, E. (2016). The right network for the right problem. *Phi Delta Kappan*, *98*(3), 8–15. doi:10.1177/0031721716677256

Groom, M. J., Meffe, G. K., & Carroll, C. R. (2006). *Principles of conservation biology* (3rd ed.). Sunderland, MA: Sinaur Associates, Inc.

Gutiérrez, K. D., Bien, A. C., Selland, M. K., & Pierce, D. M. (2011). Polylingual and polycultural learning ecologies: Mediating emergent academic literacies for dual language learners. *Journal of Early Childhood Literacy*, *11*(2), 232–261. doi:10.1177/1468798411399273

Gutiérrez, K. D., & Rogoff, B. (2003). Cultural ways of learning: Individual traits or repertoires of practice. *Educational Researcher*, *32*(5), 19–25. doi:10.3102/0013189X032005019

Haldane, J. B. S. (1926). On being the right size. *Harper's Magazine*, *152*, 424–427. doi:10.1038/ng0905-923

Haraway, D. J. (2016). *Staying with the trouble: Making kin in the Chthulucene*. Durham, NC: Duke University Press.

Hargreaves, A., & Fink, D. (2004). The seven principles of sustainable leadership. *Educational Leadership*, *61*(7), 8–13.

Hecht, M., Knutson, K., & Crowley, K. (2019). Becoming a naturalist: Interest development across the learning ecology. *Science Education*, *103*(3), 691–713. doi:10.1002/sce.21503

Henning, E., Van der Westhuizen, D., & Diseko, R. (2005). Knowledge ecologies in fragile online learning environments: Research, information and communication technologies. *Perspectives in Education*, *23*(4), 55–70. Retrieved from http://journals.sabinet.co.za/pie/index.html

Herro, D. (2016). An ecological approach to learning with technology: Responding to tensions within the "wow-effect" phenomenon in teaching practices. *Cultural Studies of Science Education*, *11*(4), 909–916. doi:10.1007/s11422-015-9688-2

Herzog, S. (2007). The ecology of learning: The impact of classroom features and utilization on student academic success. *New Directions for Institutional Research*, *135*, 81–106. doi:10.1002/ir.224

Hodkinson, I. D., & Jackson, J. K. (2005). Terrestrial and aquatic invertebrates as bioindicators for environmental monitoring, with particular reference to mountain ecosystems. *Environmental Management*, *35*(5), 649–666. doi:10.1007/s00267-004-0211-x

Horton, Z. (2018). The trans-scalar challenge of ecology. *ISLE: Interdisciplinary Studies in Literature and Environment*, (2018), 1–22. doi:10.1093/isle/isy079

Jacobson, M. J., Levin, J. A., & Kapur, M. (2019). Education as a complex system: Conceptual and methodological implications. *Educational Researcher*, *48*(2), 0013189 × 1982695. doi:10.3102/0013189X19826958

Johnson, E. S. (2008). Ecological systems and complexity theory: Toward an alternative model of accountability in education. *Complicity: an International Journal of Complexity and Education*, *5* (1), 1–10. doi:10.29173/cmplct8777

Kania, J., & Kramer, M. (2011, Winter). Collective impact. *Stanford Social Innovation Review*, 36–41. doi:10.1007/s13398-014-0173-7.2

Krishnamurthi, A. (2014). *STEM learning across settings: Cultivating learning ecosystems*. Retrieved from http://www.afterschoolalliance.org/afterschoolsnack/ASnack.cfm?idBlog=42F434BF-215A-A6B3-02FE5A2917CC75A9

Lee, C. D. (2010). Soaring above the clouds, delving the ocean's depths: Understanding the ecologies of human learning and the challenge for education science. *Educational Researcher*, *39*(9), 643–655. doi:10.3102/0013189X10392139

Lee, C. D. (2017). Understanding the ecologies of human learning and the challenge for education science. *New Perspectives on Human Development*, 123–141. doi:10.1017/CBO9781316282755.009

Lemke, J. L., & Sabelli, N. H. (2008). Complex systems and educational change: Towards a new research agenda. *Educational Philosophy and Theory*, *40*(1), 118–129. doi:10.1111/j.1469-5812.2007.00401.x

Lin, -C.-C. (2011). A learning ecology perspective: School systems sustaining art teaching with technology. *Art Education*, *64*(4), 12–17. Retrieved from http://www.arteducators.org/research/art-education

McFall-Ngai, M., Hadfield, M. G., Bosch, T. C. G., Carey, H. V., Domazet-Lošo, T., Douglas, A. E., … Wernegreen, J. J. (2013). Animals in a bacterial world, a new imperative for the life sciences. *Proceedings of the National Academy of Sciences*, *110*(9), 3229–3236. doi:10.1073/pnas.1218525110

McKenzie, M., & Tuck, E. (2015). *Place in research: Theory, methodology, and methods*. New York, NY: Routledge.

Miller, M. T., & Husmann, D. E. (1996). A holistic model for primary factors in the ecology of distance education course offerings. *Journal of Distance Education*, *11*(1), 101–110.

National Research Council of the National Academies. (2015). *Identifying and supporting productive STEM programs in out-of-school settings*. Washington, DC: The National Academies Press. doi:10.17226/21740

Patel, L. (2015). *Decolonizing educational research: From ownership to accountability*. New York, NY: Routledge.

Penuel, W. R., Fishman, B. J., Haugan Cheng, B. H., & Sabelli, N. (2011). Organizing research and development at the intersection of learning, implementation, and design. *Educational Researcher*, *40*(7), 331–337. doi:10.3102/0013189X11421826

Penuel, W. R., Lee, T. R., & Bevan, B. (2014). *Research synthesis: Designing and building infrastructures to support equitable STEM learning across settings. Research + practice collaboratory research synthesis*. San Francisco, CA.

Poon, L. (2017). *Chicago's path to become a "city of learning."* Retrieved from https://www.citylab.com/solutions/2017/09/chicago-after-school-programs-digital-youth-network/537591/

Rettig, J. (2009). School libraries and the educational ecosystem. *Change: the Magazine of Higher Learning*, *41*(2), 28–29. doi:10.3200/CHNG.41.2.28-29

Ricklefs, R. E., & Miller, G. L. (2000). *Ecology* (4th ed.). New York, NY: W.H. Freeman and Company.

Ripple, W. J., & Beschta, R. L. (2004). Wolves and the ecology of fear: Can predation risk structure ecosystems? *BioScience*, *54*(8), 755. doi:10.1641/0006-3568(2004)054[0755:WATEOF]2.0.CO;2

Roberts, J. L. (2016). Introduction: Seeing scale. In J. L. Roberts (Ed.), *Scale* (pp. 10–24). Chicago, IL: Terra Foundation for American Art.

Russell, J. L., Knutson, K., & Crowley, K. (2013). Informal learning organizations as part of an educational ecology: Lessons from collaboration across the formal-informal divide. *Journal of Educational Change*, *14*(3), 259–281. doi:10.1007/s10833-012-9203-4

Salazar-Porzio, M. (2015). The ecology of arts and humanities education: Bridging the worlds of universities and museums. *Arts and Humanities in Higher Education: an International Journal of Theory, Research and Practice*, *14*(3), 274–292. doi:10.1177/1474022215583949

Simon, H. A. (1996). *The sciences of the artificial* (3rd ed.). Cambridge, MA: The MIT Press. doi:10.1016/S0898-1221(97)82941-0

Snyder, S. (2013). The simple, the complicated, and the complex: Educational reform through the lens of complexity theory. *OECD Education Working Papers*, *96*, 35.

Society for Ecological Restoration. (2016). *Foundations of restoration ecology* (2nd ed., M. A. Palmer, J. B. Zedler, & D. A. Falk, Eds.). Washington, D.C.: Island Press.

Spaargaren, G., Weenink, D., & Lamers, M. (Eds.). (2016). *Practice theory and research: Exploring the dynamics of social life*. London, UK: Routledge.

Spillane, J. P., Gomez, L. M., & Mesler, L. (2009). Notes on reframing the role of the organizations in policy implementation. In G. Sykes, B. Schneider, & D. N. Plank (Eds.), *Handbook of educational policy research* (pp. 409–424). New York, NY: Routledge.

STEM learning ecosystems. (2015). Retrieved from U.S. Department of Education Office of Innovation and Improvement. https://innovation.ed.gov/2015/11/19/communities-come-together-to-support-stem-education/

Vicsek, L., Király, G., & Kónya, H. (2016). Networks in the social sciences. *Corvinus Journal of Sociology and Social Policy*, *7*(2), 77–102. doi:10.14267/CJSSP.2016.02.04

What are STEM ecosystems? Design principles. (n.d.). Retrieved from STEM Ecosystems website https://stemecosystems.org/design-principles/

Yohalem, N., & Pittman, K. (2006). *Putting youth work on the map: Key findings and implications from two major workforce studies*. Washington, DC: Forum for Youth Investment.

Yoon, S. A. (2011). Using social network graphs as visualization tools to influence peer selection decision-making strategies to access information about complex socioscientific issues. *Journal of the Learning Sciences*, *20*(4), 549–588. doi:10.1080/10508406.2011.563655