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Supporting science and engineering learning through an ecosystem approach

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An ecosystem perspective

Society is facing a myriad of serious issues, such as global climate change and infectious diseases, that are social-ecological in nature because they are shaped by interdependencies between human societies and the rest of the natural world. These challenges, sometimes called wicked problems, require educational approaches that help people tackle complexity and address problems creatively (Moritz & Kawa, 2022). Science and engineering education is essential for fostering interest and commitment to addressing these issues, both by training new scientists and engineers who can work on these problems professionally (Committee on Improving Higher Education's Responsiveness to Regional STEM Workforce Needs: Identifying Analytical Tools and Regional Best Practices, 2016) and by promoting civic science engagement by non-scientists (Garlick & Levine, 2017). This is a challenging prospect that depends on engaging people in science and engineering not only in school, but at all ages and in all different types of settings. It is a challenge that requires a learning ecosystem approach.

Science and engineering learning is lifelong and life-wide, which means it happens throughout our lives and in all different settings, from schools to informal institutions, such as museums, to homes and other everyday places (Penuel et al., 2014). It is also life-deep, meaning that it is bound to social practices that include spiritual and cultural values (Bell et al., 2013). Broadening participation in science and engineering, whether for civic or professional engagement, requires that educators, policy makers, researchers, families, and learners move beyond a narrow focus on schooling as the site for learning and towards an embrace of the expansive and complex nature of lifelong, lifewide, and life-deep learning.

The National Academies 2009 report *Learning Science in Informal Environments: People, Places, and Pursuits* presents an ecological framework as a valuable tool for making sense of the complexity of learning across both time and space. The authors stress learning as a process that reflects "the relations between individuals and their physical and social environments with particular attention to relations that support learning." (Committee on Learning Science in Informal Environments, 2009, p. 31). This ecological and relational framing highlights the significance of out-of-school learning for not only knowledge development, but also participation in larger learning communities and social structures.

The ecological framework has roots in Bronfenbrenner's (1979) ecological theory of human development, which describes how individuals develop through interactions at different scales beginning with microsystem elements such as family and friends and expanding outward to larger systems that connect individual development to societal structures. Educational researchers built on this conceptualization of human development by describing an ecological framework for learning that similarly emphasizes interdependencies across different learning settings (Barron, 2006). Importantly, early calls for an ecological framework also insisted on recognition of the value of the diversity of human knowledge and experience (Lee, 2008, 2010). By positioning learning as a function of complex interactions between the people, places, and cultures that inform the how, where, when, and why of learning, an ecological framing offers opportunities for multiple points of intervention which can serve to expand and strengthen science and engineering learning and engagement (Committee on Learning Science in Informal Environments, 2009). Since these early calls, an ecological framework has been widely adopted across the field of education, especially in the STEM fields. Like the many societal challenges that we hope to address through science and engineering education, learning ecosystems are also social-ecological wicked problems that require systems thinking and action. Therefore, I use the phrase learning ecosystem instead of learning ecology to emphasize the complexity of the interactions between people and places for learning, and to stress the need for systems thinking and action.

In this white paper, I begin by presenting some examples of the use of the learning ecosystem frame, with an emphasis on the ways that it has been used in science and engineering educational research and practice. I then explore ideas for how to make more effective use of the learning ecosystem framework by positioning them as *complex* rather than *complicated* systems. I consider how current understanding of restoration ecology and biological systems might support more robust design and management of learning ecosystems that takes into account outcomes such as scalar interactions and resilience. I then close by offering some ideas for furthering a learning ecosystem approach through cross sector collaborations that advance aims for equitable science and engineering learning ecosystems.

Learning ecosystems in research and practice

Since the National Academies 2009 report *Learning Science in Informal Environments: People, Places, and Pursuits*, a learning ecosystem framework has become widespread in educational research and practice. The framework has been applied to learners of all ages, including adult learners in work-focused programs (Heikkinen et al., 2022), higher education classrooms (Cwik & Singh, 2022), teacher professional development (Sancho-Gil & and Domingo-Coscollola, 2022), and the development of play opportunities for young children and families (Bermudez et al., 2023). It has also been used to consider strategies for the design of physical (Herzog, 2007) and virtual learning spaces (Berglund, 2009; Folkestad & Banning, 2010), including connecting the two (Herro, 2016; Lin, 2011).

Educational researchers have taken up the learning ecosystem framework to anchor inquiry into how to connect school systems with informal, out-of-school learning including in libraries (Rettig, 2009), museums (Salazar-Porzio, 2015), online learning spaces (Greenhow et al., 2022), and with communities (Damsa & Jornet, 2016; Russell et al., 2013). Because the learning ecosystem framework accounts for learning across time and space, it highlights the significant role that out-of-school learning settings play in fostering interest development and opportunities for learners to shape their own learning pathways (Corin et al., 2017). Perhaps most significantly, the learning ecosystem framework focuses on equity and justice issues by surfacing challenges that some learners face in academic spaces (Lee, 2017) and emphasizing the important values of community and culture for learning (Gutiérrez et al., 2011). While the learning ecosystem framework has applications across disciplines, the STEM fields have been particularly strong adopters of the concept.

Science and engineering educators, learning advocates and researchers have championed the valuable role that out-of-school settings play in learning ecosystems (Bevan, 2016; National Research Council of the National Academies, 2015). These out-of-school experiences provide opportunities for youth mentoring (Mondisa et al., 2021); help shape youth perceptions of STEM (Wade-Jaimes et al., 2023); and support pathways that respond to and foster youth interest in science (Shaby et al., 2021). These values extend to learners of all ages; for example, the learning ecosystem framework has been used to explore mechanisms to encourage community engagement by adults in citizen science (Allf et al., 2022).

There is robust work being done to support STEM ecosystems at regional and state levels. For example, the Remake Learning Network has worked to connect school and out-of-school partners and increase learner engagement, with an emphasis on STEM and maker spaces, across Western Pennsylvania (The Pittsburgh Principles: Lessons Learning from 15 Years Stewarding a Learning Ecosystem, 2022). At the national level, the STEM NEXT Opportunity Fund supports an out-of-school time STEM ecosystem through research, advocacy, and program supports for major out-of-school providers such as Boys & Girls Clubs of America (*Our Impact*, 2025), and the STEM Ecosystems initiative promotes and supports STEM-focused learning ecosystems at regional and statewide scales (*STEM Ecosystems*, 2025). Support from the federal government for STEM Ecosystems had been supported by recent administrations (e.g., White House

Office of Science and Technology Policy, 2024), though it is unclear if this will continue going forward.

The learning ecosystem framework has become an essential tool for integration and collaboration across educational sectors. It helps emphasize the important role of informal and everyday learning, is influencing policymaking and practice, and has been taken up at regional and statewide scales. The framework tethers educational practice with theoretical constructs that are being used to design and manage learning systems that aim for positive impacts and equity for learners and communities. But despite all these valuable efforts, there is still work to be done to create resilient learning ecosystems that expand science and engineering interest and improve educational outcomes in equitable and just ways. After more than 15 years of growing emphasis on learning ecosystems, we have an opportunity to further both the theory and practice of learning ecosystem design and management to not only help engage people in science and engineering, but to help engage science and engineering in the service of building healthy communities.

This is a wicked problem. To date, the application of the learning ecosystems framework has frequently treated learning ecosystems as *complicated* structures by focusing on how to engineer interventions that connect organizations to one another and to support learner pathways. But learning ecosystems are not simply complicated structures that can be engineered. Instead, they are multiscale, *complex systems* that are emergent and dynamic. Complex, wicked problems demand multidisciplinary, creative, systems thinking. We need to attend to not only the complicated nature of developing pathways for science and engineering learning, but to the complex nature of learning ecosystems.

Learning from and with nature

Learning ecosystems are social-ecological systems – they include both social and biophysical elements, as alluded to by the inclusion of *places* in the original subheading of the National Academies 2009 report – “People, Places, and Pursuits”. Positioning learning ecosystems as structures where cultural forces are intertwined with other aspects of the natural world opens space to apply a certain type of systems thinking – social-ecological thinking – to our work with learning ecosystems. Social-ecological thinking can take on different forms: it can focus on the relationships between cultural and natural aspects of the world, and it can also extend and deepen systems analysis by using metaphor to transfer theories of social and ecological principles (Spours, 2024). This latter application of social-ecological thinking offers a potentially fruitful conceptual move to help educators, researchers and policy makers design and manage healthier and more resilient science and engineering learning ecosystems.

By using social-ecological systems theory, we can draw on current understanding of biological ecosystems and apply practices used in the adaptive management of biological ecosystems by restoration ecologists for learning ecosystem design and management

(Falk & Dierking, 2018; Hecht & Crowley, 2020). Three basic ecosystem principles can help guide this work: the *systems principle*, the *complexity principle*, and the *health principle* (Akiva et al., 2022). The *systems principle* reminds us that ecosystems do not have a central focus but rather are made up of many elements that are all interacting with one another in complex ways. In a learning ecosystem, this shifts focus away from individual learners and towards relationships and interactions between system elements. The *complexity principle* builds on this by highlighting that ecosystem elements are always in a state of flux and that this constant change makes learning ecosystems dynamic and unpredictable. The *health principle* reminds us that ecosystems are not inherently healthy. We need to intentionally manage for healthy learning ecosystems if we want equitable and enriching learning opportunities with positive outcomes. This requires attention to the design and monitoring of learning ecosystem infrastructures (Penuel et al., 2014).

As social-ecological systems, learning ecosystems share several structural traits with other ecological systems that offer opportunities for transfer between the fields of education and ecosystem sciences, including that they exist at different scales, that these scales are nested within one another, and that these nested structures create complex relationships between learning ecosystem elements (Hecht et al., Manuscript in preparation). In the next section, I describe how conceptualizing science and engineering learning ecosystems as multiscale, complex social-ecological systems can help support design and management of learning ecosystems for health and resilience. While this conceptualization may be applied to learning ecosystems of all disciplines, the application to science and engineering learning ecosystems is particularly relevant for two reasons. First, science and engineering are disciplines that regular explore complexity with learners and we should be better about applying complexity theory to our own work. Second, the need for science and engineering literacy is an increasingly urgent need given the health and environmental issues we face globally. Therefore, it is essential that we design and manage science and engineering learning ecosystems that broaden professional participation and civic engagement in these fields.

Embracing complexity

Learning ecosystems are *complex* rather than *complicated*. While the word *complex* is often used colloquially to describe something that is difficult to understand, systems theory draws a valuable distinction between *complex* and *complicated* when aiming to address problems in scientific fields including health sciences (Sturmberg et al., 2017) and engineering (Grabowski & Strzalka, 2008). All systems are made up of parts. In complicated systems, those parts can be organized in a predictable, linear ways to solve problems and those solutions can be replicated. Think about how putting a three-dimensional wooden puzzle together might be difficult, but once the pattern is understood the puzzle can be broken down and put back together again with greater ease. If the same puzzle pattern were a smaller size or made of a different material, like plastic, one could simply transfer prior knowledge to solve the new puzzle. There might be minor shifts to make – perhaps the small puzzle requires a special tool, or the wood pieces fit together more neatly than the plastic – but fundamentally the operations needed to connect the pieces and solve the puzzle would remain the same.

This kind of replicable solutionism is not possible in education because learning ecosystems are *complex*. The interconnected parts of educational systems exhibit emergent and dynamic patterns of non-linear and unpredictable behavior (Yoon, 2011), and because the context for each learning ecosystem is unique, effective approaches in one setting are not easily transferrable to another setting (Snyder, 2013). Learning ecosystems are not puzzles to be solved – they are social-ecological systems. This is precisely why the phrase learning *eco*system, instead of simply learning system, is so valuable. It reminds us that the complexity of learning happens through interactions between many actors and places – including learners, families, educators, schools, libraries, parks, bus stops, etc. – and at a range of scales – from classrooms to neighborhoods to whole cities and regions and states and even the globe. All these actors are interacting across many scales in dynamic, emergent, and unpredictable ways. Therefore, efforts to make educational improvements cannot rely on linear approaches, but instead require collaborative, iterative work (Gomez et al., 2016) that can adapt and respond to actual current conditions in flexible ways (Hecht & Crowley, 2020). Easier said than done.

Thinking and working within complex systems challenges our abilities to design and manage for healthy, resilient, and equitable learning experiences. With a nod to the early ecologist Frank Egler who said that "…nature is not more complex than we think, it is more complex than we can think" (Egler, 1977, p. 2), learning ecosystems are not only more complex than we think, they are more complex than we *can* think. Observing and learning from natural systems offers some guidance for wrestling with the complexity of learning ecosystems by drawing on our current understanding of biological ecosystems and the field of ecological restoration, which is a relatively young field that is still developing. In the following, I offer three foundational conceptual moves: decentering individuals, rethinking scale, and designing for resilience and variation. I also offer some wonderings on how these conceptual shifts might influence our interventions and target outcomes.

Interactions over individuals

Learners are central to the mission of education, but they are not the center. Building on its roots in ecological theory of human development, learning ecosystem theory has predominantly positioned learners at the center of a network of learning opportunities, where the learners are being influenced by – and are ideally connected with – a host of educational institutions that are able to impact the learning experience (see Figure 1). This framing does not take into account a critical aspect of all ecosystems – that there is no center. Every element of an ecosystem is impacting and being impacted by every other aspect of that ecosystem. Positioning learners at the center of learning ecosystems overemphasizes learning as an individual act. When we center youth and pathways, we imply that equity is achievable via access and opportunity. But access to institutions does not change systems.

The lesson from ecological restoration is to focus on interactions between learning ecosystem elements (e.g., how are ideas and energy moving between school and out-of-school), rather than focusing on connecting individual actors to one another (e.g., learners and organizations). Emphasis on connecting opportunities and resources treats learning ecosystems as *complicated networks*; emphasis on supporting robust and equitable interactions between actors treats learning ecosystems as *complex, integrated systems* (Hecht & Crowley, 2020).

Figure 1. An example of a typical pictorial representation of a STEM learning ecosystem taken from the "About" page of STEM Ecosystems website.

Undoubtedly, designing and managing effective learning experiences for individuals is vital, and individuals are essential components of learning ecosystems. We can think of the individual pathway in a learning ecosystem as a *learningscape* where learners integrate their experiences from different settings and times, and where every day out-of-school learning is recognized as essential (Ardoin & Heimlich, 2021). These pathways can occur by chance; because learning is always happening, we are always moving from one experience to another through various pathways. But more equitable learning ecosystems need to be designed with learning ecosystem infrastructure that attends to what Pinkard calls the 'connective tissue' between learning opportunities (Pinkard, 2019, p. 43). A focus on the connective tissue puts the emphasis on the interactions between providers and learners, helping to support and smooth movement between learning experiences. However, this type of pathway development is just one part of learning ecosystem design.

The learning ecosystem framework has the potential to offer greater impacts on learning if we can continue to push our focal interventions towards key elements – or what restoration ecologists call *keystones* – that drive the flow of resources, ideas, and power through learning ecosystems. Restoration ecologists focus on supporting *keystone species* in biological systems; they then monitor other species that they call *indicator species* for signs of ecosystem health (Ricklefs & Miller, 2000). Who drives resources, ideas, and power through learning ecosystems? One important keystone may be intermediary organizations, such as STEM ecosystem conveners, whose role in building capacity is essential for overall learning ecosystem health (Ottinger, 2023; Penuel et al., 2011). Another keystone in learning ecosystems may be educators. If we invest in educators and support their health, then that will help support the health of the whole learning ecosystem (Colvin & White, 2022). In interconnected complex systems, healthy keystones support health throughout the system. Our attention on learners could shift towards understanding their experiences and outcomes as *indicators* of learning ecosystem health (Hecht & Crowley, 2020).

If we translate this into learning ecosystem design and management, our approach to might be to focus resources, including funding, capacity building, and structural supports, on educators and intermediary organizations. Educators, especially those in the out-of-school sectors, would benefit from more formal training, and greater support systems (Yohalem & Pittman, 2006). Overall, the interactions or relations between keystones and indicators ought to be the focal outcome of our work.

Rethinking scale

Like other complex social-ecological systems, learning ecosystems are nested. There are smaller learning ecosystems, such as a city's STEM learning ecosystem, that exist within larger ecosystems, such as a multidisciplinary learning ecosystem at the city or state level. Energy and ideas exhibit multilateral flow because individual actors (e.g., individual learners and organizations) are not only influenced by the learning ecosystems they are part of – they also exert force and affect change on the learning places they interact with. Just like the small watershed of a stream that is nested inside the large river watershed that it flows into, the learning ecosystem at the smaller scale is not subordinate to the larger one; rather, elements of nested learning ecosystems interact in multilateral, rather than hierarchical ways (Hecht & Crowley, 2020).

Learning ecosystems at all scales – from micro to macro – have significant potential impacts on learning, which means there are myriad intervention points for engagement and action. This presents both opportunities and challenges for affecting transformative change. Multilateral flows of energy, ideas, and power create useful tensions between the scales of individual action, collective action, and institutional forces that operate across time and space in learning ecosystems. Ideally, learning ecosystems can support individual agency at the same time that they push against systemic forces that impede equitable educational experiences. This scalar tension allows us to reframe scale from a tool for replication, as in 'scaling up', towards scale as a unit for managing the layers of complexity within nested learning ecosystems.

For educational advocates and researchers, it is essential to consider what scale of intervention to focus on – and to consider how that focal scale is interacting with learning ecosystems at other scales. As designers and managers of science and engineering learning ecosystems, scalar considerations include both geographic and disciplinary boundaries. For example, how might statewide STEM learning ecosystem intermediaries shift strategies when working at community vs. statewide scales as they foster interactions between and among local school districts, informal science education institutions, and families? What role might these STEM learning ecosystem facilitators play in bringing in educators from other disciplines, such as the arts?

Interactions across scales are an essential focus for attending to the complexity of learning ecosystems because learning ecosystems at different scales are not merely connected networks. Like elements of other social-ecological systems, the multi-scalar nature of these systems gives them dynamic properties (Colding & Barthel, 2019) where it is the interactions between the elements – not just the connections between them – that drives outcomes. In practice, then, science and engineering learning ecosystem designers and managers ought to focus not just on making linkages, but on ensuring that the quality of the interactions between linkages is healthy and strong enough to withstand disturbance and support a resilient ecosystem. This also requires that the field define what a healthy interaction is so that we can monitor interactions as an indicator of learning ecosystem health.

Resilience and variation

As complex social-ecological systems, learning ecosystems are dynamic and constantly changing. These changes are influenced by the layered scales of interconnected learning ecosystems, and they are also influenced by disturbances in the systems. One of the most pronounced disturbances in recent years was the COVID-19 pandemic which interrupted in-person learning experiences for more than a year in some communities and increased online interactions between learners and educational institutions in ways that persist today. More recently, we are seeing disturbances to learning ecosystems via changes to the U.S. Department of Education, and reduction in critical research funding for science and engineering learning from sources such as the National Science Foundation. Disturbance can also happen at smaller scales, such as a shift in leadership at a regional educational organization or a change in funding priorities by a private foundation.

In biological ecosystems, we know that disturbances are also constant. Some disturbances, such as abrupt and extreme flooding, can have devastating effects. Other disturbances, such as the normal overflow of a river onto a floodplain during a rain event, are an essential component of ecosystem health. The ability of an ecosystem to withstand, or even thrive, in the face of disturbance is a measure of its resilience. More resilient systems are healthier. A critical challenge for educators, advocates, and researchers is to design and manage learning ecosystems that can not only support equitable learning, but also that are resilient in the face of the inevitable change that happens. If resiliency itself is a necessary outcome of healthy learning ecosystems, then we need to also consider how we might measure this resiliency. The scalar, nested nature of learning ecosystems might offer some help here. If resiliency can be measured at smaller scales – say at the scale of interactions between a small group of ecosystem elements – then perhaps that can be used to help model learning ecosystem resilience at larger scales.

Measuring resilience also needs to account for local variation. As with ecological places, such as a flowing river, learning ecosystem *places* are made up of both space (e.g., landscape features or classrooms) and time, where history, present conditions, and future possibilities intersect (Tuck & McKenzie, 2015). This makes the places that make up learning ecosystems – whether they be libraries, parks, classrooms, or homes – more than just context where learning happens. These places are essential elements that learners not only learn *in* and *about* but can also learn *from* (Styres, 2011). Recognizing the complexity of place as a function of both space and time also means that learning ecosystem work cannot be easily replicated from one site to another. Instead, local variation and nuance must always be accounted for, just as is done with stream restoration.

Opportunities for future work

The learning ecosystem framework has become a valuable tool for educational researchers and practitioners, especially those working in informal, out-of-school settings focused on science and engineering learning. These complex systems require integrated strategies and collective action to design and manage. Robust collaboration across sectors is essential to continue to advance the health and resilience of learning ecosystems. This includes fostering research-practice partnerships at small and large scales where theory and practice can inform each other. It also demands is more authentic collaborations across educational sectors, especially where K-12 schools recognize and value the essential role that out-of-school, informal institutions play in learning ecosystems.

Learning ecosystem design and management would also benefit from closer collaboration with practicing scientists and engineers in both basic research and applied fields (Hecht et al., Manuscript in preparation). There are two potential values for this deeper connection. First, these scientists and engineers have an important role to play as essential keystones within learning ecosystems that can drive learner interest, support civic science engagement (Braaten et al., 2024), and potentially foster science and environmental identity formation (Carlone, 2017). Second, collaboration with applied restoration ecologists and ecological modelers could offer additional opportunities to transfer both theory and practice from biological ecosystem management to learning ecosystems. This might include such things as developing complex systems models of thriving science and engineering learning ecosystems through tools such as game theory and agent-based modeling. These models might offer insights into how to think concretely about specific outcomes, such as learning ecosystem resilience or interactions between ecosystem actors, that might help support more effective interventions and adaptive management.

Ultimately, understanding how to create healthy and resilient learning ecosystems that have lasting impacts will require years of inquiry and engagement with multiple parties. Ideally, there would be opportunities for large, long-term studies like the expansive and multiscale approach seen in the National Science Foundation funded long-term ecological research stations (LTERs) that have been developed for monitoring complex regional biological ecosystems. But the funding landscape has shifted – a major disturbance – making this is an unlikely near-term prospect.

So, how might we continue to advance understanding and implementation of learning ecosystems? Are there more cues and clues from biological systems that we can learn from? In treating learning ecosystems as dynamic, emergent, complex systems we can open space for bolder design and management of learning ecosystems that are ideally able to be more equitable and more resilient.

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