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Key Points:

- Create collaborative opportunities to identify and prioritize community needs, access local knowledge, and engage learners.
- Actively engage communities in geoscience, engineering, technology, and mathematics practices to address local hazards and sustainability challenges.
- Leverage social science research to broaden participation in geoscience and related fields.

Abstract

The geological sciences, technology, engineering, and mathematics (geo-STEM) have the capacity to investigate and address geological and environmental challenges. Many of these challenges are embedded in social contexts that unjustly impact communities that lack geo-STEM expertise. Geo-STEM learning ecosystems (GLEs) integrate geo-STEM and social science research paradigms to transform the culture of the geo-STEM community. GLEs are communities of practice that engage geo-STEM professionals, educators, and learners to address local issues through place-based STEM research and education. In this paper, we evaluate how the term "learning ecosystem" is used in psychology, educational technology, and STEM education research. Characterizing this transdisciplinary social science literature in terms of input, processes and outputs grounds our understanding of GLEs in a century of research and provides a framework to guide the geo-STEM education community in developing GLEs and documenting community change. One distinction between GLEs and other types of learning ecosystems is the importance of place, which connects GLEs to situation learning theory and the community of practice framework. Examples of three existing GLEs are described to demonstrate a variety of structures and functions. Finally, potential research strategies that enable our understanding of GLEs' development, functions, and impacts are proposed. As the geoscience research community seeks to become more just, equitable, diverse, and inclusive, GLEs create opportunities to foster authentic collaborations between geo-STEM practitioners and researchers and the communities in which they work.

Plain Language Summary

More communities must cope with environmental challenges and geologic hazards due to climate and environmental changes. When communities collaborate

with people who have expertise in the geosciences and related engineering, technology, and mathematics fields, these challenges are more effectively addressed. We call such collaborations geo-STEM learning ecosystems. We use findings from psychology, educational technology, and STEM education to explain how collaborations increase community awareness and learning about the capacity of geoscience and related fields to create sustainable and resilient communities. In turn, an increase in awareness inspires broader participation in the geosciences.

Keywords: geo-STEM learning ecosystem, place-based learning, broadening participation, community of practice

1 Introduction

Geosciences play an instrumental role in addressing environmental and geologic challenges. Natural disasters, natural resource unpredictability, and climate change affect communities in complex and disproportionate ways, requiring responses that merge geoscience discoveries with social and political solutions. Investing in creative and flexible collaborations between diverse stakeholders facilitates problem-solving in communities that have been underserved by the geosciences and demonstrates a commitment to community-level skill-building, innovation, and knowledge generation (National Academies of Sciences, Engineering, and Medicine [NASEM], 2016; Committee on STEM Education [CoSTEM], 2013). When stakeholders understand and value geoscience research, science-based solutions are more likely to be implemented (Harris et al., 2021). Community-level interventions have also been shown to broaden participation by connecting the geosciences to cultures and careers at the K-12 level through out-of-school experiences and teacher professional development and creating pathway partnerships between two-year colleges, minority-serving institutions, and other four-year colleges (Karsten, 2019).

However, well-documented obstacles continue to limit the participation and persistence of women, underrepresented minorities, and people with disabilities in STEM fields where inhospitable cultures exacerbate the challenges of a lack of human, financial, and academic support (Baber et al., 2010; Bernard & Cooperdock, 2018; Callahan et al., 2017; Huntoon et al., 2015; Karsten, 2019; O'Connell & Holmes, 2011). Diversity in the geosciences is further challenged by a shortage of secondary teachers trained in the geosciences, causing a lack of exposure and awareness of geo-STEM careers (careers in the fields of geoscience, geo-technology, geological engineering, and geoscience-related mathematics and computational thinking) (Karsten, 2019; Levine et al., 2007). By investing in respectful, empathetic, and sustainable collaborative relationships that map out long-term solutions and career pathways, geo-STEM fields have the potential to broaden participation in our communities (Karsten, 2019).

Ecosystems serve as an analogy for these complex relationships and interactions that foster innovative STEM communities. A community of learners and scientists that work together to solve locally relevant problems can be called a

STEM learning ecosystem. STEM learning ecosystems are communities of practice dedicated specifically to STEM endeavors (Barron, 2006, 2014; Traphagen & Traill, 2014; Vance et al., 2016; Allen et al., 2020; Hecht & Crowley, 2020). Some STEM learning ecosystems focus on children's learning (Traphagen & Traill, 2014), while others engage a variety of community members to solve a local geoscience challenge (Galkiewicz & Pandya, 2014). A geo-STEM learning ecosystem (GLE) engages local communities in sustainable programs that promote geoscience literacy and inspire people to learn the geosciences (Manning, 2020).

GLEs not only connect geoscientists with communities, but also enable the public in learning how to leverage the geosciences to address local challenges. One of the goals of the GLE model is to leverage the social dimensions of an ecosystem to accelerate their impact on both society and the science. Thus far, few studies in the geosciences have interrogated what is meant by a "learning ecosystem" and how the model may be applied in the geosciences. The purpose of this paper is to: (1) review various uses of the term "learning ecosystem", (2) connect the concept of STEM learning ecosystems to the geosciences, (3) describe examples of existing GLEs, and (4) identify potential research strategies that enable our understanding of GLEs' development, functions, and impacts. This transdisciplinary review of psychology, educational technology, and STEM education literature grounds our understanding of GLEs in a century of research and can guide the geoscience education community in developing GLEs and documenting community change.

2 GeoSTEM Learning Ecosystems: A theory-based model for community engagement in geoscience

GeoSTEM learning ecosystems (GLEs) leverage geo-STEM expertise to address local challenges through a variety of community education and outreach collaborations (Manning, 2020). GLEs focus on the domain of geoscience-related sciences, technology, engineering, and mathematics. GLEs engage communities in identifying practical solutions for dealing with environmental change, managing natural resource, and mitigating natural hazards. Because GLEs connect people to the science of the places they live, each GLE will be unique, contextualized for that community and geological-environmental setting. In order to design and build a GLE, there is value in understanding the history of the concept of learning ecosystems.

2.1 Learning as an Ecosystem

The term "learning ecosystem" has been used in a variety of ways to describe various types of learning paradigms, all of which have *inputs*, *outcomes*, and *processes* (Figure 1) (Lewin, 1936; Bronfenbrenner, 1977; Engeström, 1987; Lave & Wenger, 1991; Barron, 2004, 2006; Uden et al., 2007; Sangrà et al., 2012; Kaptelinin & Nardi, 2012; Traphagen & Traill, 2014). "Ecosystem" as an analogy for a learning system appears across the research literature because it includes the notion of feedbacks. For example, in a STEM education learning ecosystem the student learns as a result of the curriculum and the teacher, but there is also a feedback between peers where students can scaffold other students' learning.

The *inputs* in a learning ecosystem are the combination and interactions between the people, places, phenomena, and infrastructure to answer the questions, "Who is learning?" "What are they learning?" "Where are they learning?" "How is learning planned?" and "Who is facilitating and guiding?" (Figure 1.) *Processes* are the actions and strategies that identify, "How are people learning?" and "What strategies facilitate learning?" The *outcomes* determine "What knowledge and skills have peoples learned?" "What expertise have people gained?" "How have people's attitudes and beliefs changed?" and "What new interests or ideas have been inspired?"

There is a long tradition of using the ecosystem analogy in the field of educational psychology. STEM education learning ecosystems were built upon the foundation provided by educational psychology. These usages are distinct from learning ecosystems described in educational technology research communities. Therefore, we include the definition from the field of educational technology to provide clarity. Designers of GLEs should leverage the existing literature on learning ecosystems to build successful and sustainable models. Next, we highlight some of the key findings from three communities: educational psychology, educational technology, and STEM education.

Figure 1. Learning Ecosystems. All learning ecosystems are defined by the inputs listed in the orange oval, processes listed in the blue arrow, and outcomes listed in the green rectangle.

2.1.1 Learning Ecosystems in Educational Psychology

Psychologists were the first to conceptualize learning as an ecosystem (Lewin 1936; Vygotsky, 1978; Leontev, 1978; Bronfenbrenner, 1977). The *inputs* defined in psychology are the learner, their motivations and ideas, and the people and phenomena they encounter; the *processes* are cognition, action, social interactions; and, the *outputs* include conceptual change, gains in understanding and skills, and creativity (Marton, 2014; Illeris, 2018). Although this literature frequently refers to the "learner" or "child", the system level interactions in educational psychology learning ecosystems have practical applications for GLEs. For example, Social Constructivism emphasizes the role of social interactions in the learning process (Vygotsky, 1978). Vygotsky asserted that all learning happened in the context of a learning ecology made up of the cultural norms, employing cultural tools, and leveraging cultural language. Likewise, geoscience learning happens within a cultural context. Therefore, GLEs should include a focus on a given community's cultural norms to incorporate communities' perspectives in the geo-STEM work. Social Constructivism has also served as the foundation for a variety of theoretical models, described below, that position learning as a result of interactions in a learning ecosystem.

Bronfenbrenner's Ecological Systems Theory and Bioecological Model of Development (Bronfenbrenner & Morris, 1998; Bronfenbrenner, 2001a; 2001b; 2005) highlight how the individual, day-to-day experiences, stages in life, and cultural-temporal or generational experiences impact a person and their environment other over the course of a lifetime. In Activity Theory, learning occurs through feedback between the learner and their physical and social environment (Leontev, 1978; Bakhurst, 1988; Engeström, 1987; Wertsch, 1981; 1985; Bellamy, 1995; Krasny & Roth, 2010). The learner is changed through activities that, in turn, change the environment.

The concept of active learning from higher education research can be contextualized through the lens of Activity Theory (Van Horne & Titiek Murniati, 2016; Fredriksen & Hadjerrouit, 2020; Zheng et al., 2020; Tlili et al., 2020). Lombardi and others propose a “construction-of-understanding ecosystem” within which feedbacks occur between the learner, content, instructor, and learner’s peers (Lombardi et al., 2021). In these models of the “learning ecosystem”, the learner is at the center of the ecosystem and learners’ experiences and interactions with domain practices, data, and models yield conceptual understanding.

Situated Learning Theory is the most directly applicable learning theory for GLEs because it focuses on interactions between people and place. It explains how learning depends on engagement with content or phenomenon and the relationship the learner has with: what is being learned, the sense of place, and the people around when they are learning (Lave & Wenger, 1991). Situated Learning merges Activity Theory and the Bioecological Model of Development to explain that learning occurs through legitimate peripheral participation, the process in which novices engage, interact, and collaborate with community experts to gain knowledge and develop skills (Greeno, 1998). Situated Learning includes the historical development of what is being learned. Lave and Wenger emphasize the need to analyze and contextualize both the practice of learning and researchers’ positionality, acknowledging its connection to Critical Theory (Lave & Wenger, 1991). Learning is motivated by the desire to develop a degree of expertise (the *output*) (Wenger & Wenger-Trayner, 2020). Together, the domain, community, and practice create systems that are diverse in form and function, varying in size, geography, lifespan, and intentionality (Wenger, 1998). Much of the learning happens outside of the classroom because of the reciprocal relationships between the learner and the communities to which they belong (Barron, 2006). These reciprocal relationships are called communities of practice (CoPs), and are defined as groups of people who share interests, concerns, or passions and gain expertise by interacting with each other (Allee, 2000; Lave, 1988; Wenger, 1998, 2010). CoPs are defined by the *inputs* of domain (e.g., geoscience) and community, and *practice* as the process by which people interact. Outside of formal learning systems, participation in CoP is a choice that has been shown to improve performance by creating a sense of community and belonging (Eckert, 1989; Linde, 1993). In this way, CoP are learning ecosystems (Wenger, 1998) that enable deeper knowledge and skill gains because the learning is relevant, cohesive, and interactive (Handley et al., 2006; Kriner et al., 2015; Spanierman et al., 2013; Roth & Lee, 2006).

2.1.2 Learning Ecosystems in Educational Technology

Researchers of educational technology use the phrase "learning ecosystem" to describe computer-mediated and virtual learning or e-learning (Uden et al., 2007). Sangrà et al. (2012) define learning ecosystems as a type of Human-Computer Interaction (HCI), with complex interactions between learners, educational technological interfaces, designers, and the cultural contexts of learning and instruction (Carroll, 2012). Educational technology researchers situate e-learning ecosystems and HCI in Activity Theory (Carroll, 1997; Alquete et al., 2013) where human activity is purposeful, mediated, and transformative interaction between people and the world (Kaptelinin & Nardi, 2012). The *inputs* are people or actors (learners, designers, facilitators, managers), technologies (hardware, software, internet, web-based platforms), infrastructural supports that make technologies affordable, accessible, and usable, and financial resources that support the development, adaptation, and adoption of technology (Walcutt & Schatz, 2019; Khan, 2010; Farid et al., 2015; Aguti et al., 2014). The *processes* are the technological modes of delivery, functional design of programs, and purpose of use (e.g., school-based, employee training, informal education). The *outputs* include the knowledge and skills gain as assessed by the technology (Valverde-Berrocoso et al., 2020). It is important to note that actors in e-learning ecosystems function more independently because their learning is an ongoing self-motivated and self-regulated process through which knowledge, beliefs, behaviors, and attitudes change with time (Ambrose et al., 2010). In their review of instructional theories about e-learning ecosystems, Craig and Douglas (2019), emphasize the need to incorporate educational psychology learning theory to extend our understanding of educational technology beyond design, delivery, and evaluation. Because intrinsic motivation drives much of the engagement in HCI and e-learning ecosystems, there is benefit to understanding theoretical frameworks that describe these systems. Most GLEs will include some aspect of HCI to maintain connections between physically distant members of the community, therefore GLE designers can seek best practices from the educational technology literature.

2.1.3. Learning Ecosystems in STEM Education

The origins of STEM learning ecosystems (SLEs) lie in Bronfenbrenner's Ecological Systems Theory (1979) and Bioecological Model (2001), as well as learning ecologies defined by Barron (2004). In their executive summary to the Noyce Foundation, Traphagen and Traill (2014) define SLEs as efforts that:

> "… encompass schools, community settings such as after-school and summer programs, science centers and museums, and informal experiences at home and in a variety of environments that together constitute a rich array of learning opportunities for young people." (Traphagen & Traill, 2014, p.2)

Each SLE is unique, bringing together resources and establishing relationships within the context of the community in which it functions (Barron, 2006). As the SLE evolves, the diversity of organizations and resources (e.g., finances, infrastructure) shift to meet the needs of learners in the ecosystem (Vance et al., 2016). Over time, participants may take on a variety of roles as learners, facilitators, funders, and creators (National Research Council [NRC], 2014). Intersectional collaborations create opportunities to learn new skills or knowledge and to address local issues (Hecht & Crowley, 2020; Penuel et al., 2016). For example, to address a shortage of skilled workers, the Indiana Afterschool Network and Indiana-STEM Resource Network teamed up with agribusiness, manufacturing, and technology companies to create and support school-based internships and dual-credit opportunities (Abrams et al., 2017). In SLEs, learning happens in formal and informal environments and, similar to ecosystems in educational technology, is motivated by curiosity, resulting in more STEM literate communities (Falk et al., 2016). When members develop critical thinking, collaboration, and innovation skills together, a shared STEM identity emerges (Blake et al., 2017).

Traill and Traphagen (2015) outline a logic model for the development and evaluation of SLE. In this model, SLE *inputs* include schools and diverse, out-of-school learning environments. Partnerships with K-12 and business sectors are critical to meaningful SLE work. Leadership is essential for organizing and facilitating sustainable efforts (Vance et al., 2016). Anchoring organizations (also known as backbone organizations) provide that leadership and promote collaborations to develop mutual goals and strategies. Anchoring organizations acquire funding and provide the infrastructure for learning. Examples of anchoring organizations are: community organizations, learning centers, museums, colleges, and universities. Collaborators contribute talent, time, and money but financial support can also come from businesses and industry, philanthropic organizations, and government grants. To promote innovation, social science researchers should be included in the development, implementation, and evaluation of SLEs (Traill & Traphagen, 2015).

In successfully sustained SLE, symbiotic collaborations are critical to facilitate complex *processes*. Traill and Traphagan (2015) assessed SLE Communities of Practice to identify what collaborations were doing successfully. By establishing cross-sector partnerships, SLE cultivate and create structures that enable collaboration and cooperation. Through subsidies and outreach, SLE expand access to STEM-rich learning, connect learning in schools to out-of-school settings where learners can dive deeper into the integrated aspects of STEM, and provide progressive opportunities as learners get older and begin to seek professional opportunities. SLE offer educators opportunities to participate in high-quality and relevant professional development, including research experiences and connections to industry. Educators provide feedback into the SLE to better support youth seeking learning and career pathways. Traill and Traphagen (2015) assert that, when integrated with research, SLE can better identify accessibility barriers and provide timely information young people need to discover and take advantage of opportunities. SLE motivate learners by acknowledging progress along their paths. These *processes* facilitate the *outputs* of SLE (Vance et al, 2016).

SLE have *outputs* that can be grouped as follows: (1) stronger collaborations among and within communities who work together to learn and facilitate STEM learning; (2) increased community-level knowledge, skills, and motivation in STEM domains; and (3) growth and innovation in how the community engages in STEM learning practices (Traill & Traphagen, 2015). By investing in a deeper understanding of STEM concepts, SLE are attempting to create a citizenry with more transferable skills and jobs (Barron, 2014) and a more diverse and flexible workforce (Allen et al., 2020).

2.1.4 Cross-disciplinary themes

Learning ecosystems engage *inputs* (e.g. learners, communities, phenomena) in *processes* (e.g., cognition, behavior, activities) to achieve the desired *outputs* (e.g. collaboration, knowledge generation, conceptual change, skills building, innovation). The interactions between the *inputs, processes,* and *outputs* are summarized in Table 1. For example, in each of domains of educational psychology, educational technology, and STEM education, the learner is an *input* and skill and knowledge gains are an *output.* The components of these ecosystems should be considered when designing GLEs.

Table 1. Summary of the *inputs*, *processes*, and *outputs* of **learning ecosystems** in the domains of Educational Psychology, Educational Technology, and STEM Education.

	Psychology	**Educational Technology**	**STEM Education**
Inputs	Learner Intrinsic ideas and motivations Learner's community Encountered Phenomena	Technology Designers Facilitators/ managers Hardware Software & programs Internet	All learning facilitators Education Researchers Learning environments Business & Industry Funding and Infrastructure

	Psychology	**Educational Technology**	**STEM Education**
Processes	Internal cognition External actions Tools: physical objects, methods, techniques, assessment instruments Social Interactions	Types of Interactions with technology Technology design Technology-driven assessment and feedback Purpose of use (e.g., school-based, employee training, informal education)	Progression of opportunities Community Feedback Inquiry & investigations Apprenticeships Educator professional development Cross-sector Collaborations Educational Research
Outputs	Gained knowledge and skills Creativity Conceptual Change	Technological Innovation	Instructional Innovation STEM-engaged young people and educators Increased community-level motivation in STEM domains Sustainable cross-community collaborations Well-equipped educators Transferable job skills Diverse and flexible workforce

2.2 Leveraging Theory to build GLEs

GLEs emerge from social constructivism, specifically the Bioecological Model (Bronfenbrenner, 1979, 2001a), Activity Theory (Engeström & Miettinen, 1999), and Community of Practice (Wenger, 1998). Complex reciprocal interactions within and between social and physical environments impact both individuals and the environment, resulting in community learning and literacy, and enhancing participation (Bronfenbrenner, 2001b; Lent et al., 2018). This suggests that where learning happens is important to what is being learned and the depth of learning. By engaging in relevant, local problem-solving, learners develop expertise that benefits the whole community.

The focus on community issues mean that place-based education is fundamental to GLE. As described by Sobel (2013, p. 11),

> "Place-based education is the process of using the local community and environment as a starting point to teach concepts in language arts, mathematics, social studies, science, and other subjects across the curriculum. Emphasizing hands-on, real-world learning experiences, this approach to education increases academic achievement, helps students develop stronger ties to their community, enhances students' appreciation for the natural world, and creates a heightened commitment to serving as active contributing citizens. Community validity and environmental quality are improved through the active engagement of local citizens, community organizations, and environmental resources in the life of the school."

Place-based education is motivated by understanding sustainable and regenerative habitation of landscapes, communities, and environment (Semken et al., 2017; Gosselin et al., 2013; Metzger et al., 2017). Place-based education builds on what is familiar to students and educators (Sarkar & Frazier, 2008), connects science to other disciplines and other ways of knowing, and provides local context/relevance to global issues (Coker, 2017). In the geosciences, these local-to-global contextual issues are often "wicked problems", complex challenges for STEM practitioners, social scientists, and policymakers (Rittel & Webber, 1973). GLEs provide a different approach to learning and sustainable solutions when dealing with these wicked problems.

Combining place-based education and problem-based learning inspires novel solutions to local problems through community ownership, multi-disciplinary teamwork, and reflexive communication (Merrill, 2002; Savery & Duffy, 2007). Harkening back to the tenets of Activity Theory (Engeström & Miettinen, 1999), problem-based learning addresses local issues by activating prior knowledge through inclusive discussions and actions. Learners construct knowledge by researching, sharing, and developing possible solutions together (Engeström, 1987; Bellamy, 1995). Experts scaffold learning and assess progress toward proposed solutions (Yew & Schmidt, 2012; Hung, 2011). Problem-based learning requires space and time for collaboration, feedback, and compromise to enact feasible and sustainable solutions.

3 Geo-STEM learning ecosystems as mechanisms for change

As communities of practice that knit together place-based education and problem-based learning, GLE have the potential to transform geo-STEM fields by creating networks that connect novices to experts thereby broadening participation, improving literacy, creating identity, and spawning innovation

(Harris et al., 2022). GLE emerge when a geoscience issue arises and people from the community collaborate with experts to address the issue. The *inputs* are community members and the expertise they bring, and the natural and built environments with which people interact (Figure 3). The community members come from all walks of life and include concerned citizens, students and educators from K-12, informal and higher education, and those who work in government, industry, and philanthropy. Some communities can leverage local geoscience expertise; others may need to seek it from outside. Regardless of where the expertise comes from, GLE are community-led efforts with defined direction and vision, prioritizing accessibility for all. If the interactions between people and their environments are positive, community members may want to expand and sustain those environments to continue to support the health, well-being, and resilience of the community. If human-environment interactions are negative, the community may be seeking ways to regenerate and restore healthy environments through sustainable natural resources management or mitigate and adapt to environments that are changing due to natural or anthropogenic forces. Regardless of the geoscience issues that communities may be dealing with, the priorities of the GLE require stable financial support and reliable infrastructure.

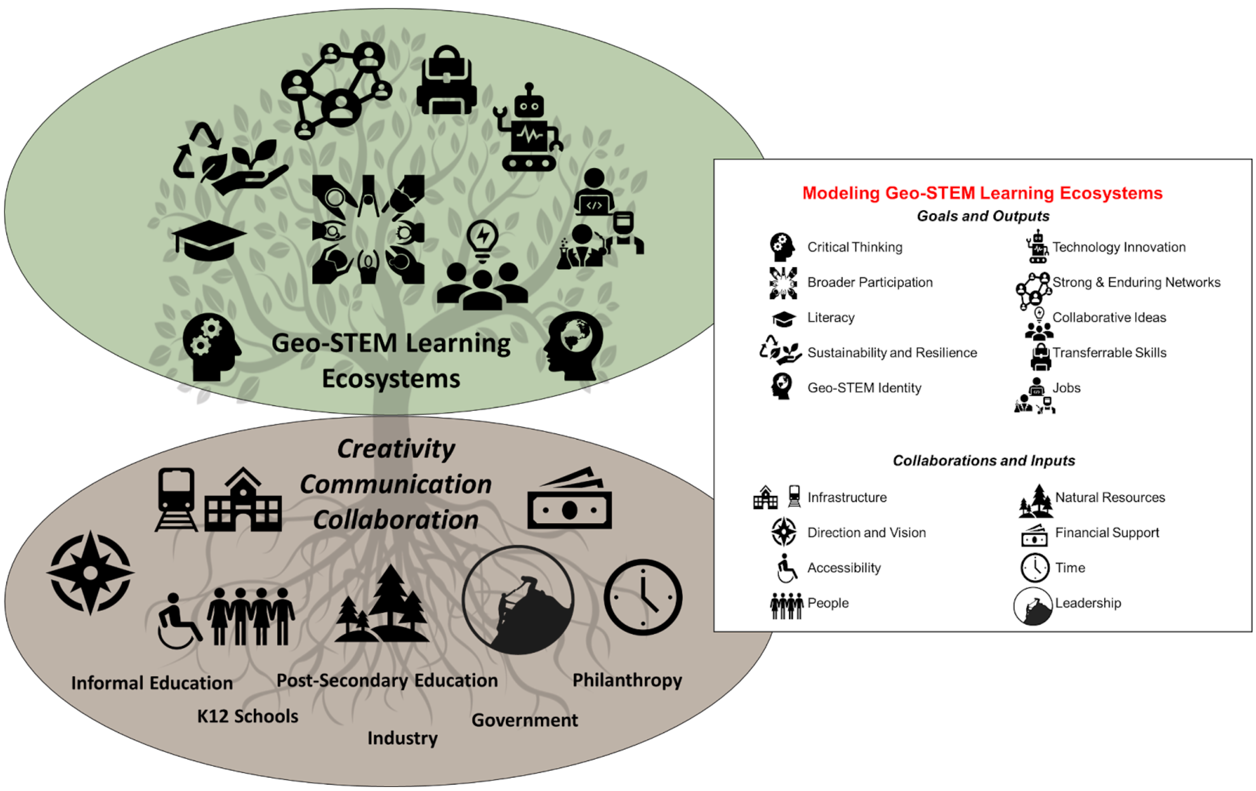

Figure 3. Conceptual Model of Geo-STEM Learning Ecosystems.

Community organizations develop systemic collaborations that engage learners from all walks of life, facilitate enduring and effective geo-STEM learning opportunities, elevate community literacy and innovation, improve networks, and activate sustainable and transformative solutions for the broader community. (Modified from Manning, 2020)

Figure 3 shows the *inputs* that can revitalize the geosciences in communities. To improve community literacy, GLE need sufficient technical infrastructure and expertise to assess and contextualize interactions between human societies and natural systems. Effective networks are the result of the vision and direction of flexible and creative leadership. By guaranteeing financial support to compensate people for their time and efforts, learner engagement and community-level conceptual change can be sustained through time. GLE must demonstrate a strong value for diversity by prioritizing justice, equitability, inclusivity, accessibility, and a culture of belonging to create transformative and regenerative solutions for communities.

While the *inputs* for GLEs are demanding, the *outputs* are transformative. Experiential learning in the geosciences can mitigate existing problems thereby inspiring interest in geoscience related fields (Pugh et al., 2015). GLEs create space and opportunities for innovative collaborations and problem-solving, growing existing networks and creating new ones. These networks have the potential to improve geoscience literacy and critical thinking, especially in young people who participate in problem-based learning where they live (Yew & Schmidt, 2011; Salame et al., 2020). When students work with geoscientists, they are more likely to consider potential of careers geosciences (Papadimitriou, 2014; Pugh et al., 2021). This development of a Geo-STEM identity contributes to efforts in broadening participation in the geosciences (Karsten, 2019; DeFelice et al., 2014). In addition to making the geosciences more diverse and inclusive, the focus on geoscience issues and concerns contributes to increased community sustainability and resilience (Harris et al., 2021). When communities and geoscientists work together, the access to socially and scientifically relevant, place-based data provides opportunities to guide decision-making at all levels (Elliott & Resnik, 2019). Through GLEs, the geosciences empower people to create transformative changes that affect generations of people.

3.1 Examples of Geo-STEM Learning Ecosystems

GLEs already exist in a variety of forms, meeting various community needs through different approaches and at a range of scales. The American Geophysical Union (AGU) Thriving Earth Exchange (TEX), the Global Learning and Observations to Benefit the Environment Program (GLOBE), and the State University of New York (SUNY) Oneonta Earth Science Peer Resource for Improved Teaching (ESPRIT) listserv are three examples of GLEs, each with their own *inputs*, *processes*, and *outputs*. These entities are also communities of practice with distinct domains, communities, and practices (Wenger et al., 2002) that evolved over time and space through collective action. The examples are described to highlight the range of approaches that could be considered a GLE.

3.1.1 American Geophysical Union Thriving Earth Exchange

Launched in 2013, AGU's Thriving Earth Exchange (TEX) has become an award-winning leader in community science (Zhongming et al., 2019). As a GLE, TEX has brought together *inputs* of leadership, financial support, infrastructural and natural resources, people, expertise, and direction and vision. TEX's *processes* are the acts of collaboration, planning and doing science, and developing and enacting solutions. The *outputs* are accessible human systems in which knowledge and solutions are co-created to make communities more sustainable and resilient (Harris et al., 2021). For example, the Gentilly TEX project in New Orleans, Louisiana brought together community leaders, geoscience researchers, and nonprofit media to investigate and address persistent flooding. Through citizen science efforts and community storytelling, the research team worked with community members to create an archive of physical data, social surveys, observations, and visual media. This archive is shared with the community and used to build green infrastructure projects . The TEX program has grown from 3 projects in the U.S. in 2013 to over 150 projects internationally. With the support of government agencies and non-governmental organizations TEX has evolved to become a stable, innovative program that inspired change in communities' perspectives of the value of the geosciences (AGU Thriving Earth Exchange, 2022). While any one TEX project may be short-lived, the on-going accessibility of TEX makes it a valuable resource to communities interested in investing in geo-STEM solutions.

3.1.2 The Global Learning and Observations to Benefit the Environment (GLOBE) Program

The GLOBE Program was founded in 1994 as an opportunity for scientists, formal and informal educators, students, and "citizen-science" enthusiasts to contribute to our understanding of Earth's systems (About GLOBE, Program History, 2022). GLOBE is an international effort promoting collaboration between scientists and communities to inspire students to achieve in science and mathematics. As a GLE, the *inputs* are the people (scientists, developers, researchers, managers, GLOBE trainers, teachers, students, and citizen scientists); the vision and direction, leadership, and time these people dedicate to the GLOBE effort; financial backing by governments, industry, philanthropy, and educational systems; and the physical and technological infrastructures that make data collection and processing possible (GLOBE, 2022). GLOBE's *processes* include the training and protocols used to collect and make sense of the data; collaborations and communications between scientists, researchers, educators, and students; the adaptations of technology to make data collection and analysis more consistent; and the community gatherings that bring people together to celebrate their work. The *outputs* of GLOBE include a strong and enduring collaborative network of scientists and science educators, multiple generations of young people around the globe who have had the chance to develop critical thinking and literacy skill using GLOBE protocols (Butler & MacGregor, 2003; GLOBE, 2022), the growing set of innovative science protocols housed on both the GLOBE website and mobile-device applications, a rich longitudinal global database, and scientific and educational research. The more than 200 million measurements (that have been reported from 125 countries are used by students and scientists conducting original research and are critical to community-level decision-making (GLOBE Impacts & Metrics, 2022). GLOBE has demonstrated positive impacts on student critical thinking, STEM literacy, and data skills (Butler & MacGregor, 2003). The GLOBE program broadens participation in STEM, engaging students in urban communities (Blake et al., 2015; Salame et al., 2020) and very remote communities (Butler & MacGregor, 2003; Huntoon et al., 2005). GLOBE continues to inspire innovations in community science data collection and analysis (Low et al., 2021).

The ongoing commitment of U.S. government agencies (National Aeronautics and Space Administration [NASA], National Oceanic and Atmospheric Administration [NOAA], National Science Foundation [NSF], and Department of State) sustains the GLOBE program so that it can continue to train teachers and support student and citizen scientist data collection. That financial backing has helped to position GLOBE as a GLE. The vision and leadership of the GLOBE Program have leveraged technological innovation to create an evolving infrastructure that is accessible by people around the world. GLOBE designates the time and money needed to train new participants in the use of protocols and equipment and create a well-networked community. While GLOBE engages people in place-based and problem-based learning, teachers report that implementing GLOBE protocols in K-12 classrooms is challenged by time and curricular constraints, administrative and team support, and costs of materials (Butler & MacGregor, 2003). Communities can lose the benefits of GLOBE when the trained teacher or leader leaves. Without long-term prioritization by school leadership, the implementation of GLOBE program protocols can be short-lived (Salame et al., 2020).

3.1.3 The Earth Science Peer Resource for Improved Teaching (ESPRIT) Listserv

Supporting Earth science teachers by creating a strong peer mentoring network was the mission of the 1989 launch of New York's "Earth Science Program – Resource Innovation Team" or ESPRIT. Ebert (2021) describes how ESPRIT was developed to recruit and train Earth science and physics high school teachers through funding from a 10-year Dwight D. Eisenhower Title II Grant. ESPRIT created professional development mentor network internal listservs for planning and communication within mentor groups. Public listservs facilitated interactions between mentors and teachers. When funding ended, the mentoring program dissolved but the public listserv lived on, expanding beyond New York, and resulting in a revised acronym to "Earth Science Peer Resource for Improved Teaching". The ESPRIT listserv is maintained by Earth and Atmospheric Science faculty at the State University of New York, Oneonta.

ESPRIT is a type of GLE with the following *inputs*: established infrastructure and financial support, a vibrant contributing community with varying expertise, an internally defined vision, and of a flat hierarchy. The community is largely self-sustaining and is made up of 2,260 teachers, faculty, researchers, and informal educators who contribute to the listserv; and the practice is the listserv archive and the shared teaching and learning materials (Ebert, 2021). The *processes* include participant listserv discussions around place-based and problem-based instruction, and these are accessible at ESPRIT Archives (ESPRIT, 2022). The ease of participation, low cost, and value of the listserv as an educational and professional development resource has made it the largest and most active SUNY Oneonta science teacher listservs, and one of the largest online Earth science education communities. Based on participants' reports, the *outputs* are collaborative support provided by the listserv, and increased knowledge base, a sense of belonging and identity as an Earth scientist and teacher, and broader participation in the Earth science teaching community. The impacts of the ESPRIT listserv on developing skills, sustainable and resilient solutions, and innovation have not been assessed.

Each of the GLE examples started as funded programs driven by the vision of a small group of collaborators who understood the value of the effort. The vision of TEX is to contribute "to global well-being by supporting communities' awareness and application of science," and promote "equity by ensuring that all communities benefit from the opportunity to participate in, contribute to, and guide the use of scientific knowledge" (About Thriving Earth Exchange, 2022). GLOBE envisions, "A worldwide community of students, teachers, scientists, and citizens working together to better understand, sustain, and improve Earth's environment at local, regional, and global scales" (About GLOBE, 2022). ESPRIT's vision has evolved to be a resource that provides high quality, sustained peer-to-peer Earth science professional development that is available, affordable, and collegial (Ebert, 2021). Further research is needed to understand how different GLEs build and regenerate communities by bringing together unique vision, progressive leadership, and sustained financial supports.

4 Recommendations

The next steps for the geoscience community is to systematically study GLEs and build in assessment so knowledge can be accumulated about what works and for whom. To this end, we present four recommendations: 1. Geoscientists should collaborate with social scientists, 2. Assess across GLEs to better understand the mechanisms that drive successful outcomes, 3. Assess how place influences the GLE, and 4. Leverage existing theoretical lenses through which to assess the GLE.

First, as with any natural ecosystem, each existing and emerging GLE is unique and complex. To develop a systematic theoretical understanding of the potential of GLEs to transform the geosciences and broaden participation, we seek to transcend traditional boundaries by engaging in transdisciplinary research that integrates natural and social sciences. This can be accomplished by examining GLEs and asking new questions in a variety of settings through diverse theoretical lenses, using a variety of methodologies, and documenting evidence of its effectiveness.

Second, GLE research questions may focus on the scale of functions and operations, the complexity of communities and problems, and the feedbacks that grow GLEs, cause them to evolve, or become extinct. Formal assessment of existing and emerging GLEs is needed to determine what factors sustain efforts to inspire geoscience literacy, technology generation, job creation, geo-STEM identity, and broader participation in these cross-sector collaborations.

Third, because GLEs are connected to the places where they are established, studying GLEs in a variety of settings will clarify systems that function effectively and positively impact affected communities. GLEs developed in natural settings will have different visions, leadership, and funding structures than those established in intensively managed landscapes. The GLE setting will also determine the breadth and depth of community involvement (how many people are engaged and how often do they participate and contribute). Differential participation in GLEs in urban, suburban, rural, or mixed communities requires a better understanding of the limitations of accessibility due to infrastructure, technology, and transportation.

Lastly, Theoretical lenses can illuminate the complexities of GLEs and help researchers and practitioners understand GLEs' potential for enduring transformational change. GLEs must be designed mindfully to avoid building ecosystems that remain entrenched in historical contexts with embedded power structures that create and prop up injustice. Table 2 lists and describes how a variety of social science theories may accelerate innovation of and by GLEs.

Table 2. Four possible theoretical lenses through which GLEs might be studied

Change Theory	Reinholz & Andrews, 2020	Build GLEs on what is known about systems and conditions that lead to community-level transformation.
Collective Impact Theory	Kania & Kramer, 2013; Ennis & Tofa, 2020	Propel emergent solutions, address system complexities, and lead to a better understanding of feedbacks that can create or limit the changes that GLEs can create.

Change Theory	Reinholz & Andrews, 2020	Build GLEs on what is known about systems and conditions that lead to community-level transformation.
Critical Theory	Lave & Wenger, 1991; Greenwood, 2013	Reveal structures of power that stem from oppressive colonial ideologies that have undermined communities' connection to place. Use GLEs to restore cultural memories and recover, conserve, transform, and recreate essential interconnections between human and natural system
Environmental Justice Theory	Bullard, 1990 Schlosberg, 2013	Connect theory and practice to understand how disadvantages and vulnerabilities are embedded in built and natural environments, as GLEs connect science and community action to justice and activism.

These recommended theoretical lenses operate within the paradigm of transformative and pragmatic social science research (Creswell & Plano Clark, 2018). Aligning research methodologies with these paradigms supports internal consistency while honoring the complexity of GLEs. Such methodologies include community-based participatory research and social network analysis. Community-based participatory research (Viswanathan et al., 2004; Davis & Ramírez-Andreotta, 2021) occurs when participants are involved in all stages of the research and engage in iterative review of results so the results can inform practice. GLE participants also contribute to publications and data ownership (Ward-Fear et al., 2018). Social network analysis has the potential of revealing how network building within GLEs might nurture interactions that affect the flow of information allowing more effective response to emergent issues, and innovation development (Cross et al., 2006; Quardokus Fisher & Riihimaki, 2021).

5 Why GLEs are the future of the geosciences

In this paper, the analogy of an ecosystem is used to identify inputs, processes, and outputs of geo-STEM learning ecosystems, and how interactions between communities, geo-STEM professionals, and the world in which we live can be transformational. The summary of inputs, processes, and outputs analyzed here provide general guidelines but should not be considered complete. As with all analogies, the strengths and limitations must be explored because it both simplifies and complexifies the proposal of creating learning communities to address geoscience challenges. Understanding a learning ecosystem's boundaries, response to disruptions, feedbacks, and other characteristics can lead to a more inclusive and resilient geo-STEM community.

We have argued that GLEs have the potential to broaden participation in the geosciences by engaging community members and addressing local geo-STEM issues. GLEs can leverage transdisciplinary expertise by including social scientists who examine the socio-scientific challenges presented by societies role in wicked problems of environmental change, pollution, natural hazards, and natural resource management. Leveraging community resources and local knowledge, the geosciences can become more accessible and inclusive to facilitate sustainable and resilient solutions that are local, interesting, and newsworthy. A well-designed GLE shifts the power from a traditional top-down education and outreach model toward non-hierarchical community transformation. GLE recognize differential intellectual, physical, and sociological capacity within communities and invest in transdisciplinary discovery and action. The power of GLE are in the co-creation of knowledge between citizens and geoscientists who together engage in community action research and work toward environmental justice.

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Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

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