Methods for Investigating Geo-Stem Learning Ecosystems: A Case-Study of Illinois Earth Science Teachers

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ABSTRACT

METHODS FOR INVESTIGATING GEO-STEM LEARNING ECOSYSTEMS: A CASE-STUDY OF ILLINOIS EARTH SCIENCE TEACHERS

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Northern Illinois University, 2023
Dr. Nicole D. LaDue, Director

The complex interactions between people and resources in communities that foster innovation can be thought of as ecosystems. These ecosystems have the potential to broaden participation in the geoscience community if we invest in collaborations that map out long-term solutions and career pathways for young community members. Geo-STEM learning ecosystems (GLE) engage local communities in sustainable programs that promote geoscience literacy and inspire people to learn the geosciences. A goal of GLE is to leverage existing social systems and accelerate geo-STEM solutions for society. 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. In this research, an emerging theory of geo-STEM learning ecosystems is outlined and used to guide a mixed-methods case study investigation into Illinois Earth science teachers who are expected to teach Earth science (ES) sustainability concepts in the Next Generation Science Standards (NGSS). However, the shortage of teachers qualified in ES introduces a need for multifaceted support focused on the relationship between humans and the planet.

We used a three-pronged approach to (1) identify the attributes that prepare ES teachers for the NGSS sustainability standards; (2) learn how ES teachers’ experiences, sense of belonging in science, knowledge, and ecological worldview contribute to their instruction; and (3) describe ES teachers’ networks of supports. For phase 1 and 2, 245 self-identified Illinois ES
teachers were surveyed. Illinois is an NGSS-adopting state without a cohesive plan for implementing the Earth and Space Science standards. In phase 1, an evaluation of the survey results found that ES teachers’ content knowledge, ecological worldview and use of place-based strategies were interrelated. To untangle these, we used path analysis in phase 2 and found that teachers’ degree predicted their sense of belonging in science, which affected their content knowledge, worldview, and use of place-based instructional strategies. In phase 3, we interviewed a subset of the surveyed teachers about the networks they rely on for support when teaching ES. To different degrees, teachers rely on networks that include colleagues from schools and previous workplaces; online resources; community, state, and national organizations; and known faculty at colleges and universities.
METHODS FOR INVESTIGATING GEO-STEM LEARNING ECOSYSTEMS:
A CASE-STUDY OF ILLINOIS EARTH SCIENCE TEACHERS

BY

CHERYL L.B. MANNING
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A DISSERTATION SUBMITTED TO THE GRADUATE SCHOOL
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE
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DEPARTMENT OF EARTH, ATMOSPHERE AND ENVIRONMENT

Doctoral Director:
Nicole D. LaDue
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In June 2009, Nicole LaDue and I met at a small conference near Tucson, Arizona. She was an Albert Einstein Distinguished Educator Fellow at NSF-GEO. She struck me as an intelligent educator and passionate geologist. We had so much in common and stayed in touch while she earned her Ph.D. and became a professor at Northern Illinois University. In 2019, I was an Albert Einstein Distinguished Educator Fellow at NSF-GEO. Dr. LaDue stopped by and asked me how I was doing. I told her I was interested in ways to connect Earth science teachers to geoscience researchers and maybe I would write a paper about it. She invited me to work with her. Four and a half years later, I am writing the acknowledgments for my Ph.D. dissertation. Thank you, Dr. Nicole LaDue, for seeing my potential and, amidst a global pandemic, moving heaven and Earth to help me make this dream a reality. With great patience and kindness, you challenged me to become a researcher in my own right. Please know that this degree was made possible by your expertise, guidance, and feedback.

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INTRODUCTION

Geosciences play an instrumental role in addressing environmental and geologic challenges. When stakeholders understand and value geoscience research, science-based solutions are more likely to be implemented. One way to connect scientists and stakeholders is through an ecosystem approach. The metaphor of the learning ecosystem is used to describe how stakeholders with a broad range of experiences (e.g., community members, students) and knowledge (e.g., science experts, teachers) work together to solve locally relevant problems. Few studies in the geosciences have interrogated what is meant by a “learning ecosystem” and how the model may be applied in the geosciences. Although learning ecosystems do not necessarily involve formal K-12 schooling, public education can have an important role in communicating science to communities. In this research, I seek to explore different methods to investigate Geo-STEM learning ecosystems through an in-depth case study of Illinois Earth science teachers.

Chapter 1 outlines a theoretical framework for Geo-STEM Learning Ecosystems (GLEs), which are place-based communities of practice that integrate geo-STEM and social science research paradigms to broaden civic engagement in the geosciences. I examine how the term “learning ecosystem” has been used in psychology, educational technology, and STEM education research, thus grounding GLE in a century of research. I identify the inputs, processes, and outcomes that guide the development of GLEs and provide examples of three existing GLEs to demonstrate the importance of place and the range of structures and functions GLEs serve. One of the goals of the GLE model is to leverage the social dimensions of learning ecosystems to accelerate their impact on society and science. I hypothesize that people will be more inspired to
learn the geosciences if they engage in GLEs that connect communities and geoscience to address local challenges. In the subsequent chapters, I describe a case study investigation of how a GLE may impact Earth science (ES) teachers in Illinois.

Chapter 2 investigates the attributes that predict in-service ES teachers’ readiness to teach the Next Generation Science Standards (NGSS) for sustainability concepts in Illinois, a state that has adopted the NGSS but lacks a cohesive plan to implement the Earth science standards. These standards are more advanced than previous versions and include a focus on complex interactions between humans and Earth’s systems. Other researchers have recognized a gap between what is expected from the NGSS-ESS and teachers’ knowledge and skills, demonstrating that the supply of teachers trained to teach these standards is inadequate. This study examines how in-service teachers’ pedagogical content knowledge may contribute to their readiness to teach NGSS-ESS sustainability content. I assessed the content knowledge, training, worldview, sense of belonging in science, and self-reported use of place-based strategies of 245 Illinois ES teachers with the goal of understanding how future professional development can be designed to meet teachers’ needs.

In Chapter 3, I use path analysis to learn how these 245 Illinois ES teachers’ education and teaching experience affect their sense of belonging in the sciences, knowledge of anthropogenic environmental change, ecological worldview, and use of place-based practices. I hypothesize that when teachers have a strong sense of belonging in the geosciences, they are more likely to invest in further geoscience learning and maintain stronger ecological worldviews, resulting in relevant place-based instruction about local geoscience phenomena. Furthermore, I propose that teachers’ use of place-based instructional strategies and understanding of
sustainability concepts can be supported by the development of GLEs that connect teachers with geoscientists conducting local research.

Chapter 4 describes the professional networks of ten Illinois ES teachers. Semi-structured interviews and social network analysis are used to understand how teachers connect to others and their professional growth sources. Teachers are asked to define their networks at multiple time points, including an activity in a 2021 workshop and two interviews. Teachers are asked to elaborate on the people, organizations, and resources they interact with when they have questions about the ES that they teach. Social network analysis is used to capture the structures of teachers’ networks. Combining both data sources will provide information about how teachers access their networks, what they value, and the support that they wish they had. The interviews and social network analysis results can inform the development of a GLE for ES teachers in Illinois.
CHAPTER 1: GEO-STEM LEARNING ECOSYSTEMS: A TRANSDISCIPLINARY THEORY-BASED FRAMEWORK TO ESTABLISH AND ENGAGE COMMUNITIES IN THE GEOSCIENCES

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, 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, geotechnology, 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).

One way to enact this type of relationship is through a STEM learning ecosystem.

The complex interactions between people and resources in communities that foster STEM innovation may be thought of as an ecosystem. There are several examples in the literature describing STEM learning ecosystems (Allen et al., 2020; Barron, 2006, 2014; Hecht & Crowley, 2020; Traphagen & Traill, 2014; Vance et al., 2016). Generally, the metaphor is used to describe how stakeholders with a broad range of experiences (e.g., community members, students) and knowledge (e.g., science experts, teachers) work together to solve locally relevant problems. Some researchers apply the STEM learning ecosystem metaphor when describing children’s learning (Traphagen & Traill, 2014), while others use the metaphor to describe how to engage a variety of community members to solve a local geoscience challenges (Galkiewicz & Pandya, 2014).
Hypothesis

Our hypothesis is that geo-STEM learning ecosystems (GLEs) engage 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.

Research Design & Methods

In this paper we outline an emerging theory of geo-STEM learning ecosystems by (1) reviewing various uses of the term “learning ecosystem”, (2) identifying connections between the concept of STEM learning ecosystems and the geosciences, (3) describing and evaluating examples of existing GLEs, and (4) identifying 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.

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 resources, and mitigating natural hazards. Because GLEs connect people to the science of the places they live, each GLE will be unique, and 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.

Results

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.
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 outcomes 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 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, 2001; 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 & 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 outcome) (Wenger-Trayner & 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).

**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 outcomes 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.

**Learning Ecosystems in STEM Education.** The origins of STEM learning ecosystems (SLE) 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 SLE 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 Traphagen (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 *outcomes* of SLE (Vance et al, 2016).

SLE have *outcomes* 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).

**Cross-Disciplinary Themes.** Learning ecosystems engage *inputs* (e.g., learners, communities, phenomena) in *processes* (e.g., cognition, behavior, activities) to achieve the
desired outcomes (e.g., collaboration, knowledge generation, conceptual change, skills building, innovation). The interactions between the inputs, processes, and outcomes 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 gains in skill and knowledge are outcomes. The components of these ecosystems should be considered when designing GLEs.

**Leveraging Theory to build GLEs**

GLEs emerge from social constructivism, specifically the Bioecological Model (Bronfenbrenner, 1979, 2001), 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, 2001; 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 means that place-based education is fundamental to GLEs. As described by Sobel:

“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.” Sobel (2013, p. 11)
### Table 1

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

<table>
<thead>
<tr>
<th></th>
<th>Psychology</th>
<th>Educational Technology</th>
<th>STEM Education</th>
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<tbody>
<tr>
<td><strong>Inputs</strong></td>
<td>Learner</td>
<td>Learner</td>
<td>Learner</td>
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<tr>
<td></td>
<td>Intrinsic ideas and motivations</td>
<td>Technology Designers</td>
<td>All learning facilitators</td>
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<td></td>
<td>Learner’s community</td>
<td>Facilitators/ managers</td>
<td>Education Researchers</td>
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<td></td>
<td>Encountered Phenomena</td>
<td>Hardware</td>
<td>Learning environments</td>
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<td>Software &amp; programs</td>
<td>Business &amp; Industry</td>
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<td></td>
<td></td>
<td>Internet</td>
<td>Funding and Infrastructure</td>
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<tr>
<td><strong>Processes</strong></td>
<td>Internal cognition</td>
<td>Types of Interactions with technology</td>
<td>Progression of opportunities</td>
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<td></td>
<td>External actions</td>
<td>Technology design</td>
<td>Community Feedback</td>
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<tr>
<td></td>
<td>Tools: physical objects, methods, techniques,</td>
<td>Technology-driven assessment and feedback</td>
<td>Inquiry &amp; investigations</td>
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<tr>
<td></td>
<td>assessment instruments</td>
<td>Purpose of use (e.g., school-based, employee</td>
<td>Apprenticeships</td>
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<td></td>
<td>Social Interactions</td>
<td>training, informal education)</td>
<td>Education Researchers</td>
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<td></td>
<td></td>
<td></td>
<td>Learning environments</td>
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<tr>
<td><strong>Outcomes</strong></td>
<td>Creativity</td>
<td>Technological Innovation</td>
<td>Instructional Innovation</td>
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<td></td>
<td>Conceptual Change</td>
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<td>STEM-engaged young people and educators</td>
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<td>Increased community-level motivation in STEM domains</td>
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<td>Sustainable cross-community collaborations</td>
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<td>Well-equipped educators</td>
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<td>Transferable job skills</td>
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<td>Diverse and flexible workforce</td>
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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.

**Geo-STEM Learning Ecosystems as Mechanisms for Change.** As communities of practice that knit together place-based education and problem-based learning, GLEs 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., 2021). GLEs 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 2).

Figure 2. Conceptual Model of Geo-STEM Learning Ecosystems. Collaborations and inputs are shown in the brown oval over the tree roots and listed at the bottom of the legend. Goals and outputs are shown in the green oval and listed at the top of the legends. (Modified from Manning, 2020)

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, GLEs 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 a GLE requires stable financial support and reliable infrastructure.

Figure 2 shows the inputs that can revitalize the geosciences in communities. To improve community literacy, GLEs 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. GLEs 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 outcomes 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, 2012;
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.

**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 outcomes. 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.

**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 outcomes 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.

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 outcomes 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).

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 outcomes 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.

**Discussion**

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.

The next steps for the geoscience community are 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 GLEs, and 4. Leverage existing theoretical lenses through which to assess GLEs.

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>
<thead>
<tr>
<th>Change Theory</th>
<th>Reinholz &amp; Andrews, 2020</th>
<th>Build GLEs on what is known about systems and conditions that lead to community-level transformation.</th>
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</thead>
<tbody>
<tr>
<td>Collective Impact Theory</td>
<td>Kania &amp; Kramer, 2013; Ennis &amp; Tofa, 2020</td>
<td>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.</td>
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<tr>
<td>Critical Theory</td>
<td>Lave &amp; Wenger, 1991; Greenwood, 2013</td>
<td>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</td>
</tr>
<tr>
<td>Environmental Justice Theory</td>
<td>Bullard, 1993 Schlosberg, 2013</td>
<td>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.</td>
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Table 2
Possible theoretical lenses to study GLEs.
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., 2020). Social network analysis has the potential to reveal how network building within GLEs might nurture interactions that affect the flow of information allowing more effective responses to emergent issues, and innovation development (Cross et al., 2006; Quardokus Fisher & Riihimaki, 2021).

**Implications: Why GLEs are the Future of the Geosciences**

In this paper, the analogy of an ecosystem is used to identify inputs, processes, and outcomes 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 outcomes analyzed here provides general guidelines but should not be considered complete. As with all analogies, the strengths and limitations must be explored because they both simplify and complexify 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. GLEs recognize differential intellectual, physical, and sociological capacity within communities and invest in transdisciplinary discovery and action. The power of GLEs is in the co-creation of knowledge between citizens and geoscientists who together engage in community action research and work toward environmental justice.
CHAPTER 2: WHAT ATTRIBUTES PREPARE TEACHERS FOR THE NGSS
SUSTAINABILITY STANDARDS: A CASE STUDY OF
ILLINOIS EARTH SCIENCE EDUCATORS

Introduction

Science education reform has changed how science teachers are trained (Morrell et al., 2020). In the last three decades, two major efforts have shifted the focus of science teachers’ work. The first was the development of the National Science Education Standards (NSES) (National Research Council [NRC], 1996) in response to the 1983 *A Nation at Risk Report* (National Commission on Excellence in Education, 1983). In conjunction with the American Association for the Advancement of Science’s Project 2061 (American Association for the Advancement of Science, 1994), the National Committee on Science Education Standards and Assessment created standards that defined the science knowledge, understanding, and skills that all students should have (NRC, 1996). The NSES presented a “vision of a scientifically literate populace” (NRC, 1996, p. 2) facilitated by teachers empowered to make pedagogical decisions for effective learning. NSES impacted teacher training by emphasizing the importance of students’ prior knowledge, promoting science inquiry, and shifting toward student-centered learning.

In the years following, advancements in both science and science education identified emerging gaps in the NSES (NRC, 2012), leading to the development of *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas* (Framework) (NRC,
The Framework outlines three dimensions of learning: Science and Engineering Practices (SEP), Crosscutting Concepts (CC), and Disciplinary Core Ideas (DCI). These grounded the creation of the Next Generation Science Standards (NGSS) in both science and science education research (NGSS Lead States, 2013). The NGSS organized SEP, CC, and DCI in learning progressions designed to better prepare students for careers in a rapidly changing world. At the time of this writing, twenty states and the District of Columbia have fully adopted the NGSS affecting more than 36% of American students. Another twenty-eight states have developed standards based on the recommendations of the Framework affecting 55% of American students (NSTA, 2023). Therefore, the Framework and NGSS affect approximately 91% of American students.

One of the most significant changes presented by the NGSS is the emphasis on the Earth and Space sciences (ESS) (NGSS Lead States, 2013), which make up one-third of the standards. ESS standards are more advanced than those presented in the NSES and include a focus on complex interactions among Earth systems and the pressures that humans place on these systems (Wysession, 2014). Researchers recognized there was likely to be a gap between teachers’ existing knowledge and skills and what was needed to teach NGSS-ESS. Prior to entering the classroom, many science teachers did not have the opportunity to learn Earth science (ES) content, how it connects with other science disciplines, or how Earth scientists conduct their research (Egger et al., 2017; NASEM, 2015). While it is not entirely clear how prepared teachers are to teach ES, a 2015 report on science teachers’ learning by the National Academy of Science, Engineering, Mathematics and Medicine states that 35-62.5% of ES teachers are certified to teach ES; however, Wilson (2018) reports that only 3% of secondary STEM teachers have
degrees in ES. Both are possible since many states certify teachers to teach all science topics with one license, regardless of degrees earned.

To address sustainability as it is presented in the NGSS, Earth Science (ES) teachers need a deep understanding of Earth systems science including interactions between natural and human systems (Metzger et al., 2017). Many teachers may not have received formal training in the sustainability of human and natural systems as addressed in the NGSS, especially Earth Systems (NGSS-ESS2) and Earth and Human Activity (NGSS-ESS3) (NGSS Lead States, 2013). Research has shown that secondary ES teachers are not well prepared to teach these standards. There is a gap between the coursework available to preservice teachers and the expectations of the NGSS-ESS (Egger et al., 2017). In a federally funded survey of secondary science teachers in the United States, Banilower and others (2012) found that only 28% of secondary ES teachers had taken more than three ES courses, less than half of these felt “very well prepared” to teach Earth and space science concepts, and only 39% considered themselves “very well prepared” to teach about climate and weather.

Other research has shown that teacher professional development significantly impacts those who seek it out. A national survey conducted by Sullivan and others (2014) suggested that teachers who participate in content-focused professional development were more likely to feel confident in their abilities to teach about anthropogenic climate change and develop effective instructional practices. However, content knowledge is only one component critical to the teaching of ES (Lewis, 2008). For teachers to engage students in all three NGSS dimensions of learning, teacher training and professional development are essential (Morrell et al., 2020; Penuel et al., 2015; Wysession, 2014). New teachers need extensive training and current teachers need professional development to acquire a deeper understanding of the SEP, CC, and DCI, as
well as strategies to transition curriculum and concrete methods for implementation (Harris et al., 2017; Toolin et al., 2021). This includes the incorporation of local examples and local data in ES instruction for all grade bands (K-5, 6-8, and 9-12) (NGSS Lead States, 2013). Where the implementation of NGSS-ESS instruction has been intentional, educators who participated in long-term, three-dimensional professional development opportunities acquired a more complete understanding of the complexities of sustainability and environmental science issues and were more likely to focus on these issues in their classrooms (Hayes et al., 2019).

For those teachers who do not participate in professional development or are teaching in places where NGSS has not been implemented with intention, we do not know the state of their knowledge or confidence in teaching sustainability topics (Egger et al., 2017; Hayes et al., 2019; Metzger et al., 2017; Sullivan et al., 2014). Therefore, in the context of the widespread adoption of NGSS, and studies that suggest teachers are under-prepared (Banilower et al., 2012; Egger et al., 2017; Wilson, 2018), we investigated in-service ES teachers’ readiness to teach NGSS sustainability concepts in an NGSS-adopting state that lacks a cohesive plan to implement NGSS-ESS. This study identifies which characteristics (e.g., grade level, number of ES credits) are associated with adequate content knowledge and teachers’ use of place-based strategies when implementing NGSS ESS sustainability content in their classrooms. While many studies demonstrate that there is an inadequate supply of trained teachers, this study (1) provides data about the readiness of in-service teachers who are teaching ES sustainability concepts and (2) creates a foundation upon which future professional development can be built to address teachers’ needs.
**Theoretical Framework**

Given the importance of the practices and knowledge necessary to teach NGSS, we selected the Pedagogical Content Knowledge (PCK) framework developed by Gess-Newsome (1999) to describe teachers’ readiness to teach ES sustainability topics. Gess-Newsome describes PCK as the blend of teachers’ knowledge of the content, teaching practices, and student learning. PCK goes beyond knowledge of a particular domain of science content and includes how one represents and solves problems in a domain.

In a recent international effort, science education researchers came together to create the Refined Consensus Model of Pedagogical Content Knowledge (Figure 3) (Carlson et al., 2019). In this model, PCK is represented by a multifaceted and layered conglomerate of knowledge, skills, and experiences that contribute to a teacher’s practices that affect student outcomes. There are five layers in the refined model, three of which are different aspects of PCK. The innermost enacted PCK (ePCK) to personal PCK (pPCK) exist within the Learning Context and include the teacher and their students. Beyond the Learning Context, the collective PCK (cPCK) encompasses the topics and concepts, skills and practices, and ways of thinking unique to a discipline held by the teacher and other educational professionals. The collective PCK resides within and is informed by Professional Knowledge Bases including the science research community, educational research community, psychology, and sociology.

Enacted PCK is the knowledge and skill set that a teacher uses to support student outcomes in a particular setting (Gess-Newsome, 2015). From instructional planning and implementation to assessment and reflection, enacted PCK mirrors the context of learning for students, the classroom, and the school.
Personal PCK is the personal knowledge and expertise that a teacher has in a subject area and are the result of the teacher’s experiences with students and others (Gess-Newsome, 2015). Personal PCK also includes the teacher’s beliefs and attitudes that filter or amplify what the teacher brings to the learning environment (Magnusson et al., 1999).

Personal PCK exists within the Learning Context, which includes factors that define and mediate learning. Learning Context includes government policies, educational standards, state and district controls, the school, classroom, and student attributes (e.g., grade level, life
experiences, language, culture) that mediate learning outcomes (Berry et al., 2016). The Learning Context connects the personal PCK to the collective PCK.

Collective PCK is the continuum of dynamic public knowledge maintained by and shared in a community of educators and researchers (Shulman, 1986). Within a particular discipline, collective PCK includes the topics and concepts, skills and practices, and ways of thinking that are unique to how a particular subject matter is being taught to a particular group of students.

Beyond the collective PCK lie the Professional Knowledge Bases, the complex combination of knowledge of content, pedagogy, students, curriculum, and assessment that define teaching (Carlson et al., 2019). The Professional Knowledge Bases connect teachers to academic disciplines, pedagogical theory, child psychology and sociology, curriculum design, and assessment methodologies.

By connecting collective and professional knowledge to a teacher’s personal enactment of pedagogical practice, the Refined Consensus Model of PCK encourages researchers to situate studies in the different realms of the model (Carlson et al., 2019). The model does not specify how to strengthen teachers’ PCK, but it does create a structure to study the relationships between the PCK categories.

The research presented here can be analyzed through the lens of the Refined Consensus Model of PCK (Figure 4). To understand Illinois ES teachers’ readiness, we focused primarily on their personal PCK by assessing their content knowledge of anthropogenic environmental change (Libarkin et al., 2018; Soltis et al., 2021), ecological worldview (Dunlap et al., 2000), sense of belonging in science (Feser, 2020), and their ES training (degree and number of ES credits). We asked ES teachers to self-report their use of local examples and local data sets to encourage
What attributes predict Illinois Earth science teachers’ personal and enacted pedagogical content knowledge when teaching NGSS sustainability content?

Figure 4. Model of this research through the lens of the Refined Consensus Model of PCK. Measured variables are shown in light gray. The analyzed variables are outlined in black. *Teachers self-reported their use of Place-based strategies.

students to learn sustainability science in the context of where they live and consider this a proxy for enacted PCK. Their learning context includes the type of courses in which ES is taught, the type of school, grade level, and the NGSS. The NGSS have been adopted by the state of Illinois but there is no cohesive plan for the implementation of NGSS-ESS. Although not measured for this study, collective PCK is embedded within the NGSS, where the topics and concepts are the Disciplinary Core Ideas, skills and practices are the Science and Engineering Practices, and ways of thinking are the Crosscutting Concepts. Also, beyond the scope of this study, the Professional Knowledge Bases include the following: (1) the science of sustainability and anthropogenic environmental change, (2) the research on pedagogy of place, (3) the theoretical and practical
understanding of the psychology of students and the culture of their communities, and (4) the research basis of the NGSS curriculum design, implementation, and assessment.

Placing our research within this framework gives us the opportunity to explore how different types of PCK may contribute to readiness to teach the complexities of sustainability science presented in the NGSS. By examining ES teachers’ instructional context, training, academic knowledge, practices, beliefs, and perspectives, we may be able to identify how these components of an ES teacher's PCK come together to support their work.

Our primary research question is, “What attributes predict Illinois ES teachers’ personal and enacted pedagogical content knowledge when teaching NGSS sustainability content?” We break this question down and explore the following:

- What are the attributes of teachers who have content knowledge sufficient to support teaching NGSS sustainability?
- What are the attributes of teachers who have worldviews that support teaching NGSS sustainability?
- What are the attributes of teachers who have a strong sense of belonging in the sciences?
- What are the attributes of teachers who report using place-based strategies to teach sustainability as described by NGSS?

We hypothesize that to teach NGSS sustainability concepts, 1) teachers’ enacted PCK includes their use of place-based strategies to make ES sustainability content relevant (Lewis, 2008); and 2) teachers’ personal PCK includes valuing the ES discipline (Orion & Libarkin, 2014), understanding anthropogenic environmental change concepts (Egger et al., 2017; Hayes et al., 2019; Metzger et al., 2017; Sullivan et al., 2014), maintaining a positive ecological
worldview (Arcury et al., 1986; Cobern, 2000; Lwo et al., 2017), and having a strong sense of belonging in science (Balgopal et al., 2022; Feser, 2021).

Methods

The research presented here is a quantitative descriptive analysis in which we sought to explore ES teachers’ training, experiences, belonging, worldview, content knowledge, and practices related to their teaching of sustainability concepts presented in the NGSS. Here we present the results of a survey designed for and distributed to ES teachers in Illinois, a midwestern U.S. state (Appendix A).

Data Collection

The survey was administered online, and the survey link was available to anyone with the URL. We distributed the survey to teachers around the state through recruitment postings on state-wide email lists (e.g., Illinois P-20 Center newsletter), professional societies (e.g., National Earth Science Teachers’ Association), and social media platforms (e.g., Facebook Groups). In a separate linked survey, teachers could share their email to receive a survey incentive. The first 200 respondents who completed the survey received a ten-dollar gift card. Our sampling methods resulted in a nonrandom convenience sample in which we likely oversampled educators with degrees in the Earth sciences.

Survey Design

The survey instrument consisted of 60 questions with a combination of open-ended, multiple-choice, and 5-point Likert scale questions. Skip logic facilitated customized survey flow
depending on individual responses. The survey was composed of seven sections in the following order: (1) teachers’ experience learning and teaching ES, (2) teachers’ use of place-based instructional strategies, (3) teachers’ ecological worldview (Dunlap et al., 2000), (4) teachers’ knowledge of anthropogenic environmental change (Libarkin et al., 2018; Soltis, 2020), (5) teachers’ sense of belonging in the scientific community (Feser, 2020), (6) teachers’ funds of knowledge, and (7) teachers’ demography. Except for teachers’ funds of knowledge, these survey components were analyzed for this study and are described below.

**Teacher Context & Experience.** Effective ES instruction depends on teachers’ abilities to translate current science into lessons and activities for student learning (Harris et al., 2017). We asked teachers four multiple-choice questions to better understand the foundation of their personal PCK, specifically the discipline of their college degrees and the number of ES credits they had earned. Five multiple-choice questions were asked about the Learning Context in which they teach: if they have taught ES in the last 3 years and/or will teach ES in the upcoming year, the grade level they teach, type of course (stand-alone, integrated, mandatory, elective, dual/college credit), and type of school (public, charter, magnet, or private).

**Place-based Strategies.** The NGSS explicitly states that all students should be interacting with local phenomena when studying Earth’s Systems (NGSS-ESS2) and Earth and Human Activity (NGSS-ESS3). Specifically, the NGSS Science and Engineering Practices ask students to (1) gather and analyze relevant local geoscience data to understand local conditions, (2) make claims about local human impacts on natural systems, (3) evaluate efforts to address those impacts, and (4) design sustainable solutions for local challenges (NGSS Lead States, 2013). Because these types of activities are grounded in the teacher’s knowledge and skills that support student outcomes, we classify the use of Place-based strategies as enacted PCK.
To learn how teachers use local ES phenomena in their course design, we developed three 5-point Likert-scale questions. Responses ranged from strongly disagree to strongly agree with a midpoint value of neither agree nor disagree. The questions were (1) Earth science is relevant to my students, (2) I use state-specific examples when teaching Earth science, and (3) My students collect and/or analyze state-specific Earth science data. The values reported here are averaged out of 5. The Cronbach alpha for these three items was $\alpha = 0.71$ is acceptable for exploratory research (Konting et al., 2009).

**Worldview.** We used the New Ecological Paradigm Scale, Revised by Dunlap and others (2000) to assess teachers’ ecological worldview, a component of teachers’ personal PCK. This five-factor, 15-item, 5-point Likert-scale instrument has been tested internationally to study populations’ sustainable worldviews, attitudes, and beliefs with Cronbach alpha values ranging from 0.73-0.86 (Dunlap et al., 2000; Harraway et al., 2012; Gomera et al., 2013; Reyna et al., 2018; Sanchez-Dominguez et al., 2021). The instrument is considered internally consistent (Arcury, 1990; Arcury et al., 1986; Bernstein, 2020) tapping into a wide range of worldview facets and offering a balance of positively and negatively worded items. We administered all five factors to assess teachers’ perspectives about: (1) the possibility of an ecological crisis, (2) rejecting the idea that humans are exempt from the impacts of an ecological crisis, (3) accepting that the balance of nature is fragile, (4) rejecting the idea that humankind is the central or most important element of the universe, and (5) the reality that there are limits to the growth of human civilization. Following Dunlap and others (2000), we averaged the factors. The reliability of the items ($\alpha = 0.740$) is acceptable for exploratory research (Konting et al., 2009).

**Content Knowledge.** To assess teachers’ content knowledge of anthropogenic environmental change (personal PCK), we selected eighteen multiple-choice questions from
existing instruments previously used with U.S. undergraduates. Thirteen questions were included from the Climate Change Concept Inventory (Libarkin et al., 2018) and assessed teachers’ understanding of greenhouse gas compositions, processes, and functions in recent atmospheric temperature changes. Five questions from the Biogeochemical Cycles & the Earth System Concept Inventory (Soltis et al., 2021) assessed teachers’ understanding of the carbon, nitrogen, and phosphorus cycles, all of which have been disrupted by human behaviors (Rockström et al., 2009; Kumar et al., 2018). Each question was worth one point, with a maximum score of 18 on this content knowledge measure.

**Belonging.** To evaluate teachers’ sense of belonging in the science community, another component of personal PCK, we modified a scale developed to assess teachers’ sense of belonging in science (Feser, 2020). The original instrument is a 5-factor scale with 21 5-point Likert scale questions. In this study, items were merged and modified to simplify language and minimize participant fatigue, resulting in 5 questions measuring (1) sense of connectedness, (2) feeling of recognition, (3) sense of contribution to science, (4) feeling of well-being, and (5) sense that scientists are trustworthy. The Likert scale items were averaged. The reliability of the 5 questions ($\alpha = 0.712$) is within the acceptable range for exploratory research (Konting et al., 2009) and comparable to Feser’s preliminary results $\alpha = 0.72$ (Feser, 2020).

**Demographic Information.** Demographic questions were placed at the end of the survey to reduce stereotype threat (Teclaw et al., 2011). Following the recommendations of Fernandez and others (2016), we asked multiple choice questions inquiring about teachers’ age range, gender identity, and racial and ethnic identities. Gender and racial/ethnic identity questions included short text response options. These variables are reported to provide a description of the study sample but were not analyzed as they were not the focus of the research questions.
Data Analysis

Survey data were collected using Qualtrics software (Qualtrics, Provo, UT) with IP addresses retained. Survey responses were removed if they were incomplete, redundant, came from outside of the region, or did not pass the filter questions (one text response and one multiple-choice response).

Using IBM®-SPSS Statistics for Macintosh (v. 29.0), missing values were specified, variable types were classified and described, and correlation tables were generated. The variables (i.e., parameters) were all treated as continuous variables and include teachers’ college degrees, the number of ES credits earned, the grade level at which they teach ES, their self-reported use of place-based instructional strategies, and teachers’ scores on content knowledge, worldview, and belonging measures. Because school and course types were categorical variables, they were described but not included in statistical analysis.

Given the number of variables assessed, we evaluated response outliers as those beyond 2 standard deviations on the content knowledge scale. Because all outliers were evenly distributed between the different grade levels, we decided to not remove them. We removed responses from teachers who taught multiple grade levels to prevent counting 15 individual responses multiple times. The final sample included 245 responses. To describe the teachers’ experience and responses to survey items, graphical analyses were conducted using SPSS version 29 for Mac, Microsoft Excel version 16.75.2 for Mac, and BioVinci version 3.0.9 for Mac.
Results

The sample is composed of responses from 245 self-identifying Earth science (ES) teachers from the state of Illinois. The geographic distribution of survey participants was generated using the zip codes of the school where they self-reported they currently taught (Figure 5).

Figure 5. Map showing the distributions of the surveyed teachers’ schools.
**Teacher Context & Experience**

Table 3 shows the demographics and professional experience of the surveyed Illinois ES teachers separated by degree. On the survey, ninety-one teachers indicated that they did not have science degrees and were binned into the “Non-science” degree group. If they did have a science degree, they selected their degree from a list (Astronomy, Atmospheric Science, Biology, Chemistry, Geology, Oceanography, Physical Geography, Physics) and they could select “Other” and describe their degree. Eighty-seven teachers were binned into the ES Major indicating that they had earned degrees in Astronomy (n=2), Atmospheric Science (n=19), Environmental Science (n=1), Geology (n=14), or Physical Geography (n=51). Thirty-one teachers indicated that they had earned minors in ES and were binned into the “ES Minor” category. The “Other Science” category was made up of 36 teachers, indicating that they had earned degrees in Biology (n=15), Marine Biology (n=2), Chemistry (n=6), Physics (n=3), and 10 indicated that they had general science (n=4) or science education (n=6) degrees.

Demographically, the majority of the teachers were white (83%), male (60%) between the ages of 36-45 years (53%). The largest proportion of teachers taught grades 9-12 (47%, n=116), while 35% (n=86) taught grades 6-8 and 18% (n=43) taught grades K-5. The majority of teachers worked at traditional public schools (60%, n=148), 16% (n=39) taught at public magnet schools, 12% (n=30) taught at private schools, and 11% (n=28) at public charter schools. One of the survey access questions asked them if they taught ES currently or in the past three years. Therefore, the majority reported that they taught ES in the previous three years (71% (n=173), 21% (n=52) reported they would be teaching ES in the subsequent year, and 8% (n=20) taught ES in the previous three years and would be teaching ES in the subsequent year.
### Table 3

**Sociodemographic and Experience of ES Teachers in Illinois separated by degree.**

<table>
<thead>
<tr>
<th>Teacher Characteristics</th>
<th>Nonscience (n=91)</th>
<th>Other Science (n=36)</th>
<th>ES Minor (n=31)</th>
<th>ES Major (n=87)</th>
<th>Full Sample (N=245)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n</td>
<td>%</td>
<td>n</td>
<td>%</td>
<td>n</td>
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<tr>
<td>20-25</td>
<td>2</td>
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<tr>
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<td>47.2</td>
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</tr>
<tr>
<td>36-45</td>
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<td>46.2</td>
<td>18</td>
<td>50.0</td>
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<td>46-55</td>
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<td>2.8</td>
<td>6</td>
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<td>24</td>
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<td>20</td>
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<tr>
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<td>42.8</td>
<td>11</td>
<td>30.6</td>
<td>11</td>
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<td>2</td>
<td>5.6</td>
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<td>76</td>
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<td>61.1</td>
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<td>&gt; 1 of these</td>
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<td>2.2</td>
<td>5</td>
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<td></td>
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<td>Taught last 3 yrs</td>
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<td>63.7</td>
<td>25</td>
<td>69.4</td>
<td>22</td>
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<tr>
<td>Will teach next yr</td>
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<td>29.7</td>
<td>8</td>
<td>22.2</td>
<td>5</td>
</tr>
<tr>
<td>Both</td>
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<td>6.6</td>
<td>3</td>
<td>8.3</td>
<td>4</td>
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<td>70.3</td>
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<td>33.0</td>
<td>20</td>
<td>55.5</td>
<td>10</td>
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<tr>
<td>Integrated</td>
<td>23</td>
<td>25.2</td>
<td>3</td>
<td>8.3</td>
<td>1</td>
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<td>11</td>
<td>12.1</td>
<td>1</td>
<td>2.8</td>
<td>3</td>
</tr>
<tr>
<td>Elective</td>
<td>10</td>
<td>11.0</td>
<td>2</td>
<td>5.6</td>
<td>5</td>
</tr>
<tr>
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<td>1.1</td>
<td>0</td>
<td>0.0</td>
<td>2</td>
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<tr>
<td>&gt; 1 of these</td>
<td>16</td>
<td>17.6</td>
<td>10</td>
<td>27.8</td>
<td>10</td>
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<tr>
<td>K-5</td>
<td>23</td>
<td>25.2</td>
<td>3</td>
<td>8.3</td>
<td>2</td>
</tr>
<tr>
<td>6-8</td>
<td>51</td>
<td>56.0</td>
<td>12</td>
<td>33.3</td>
<td>10</td>
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<tr>
<td>9-12</td>
<td>17</td>
<td>18.7</td>
<td>21</td>
<td>58.3</td>
<td>19</td>
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</table>
Characterizing Teachers’ Content Knowledge, Worldview and Belonging

Figure 6 shows the frequency distribution histograms and associated normal curves of scores for teachers’ content knowledge, worldview, belonging, and use of place-based strategies. The highest possible score for Content Knowledge was 18. Teachers in the survey sample earned scores in the full range of possibilities from 0-18, with an overall mean of 7.84 (SD=3.32).

Figure 6. Score distribution with normal curves, means, standard deviation, and sample size for each measure: Content Knowledge, Worldview, Belonging, and Place-based.
The highest possible score for teachers’ use of Place-based strategies was 5. Teachers earned a maximum of 5, a minimum of 1.67, and a mean of 3.74 (SD=0.780). The sample distribution of Content Knowledge and Place-based strategies were normally distributed. Distribution of Content Knowledge scores had positive skew (0.466) and kurtosis (0.358). The distribution of Place-based scores had negative skew (-0.156) and kurtosis (-0.787).

Out of a possible score of 5 on the Belonging scale, teachers indicated that their sense of belonging in science ranged between 1.6-5 with a mean of 3.79 (SD=0.660). Belonging was distributed bimodally with peaks at 3.4 and 4.2.

The highest possible score on the Worldview scale was 5 and teachers earned a maximum of 5, a minimum of 2.3, and a mean of 3.32 (SD=0.517). Worldview scores were distributed somewhat bimodally with peaks at 3.1 and 3.7.

The bimodal distribution of both Belonging and Worldview warranted further inquiry. Figure 7 shows two sets of violin plots comparing the probability distribution of Content Knowledge, Worldview, Place-based strategies, and Belonging for Grade Level and Degree groups.

In Figure 7, to make the comparisons of the four variables visually equivalent, Content Knowledge scores were rescaled to have a maximum score of 5. The variability of Content Knowledge, Worldview, Place-based strategies, and Belonging was similar across Grade Level groups. However, across Degree groups, the variability of the measures suggested that a teacher’s degree may have affected their scores; therefore, subsequent analyses used Degree as the grouping variable.
Figure 7. Violin plots of the probability distribution of measures for grade level (on the left) and degree (on the right). Plots made with BioVinci 2.0 (BioTuring, 2020).

Figure 8 shows the probability distributions of the different measures, Content Knowledge, Place-based strategies, Belonging, and Worldview, disaggregated by Degree. To explore teachers’ readiness, we provide a specific description for each measure by degree group.

**Content Knowledge.** The Other Science group had the highest mean of 9.7 (SD 2.8) and ranged from 4-17. The ES Major group had the next highest mean of 8.0 (SD = 3.6) and scores ranging from 1-18. The Non-science group had a range from 0-16 with a mean of 7.3 (SD 2.9). The ES minor group’s scores ranged from 3-18 with a mean of 6.9 (SD = 3.3).

**Place-based Strategies.** As with the content knowledge, the highest mean group was the Other Science degrees with a mean of 4.18 (SD 0.50) and scores between 3-5. The ES Major
Figure 8. Violin plots of measure probability distribution disaggregated by degree. Embedded box plots show lower and upper quartiles, white dot shows mean, white line shows median, and whisker plots show minimum and maximum. Plots made with BioVinci 2.0 (BioTuring, 2020).
group’s scores ranged from 2-5 with a mean of 3.73 (SD = 0.72). The ES Minor group’s scores ranged from 3-5 with a mean of 3.87 (SD 0.64). The Non-science group scored between 2.33-5 with a mean of 3.67 (SD 0.61). Both the Non-science and ES Majors groups are bimodally distributed with higher probability densities at 3.3 and 4.3.

**Belonging.** For this variable, the Other Science degrees group again outperformed the other groups. Teachers with Other Science degrees scored between 2.67-5 with a mean of 4.19 (SD 0.69). The ES minor group’s scores ranged from 2.67-5 with a mean of 3.71 (SD 0.78). The Non-science group scored between 1.60-5 with a mean of 3.7 (SD 0.65). The ES Majors’ scores were the lowest overall with a mean of 3.6 (SD = 0.90) and range of 1.67-5. ES Majors show a bimodal distribution with higher probability densities at 2.8 and 4.2.

**Worldview.** As with the other variables, teachers with Other Science degrees had the highest mean of 3.63 (SD 0.54) with scores between 2.6-4.6. The ES minor group’s scores ranged from 2.67-5 with a mean of 3.41 (SD 0.60). The ES Major group’s scores ranged from 2.33-5 with a mean of 3.25 (SD = 0.52). ES Majors show a bimodal distribution with higher probability densities at 2.8 and 4.2. In keeping with the pattern of the other variables, the Non-science group scored the lowest with a mean of 3.23 (SD 0.43) and scores between 2.67-5.

The distributions of scores were not what we expected. Teachers with degrees in Other Science had the highest average scores in all categories. Given that teachers with ES Majors would have taken the most ES course work, we predicted they would outperform the other groups on the Content Knowledge measure. As a group, teachers with ES Majors performed above average on the Content Knowledge measure but below average on all the other measures, with the lowest average Belonging score. Teachers with ES minors had the lowest Content Knowledge score. The Non-science group had the lowest averaged scores in Place-based and
Worldview measures.

To understand why the Other Science group may have done well on the Content Knowledge measure, we separated the 5 items that addressed biogeochemical cycles (Soltis et al., 2021) from the 13 that addressed climate science (Libarkin et al., 2018). Figure 9 shows that teachers in the Other Science group performed better in both sets of questions.

![Figure 9. Mean content knowledge scores earned by surveyed teachers grouped by degree, disaggregated biogeochemical cycle (out of 5) and climate science (out of 13) subsection scores.](image)

Visual differences between the performance of degree-based groups of teachers on each of the scales warranted further investigation using statistical analysis. Next, we analyzed the correlations and ran an ANOVA and post hoc Tukey test to test our hypotheses that teachers’ grade level and degree contributed to their performance on the Content Knowledge measure, Worldview, Belonging, and use of Place-based strategies.
Correlations and ANOVA

Table 4 shows correlations between Degree, ES Credits, Grade Level, Content Knowledge, Worldview, sense of Belonging, and use of Place-based strategies, all variables measured in this study. Upon evaluation of ES teachers’ education, experiences, Content Knowledge, Worldview, Belonging, and Place-based strategies, we found strong correlations between multiple survey components. Assuming that teaching higher grade level (i.e., high school versus elementary school) would require more sophisticated and advanced coursework, we hypothesized that grade level would affect Content Knowledge, Belonging, and use of Place-based strategies.

Table 4

Correlations between teachers’ earned degrees, ES credits, the grade level taught, Content Knowledge, Worldview, Belonging, and use of Place-based strategies (N=245).

<table>
<thead>
<tr>
<th></th>
<th>Degree</th>
<th>Credits</th>
<th>GL</th>
<th>CK</th>
<th>WV</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>ES Credits</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grade Level (GL)</td>
<td><strong>0.370</strong>*</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Content Knowledge (CK)</td>
<td><strong>0.363</strong>*</td>
<td>0.170**</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Worldview (WV)</td>
<td>0.083</td>
<td>0.101</td>
<td>-0.009</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Belonging (B)</td>
<td>-0.059</td>
<td>-0.167***</td>
<td>-.150*</td>
<td>0.312***</td>
<td>0.417***</td>
<td>0.695***</td>
</tr>
<tr>
<td>Place-based (PB)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* p < 0.05. ** p < 0.01. *** p < 0.001
A one-way ANOVA was performed to compare the effect of Grade Level on Degree, ES Credits, Content Knowledge, Worldview, Belonging, and Place-based strategies. This ANOVA revealed statistically significant differences in: (1) Degree between at least two groups (F(2, 243) = 26.795, \( p < 0.001 \)); (2) ES Credits between at least two groups (F(2, 242) = 8.937, \( p < 0.001 \)); and (3) use of Place-based strategies between at least two groups (F(2,242) = 3.619, \( p = 0.028 \)).

There were no significant differences between Grade Level groups for Content Knowledge, Worldview, and Belonging. Therefore, we cannot reject the null hypothesis that all Grade Level group means are statistically equal for these variables.

We hypothesized that the discipline of teachers’ degrees would affect their Content Knowledge, Worldview, Belonging, and use of Place-based strategies. To test that prediction, we conducted a second ANOVA to evaluate the differences of Degree group on ES Credits, Grade Level, Content Knowledge, Belonging, and use of Place-based strategies (Table 5). In this case, the significant ANOVAs indicated that at least one group mean was different for each variable. Therefore, we were able to reject the null hypothesis, that all group means are statistically equal for the variables.

While the sizes of the Degree groups were different, we found that the assumptions for the ANOVA were met: the variance within the groups is similar as tested by the Levene Statistic (\( p > 0.05 \)) and both Welch’s F and Brown-Forsythe’s F are large. Because of the differences in group sizes, post hoc Tukey HSD test results were cross-checked with Hochberg post hoc test to control Type I and Type II errors. Both post hoc tests showed the same results; therefore, the more rigorous Tukey results are reported.
We conducted a Tukey’s HSD Test comparing Degree groups and significant results are shown in Table 6. The Mean Difference (I-J) column shows positive differences between the degree groups, (I) and (J). Teachers with Non-science degrees ((J) Degree) had earned fewer ES credits and taught lower grade levels compared to all other Degree groups ((I) Degree). Teachers who had earned degrees in Other Sciences scored significantly better in Content Knowledge than all other degree groups; and better in Belonging, Worldview, and Place-based strategies than those with Non-science degrees and ES Majors.
Table 6

Hoc Tukey HSD. Significant comparison of the means of dependent variables between groups defined by Degree.

<table>
<thead>
<tr>
<th>Dependent Variable</th>
<th>(I) Degree</th>
<th>(J) Degree</th>
<th>Mean Difference (I-J)</th>
<th>Std. Error</th>
<th>95% Confidence Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Lower</td>
</tr>
<tr>
<td>Credits</td>
<td>Other Science</td>
<td>Non-science</td>
<td>0.381**</td>
<td>0.103</td>
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</tr>
<tr>
<td></td>
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<td>Non-science</td>
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<tr>
<td></td>
<td>ES Major</td>
<td>Non-science</td>
<td>0.460***</td>
<td>0.079</td>
<td>0.26</td>
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<td>Other Science</td>
<td>Non-science</td>
<td>0.566***</td>
<td>0.138</td>
<td>0.21</td>
</tr>
<tr>
<td></td>
<td>ES Minor</td>
<td>Non-science</td>
<td>0.614***</td>
<td>0.146</td>
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<td></td>
<td>ES Major</td>
<td>Non-science</td>
<td>0.572***</td>
<td>0.105</td>
<td>0.3</td>
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<td>Other Science</td>
<td>Non-science</td>
<td>2.398**</td>
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<td>0.7557</td>
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<td></td>
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<td>0.790</td>
<td>0.7155</td>
<td>4.8024</td>
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<td></td>
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<td>1.717*</td>
<td>0.639</td>
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<td>Worldview</td>
<td>Other Science</td>
<td>Non-science</td>
<td>0.404***</td>
<td>0.098</td>
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<td></td>
<td>ES Major</td>
<td>0.384***</td>
<td>0.099</td>
<td>0.1279</td>
<td>0.6401</td>
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<tr>
<td>Belonging</td>
<td>Other Science</td>
<td>Non-science</td>
<td>0.507***</td>
<td>0.126</td>
<td>0.1806</td>
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<tr>
<td></td>
<td>ES Major</td>
<td>0.444**</td>
<td>0.127</td>
<td>0.1155</td>
<td>0.7734</td>
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<tr>
<td>Place-based strategies</td>
<td>Other Science</td>
<td>Non-science</td>
<td>0.482**</td>
<td>0.151</td>
<td>0.0907</td>
</tr>
<tr>
<td></td>
<td>ES Major</td>
<td>0.584***</td>
<td>0.152</td>
<td>0.19</td>
<td>0.9773</td>
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</table>

* p < 0.05. ** p < 0.01. *** p < 0.001

**Discussion**

Our goal in this study was to learn what attributes predict teachers’ personal and enacted PCK when teaching NGSS sustainability concepts, which are most thoroughly addressed in Earth’s Systems and Earth and Human Activity standards (MS-ESS2, MS-ESS3, HS-ESS2, and HS-ESS3). We assessed teachers’ personal PCK by examining their Content Knowledge, Worldview, and sense of Belonging in science. We assessed teachers’ enacted PCK by having
them report on their use of Place-based strategies. We hypothesized that teachers’ Learning Context (e.g., implementation of NGSS, school type, Grade Level, and type of ES course) would predict their personal PCK (Content Knowledge, Worldview, and Belonging) and that teachers’ personal PCK would impact their enacted PCK. The Learning Context played less of a role than we predicted. We found no correlation between Grade Level and Content Knowledge, Worldview, or Belonging, and a negative correlation between Grade Level and teachers’ use of Place-based strategies, such that teachers of K-5 were more likely to report they used Place-based strategies than teachers of upper grades. Place-based strategies were independent of Degree and teachers were less likely to report using them if they had a high number of ES Credits. Degree correlated only to Belonging; but we found that Belonging, Content Knowledge, Worldview, and use of Place-based strategies were interrelated.

**Attributes of Teachers who have sufficient Content Knowledge.**

Teachers who scored higher on the Content Knowledge portion of the survey had degrees in the sciences (not necessarily ES), strong Belonging in the sciences ($r = 0.320, p < 0.001$), positive Worldviews ($r = 0.471, p < 0.001$), and reported using Place-based strategies ($r = 0.312, p < 0.001$). Teachers with degrees in Other Science scored an average of 9.7, ES Majors scored an average of 8.0, Non-science degrees scored an average of 7.3, and those with ES minors averaged 6.9 (Figure 9). The overall average score earned on the Content Knowledge measure was 7.8 out of 18 indicating that most teachers did not understand the fundamentals of biogeochemical cycles (Soltis et al., 2021) or climate science (Libarkin et al., 2018).

Egger and others (2017) found the ES content that pre-service teachers learn is not necessarily congruent with NGSS, resulting in them not learning the sustainability concepts they
will be expected to teach. Our results support the assertions of those investigating teachers’ understanding of climate change science. In a sequence of four national surveys, Sullivan and others (2014) found that the NGSS demands a greater understanding of climate science than what teachers and other undergraduates may have learned in college (Sullivan et al., 2014). In a survey of 1500 U.S. teachers, Plutzer and others (2016) found that less than 50% of teachers reported receiving formal instruction in college and needed significant support to develop the confidence and worldviews needed to support student learning. The present study provides direct evidence of teachers’ content knowledge to confirm the assumptions made in many previous studies. Surprisingly, teachers who earned Other Science degrees did better on the Content Knowledge measure than other groups, including those with ES degrees. This may be because if teachers studied biology, they likely would have had more training in ecological principles and biogeochemical cycles than a typical geology or earth science major (Klyce & Ryker, 2022). If they studied chemistry, they may have learned the fundamental chemistry of climate change and biogeochemical cycles.

Attributes of Teachers who hold Pro-Ecological Worldview.

We used the New Ecological Paradigm, Revised scale (Dunlap et al., 2000) to evaluate teachers’ ecological worldviews. Out of a possible score of 5, the overall average was 3.32. Teachers with Other science degrees had an average of 3.63, ES minors had an average of 3.41, ES Majors had an average of 3.25, and those with Non-science degrees had an average of 3.23. The mean difference between the degree groups was significant between the Other Science degree group and those with Non-science (0.404, \( p < 0.001 \)) and those who had ES Majors (0.384, \( p < 0.001 \)) (Table 6). This indicates that teachers with degrees in Other Science held
more pro-ecological worldviews. If those Other Science degrees were in the biological sciences, our finding supports Arcury and others (1986), that teachers’ training in ecology contributes to their Worldviews.

We found that teachers with pro-ecological Worldviews performed better on the Content Knowledge measure ($r = 0.471, p < 0.001$), were more likely to implement Place-based strategies ($r = 0.417, p < 0.001$), and had a strong sense of Belonging in science ($r = 0.405, p < 0.001$). Although we did not use Content Knowledge as an outcome variable in the ANOVA, the strong correlation between Worldview and Content Knowledge indicates that teachers’ beliefs predict their Content Knowledge of anthropogenic climate change. This confirms the findings of Arcury (1990) and Plutzer and others (2016), that the knowledge of fundamental ecological principles and understanding of anthropogenic environmental change are closely related to Worldview. Our finding that teachers with pro-ecological Worldviews are more likely to use Place-based strategies supports the idea that Worldviews are geographically rooted (Orr, 1992) and emerge from an understanding of place (Cajete, 2000). Teachers with pro-ecological Worldview also have a strong sense of Belonging in science and are more likely to have degrees in STEM (especially Other Sciences), a finding that supports the work of Feser (2021), Ogunbode (2013), and Ridenor (1999).

**Attributes of Teachers who have a Strong Sense of Belonging in the Sciences.**

To assess ES teachers’ sense of Belonging in science, we used a scale modified from Feser (2020). Out of a scale of 5, the overall average was 3.79. Teachers with degrees in Other Science averaged 4.18, ES minors averaged 3.87, ES Majors averaged 3.73, and those with Non-science degrees averaged 3.67. The difference between degree groups was significant between
those with Other Science degrees and those with ES Majors (0.444, \( p < 0.001 \)) and those with Non-science degrees (0.507, \( p < 0.001 \)) (Table 6).

We found that ES teachers’ sense of Belonging in science is important to their Worldview (\( r = 0.405, p = 0.01 \)), Content Knowledge (\( r = 0.320, p < 0.001 \)), and Place-based strategies (\( r = 0.695, p < 0.001 \)). The connection between Belonging and Worldview has been found in other studies. Noblet and others (2013) used the New Ecological Paradigm to evaluate how Maine citizens’ affiliations and Worldviews affected their trust of science researchers. They found that those who had studied the natural sciences or were members of an environmental organization had statistically significantly more trust in science and had more pro-ecological Worldviews. Amongst educators, Balgopal and others (2022) found that teachers with stronger connections to the science community had deeper Content Knowledge. A stronger sense of Belonging in science may inspire teachers to continue to learn the emerging science of sustainability and anthropogenic environmental change. Feser (2021) found that teachers’ Belonging is related to their earned degrees, suggesting that teachers’ relationships with the science faculty and degree-granting programs are important.

**Attributes of Teachers who use Place-based Strategies.**

The use of Place-based strategies supports NGSS SEP and CC (Appendix B). The correlations between teachers’ implementation of Place-based strategies and Belonging (\( r = 0.695, p < 0.001 \)), Content Knowledge (\( r = 0.312, p < 0.001 \)), and Worldview (\( r = 0.417, < 0.001 \)) indicate a complex relationship between these measures. As discussed above, we confirmed Balgopal and others’ (2022) finding that teachers with stronger connections to their science communities were more likely to implement research Place-based strategies. We suggest
this is because those teachers are more likely to develop learning opportunities by seeking out resources from their science communities. Lowenstein and others (2018) found that teachers need a community of similar practicing teachers and professional science networks that support the use of Place-based strategies. The correlation between Belonging and Place-based uncovered in our study sample supports Lowenstein et al. (2018).

We found that teachers’ knowledge of Content Knowledge correlated to their use of Place-based strategies. This is supported by Semken and others (2017) who suggest that educators’ use of Place-based strategies can be attributed to a combination of their factual, conceptual, procedural, and metacognitive knowledge. However, we found that teachers with more ES credits and who taught higher grade levels were less likely to implement Place-based strategies. This may be the result of constraints in the Learning Context.

Learning Context, as described by the Refined Consensus Model of PCK (Figure 3), includes school culture and controls. We identify grade level as a component of Learning Context (Figure 4). We found that teachers who taught at higher grade levels had more ES credits ($r = 0.170, p = 0.007$) but used Place-based strategies less ($r = -0.167, p = 0.009$). Other research has found that in higher grades, time, school administration, and community culture limit teachers’ use of Place-based strategies. Middle and high school teachers’ time with students is limited to academic periods or blocks and any learning outside of those times requires cross-curricular collaboration or student self-study (Gruenewald, 2005). Because Place-based strategies do not look like conventional learning, they can be limited by the assumptions and expectations of school administrators (Smith, 2007), such as students should be sitting quietly in their seats in the classroom and that other learning strategies limit students’ success rates on standardized assessments. Furthermore, if community members beyond the school do not value...
collaborating with secondary students, school administrators and teachers are less likely to promote Place-based strategies (Cincera et al., 2019).

**Limitations**

This study was a case study of the attributes that predict teachers’ readiness to address NGSS sustainability concepts. We focused on Illinois because it is an NGSS-adopter state and secondary licensure endorses teachers to teach all sciences, therefore many ES teachers are not trained in ES (the National Council on Teacher Quality state that only 11 states require that science teachers have discipline-specific degrees (Jacobs, 2010)). The results of the survey describe Illinois’ teachers’ experience and may not be generalizable beyond Illinois. Nevertheless, it is the first to publish results directly measuring the variables selected for this study with a large group of ES teachers and is one of few that comprehensively measures personal PCK (Carlson et al., 2019). When designing the survey, we attempted to create a comprehensive set of questions that addressed multiple factors of ES teachers’ training, teaching environment, knowledge, beliefs, and practices. However, we did not do classroom observations to directly measure enacted PCK (Mazibe et al., 2020), which is a limitation of our study.

Our assessment of teacher training included questions on degrees and ES credits earned. Teachers chose from a selection of degrees including non-science, astronomy, atmospheric science, biology, chemistry, geology, oceanography, physical geography, and physics. Teachers could select more than one option. This limited our ability to accurately bin degrees into Other Science, ES minor, and ES Major. The number of participants selecting each degree and groups of degrees were not of equal sizes. When responding to questions about the number of ES credits earned, teachers responded to one of 3 binned options: 0-11, 12-18, or 19+. We did not specify if
credits were earned through quarter or semester systems nor did we ask if the ES credits were earned through degree programs, teacher licensure programs, or continuing education. Teachers' ages and years of teaching ES were also binned, limiting the precision of responses to these questions.

We found no existing scales that measured Content Knowledge or Place-based strategies amongst teachers specifically. To assess teachers’ Content Knowledge, we combined 5 questions from Soltis and others (2021) on biogeochemical cycles and 13 questions from a concept inventory measuring climate change understanding by Libarkin and others (2018). Both concept inventories are relatively new and have been tested on limited populations. The biogeochemical cycle questions were tested on undergraduates and the climate change questions have been used with undergraduates and the public. This study presents results of the questions with a population of ES teachers. The use of Place-based strategies measure consisted of three questions generated by the research team. These questions focused on teachers’ use of relevant local phenomena in their instruction and have not been validated beyond use in this study. We did not ask about teachers’ personal sense of place (Semken & Freeman, 2008), place-attachment (Williams & Vaske, 2003), or place-meaning (Young, 1999).

The distribution of the survey may have introduced some limitations due to non-response bias, sampling bias, and recall bias (Bhattacherjee, 2012). We attempted to reach as many of the state’s ES teachers as possible through a variety of means including alma mater newsletters, professional association listservs, and professional social media platforms. However, we cannot be sure that we reached all ES teachers in the state. Sampling bias may have been introduced as completion of the survey was voluntary and there was an incentive for completion by the first 200 teachers. Recall bias may exist as teachers may not remember what they have learned about
anthropogenic environmental change. Furthermore, the survey was given at the end of the school year when teachers are very busy.

**Implications**

These results have meaningful practical implications for teacher preparation and teacher professional development. We have uncovered some important relationships between Illinois ES teachers’ Content Knowledge, Worldview, and sense of Belonging in science and how these contribute to their personal PCK. There is much to learn about the efficacy of teachers’ understanding and use of NGSS disciplinary core ideas, science and engineering practices, and crosscutting concepts related to sustainability (Pruitt, 2014) and how these reflect teachers’ personal PCK. For a generalizable understanding of how Content Knowledge, Worldview, and sense of Belonging in science develop, change, and affect student learning in general, data is needed from other states (Nation & Feldman, 2021).

To better prepare ES teachers to teach NGSS sustainability concepts, their college coursework needs to be better aligned with the pedagogy of the Framework (NRC, 2012) and specific expectations of the NGSS (Penuel, 2015). This includes developing teachers’ understanding of anthropogenic environmental change, encouraging a more positive ecological worldview, modeling place-based strategies, and creating a strong sense of belonging by celebrating teachers’ positionality in the science community.

We found that teachers with "Other Science" degrees were more knowledgeable about climate change and biogeochemical cycles, suggesting that teachers trained in ES may not have the requisite content knowledge to teach NGSS. ES teachers need to learn the science behind the ESS Disciplinary Core Ideas and practice weaving these together with the Science and
Engineering Practices and Crosscutting Concepts. Professional development efforts should model the Framework pedagogy by demonstrating three-dimensional NGSS instruction (Smith, 2020), focusing on ESS Disciplinary Core Ideas that have been neglected by teacher training programs (Egger et al., 2017; Plutzer et al., 2016). In states that have not adopted the NGSS, national organizations and science centers should develop efforts to work at the state level, better addressing the standards of that state.

Teachers’ Ecological Worldview was highly correlated with Content Knowledge, sense of Belonging in science, and use of Place-based strategies. It is unclear if Worldview is causal in these correlations. However, because one’s ecological worldview develops through lived experiences and cultural beliefs (Prévot et al., 2018) many researchers argue that it cannot be taught to adults and is independent of behaviors (Buissink-Smith et al., 2011). However other researchers have found that engaging college students in environmental advocacy and actions can shift students’ perspectives about humans' relationship with the natural world (Egger et al., 2017; Harraway et al., 2012; Liu & Lin, 2014; Metzger et al., 2017; Ogunbode, 2013). For ES teachers to develop a more pro-environmental Worldview, incorporating environmental advocacy and action appears to be important to ES teachers’ development.

Teachers’ sense of Belonging in science was highly correlated with Ecological Worldview, Content Knowledge, and use of Place-based strategies suggesting that professional connections with scientists bolster teachers' learning and classroom practice. Cultivating and maintaining professional relationships between scientists and science teachers begins in college (Varelas et al., 2005) as pre-service teachers engage in the science community of practice (Wenger, 1998) by developing their laboratory and field skills. These practical experiences deepen teachers’ Content Knowledge, skills, and understanding of the Nature of Science (Kite et
They begin to feel and think like scientists (Varelas et al., 2005). This suggests that teachers’ sense of Belonging in science emerges from their science identity (Chung-Parsons & Bailey, 2019; Varelas et al., 2005). Once in the classroom, teachers’ sense of Belonging in science depends on their participation in scientific endeavors (e.g., Research Experiences for Teachers) (Davidson et al., 2022). Developing more of these types of experiences for ES teachers may enhance their lifelong sense of Belonging in the ES community and encourage their use of Place-based practices (Meichtry & Smith, 2007).

Our investigation has only scratched the surface of understanding how teachers’ use of Place-based strategies reflects their enacted PCK. We found that teachers of younger students were more likely to use place-based strategies, indicating that teachers of upper grades need professional development and support in using these strategies. Teachers need support, practice, and examples of how to incorporate local data and resources to address local ES issues. Classroom observations and qualitative data would shed light on teachers’ pedagogical decision-making processes around using Place-based strategies and how their personal PCK affects those decisions (Mazibe et al., 2020). This research could examine the development of teachers’ sense of place (Semken & Freeman, 2008), teachers’ place-attachment (Williams & Vaske, 2003), and their place-meaning (Young, 1999). We do not understand how these factors affect teachers’ use of place-based strategies and result in students’ learning. To assess the complexities of implementing place-based strategies at all levels, we need a comprehensive measure (Zandvliet, 2012) that would help to identify barriers and challenges of enacting place-based learning (Gruenewald, 2005) in different contexts and environments.
CHAPTER 3: HOW TEACHERS’ EXPERIENCE, SENSE OF BELONGING, KNOWLEDGE, AND WORLDVIEW CONTRIBUTE TO PLACE-BASED SUSTAINABILITY SCIENCE INSTRUCTION

Introduction

The majority of U.S. public schools (78%) struggle to fill physical and Earth science positions with qualified teachers (U.S. Department of Education Institute of Educational Sciences, 2022). Science teacher shortages have been made more complex by the geography of inequitable school funding, racial injustice, and the COVID pandemic (Nguyen et al., 2022). For quality Earth and space science education, these shortages are worsened by a lack of highly qualified Earth science (ES) teachers. In 2015, 41% of secondary science, technology, engineering, and mathematics (STEM) teachers held STEM degrees. Of these, only 3% had degrees in geoscience (Wilson, 2018). This matters because ES teachers are expected to translate complex and emerging ES concepts presented in the Next Generation Science Standards (NGSS) into lessons and activities for students (Harris et al., 2017).

The NGSS endeavor to improve science education for all students through a set of research-based, up-to-date standards for student knowledge and skills from kindergarten through high school (K-12) (NGSS Lead States, 2013). The NGSS attempt to revolutionize pedagogical practices with a three-dimensional instructional approach where science and engineering practices, disciplinary core ideas, and crosscutting concepts are woven together through phenomenon- and problem-based instruction. Human impacts on climate and the environment
feature prominently in the NGSS K-12 Disciplinary Core Ideas for Earth’s Systems (NGSS-ESS2) and Earth and Human Activity (NGSS-ESS3). Teachers expected to teach the science of climate change and other environmental change must understand how the science is evolving; however, many teachers have not completed coursework on anthropogenic environmental change and must learn the science independently (Wise, 2010).

The multi-disciplinary nature of anthropogenic environmental change leaves teachers feeling unprepared and uncertain because they must untangle their own beliefs and learn how to address the political, moral, and ethical challenges presented by the science (Hestness et al., 2014, Plutzer et al., 2016). Research shows that teachers’ lack of content knowledge about anthropogenic environmental change causes them to struggle to prepare students for the impacts of future changes (Brennan, 2017; Plutzer et al., 2016; Sullivan et al., 2018; Xiang & Meadows, 2020). In a comprehensive study of U.S. secondary science teachers, Sullivan and others (2014) found that a lack of knowledge of science coupled with the perceived controversial nature of climate change inhibited the teaching of accurate and current scientific understanding. Traditionally, educational systems have avoided the entanglements of anthropogenic environmental change science with global economics and politics, assigning the teaching of these topics to neither science nor social studies (Brennan, 2017); therefore, these critical topics may be taught in both curricula, or neither. The NGSS changed this by placing anthropogenic environmental change squarely in Earth’s Systems (NGSS-ESS2) and Earth and Human Activity (NGSS-ESS3). Through the Crosscutting Concepts, the NGSS emphasize that students learn how ethical, social, and cultural contexts must guide decision-making regarding the impacts of scientific discoveries and innovative technologies on human and natural systems (NGSS Lead States, 2013). However, if those standards do not fit with teachers’ existing knowledge and
ideology, the depth and context of the anthropogenic environmental change that is taught in a classroom may be affected (Hannah & Rhubart, 2020).

Strides have been made in preparing teachers through the development of rigorous and relevant college coursework, such as the Interdisciplinary Teaching about Earth for a Sustainable Future project (InTeGrate) (White et al., 2018), and the accessibility of the expert-reviewed Climate Literacy and Energy Awareness Network (CLEAN) Resource Collection (Ledley et al., 2014). However, knowledge of how humans are impacting Earth’s environment is not enough. Research shows that teachers need sustained learning communities, pedagogy that focuses on solutions, and an emphasis on competencies such as systems-thinking, future-thinking, values-thinking, strategic action, and stakeholder engagement (Darling-Hammond et al., 2017; Nilsen & Iveland, 2022; Redman et al., 2021). These competencies cultivate teachers’ positive ecological worldviews, self-efficacy in the instruction of anthropogenic environmental change (Lombardi & Sinatra, 2013), enable transdisciplinary approaches, and encourage the use of place-based strategies (Beach, 2023).

Teachers’ subject matter knowledge affects the content they teach (Gess-Newsome & Lederman, 1995). However, the relationship between teachers’ content knowledge and their teaching is not entirely straightforward (Smith, 1997). ES teachers have both formal pedagogical content knowledge and knowledge of their community’s sociocultural context (Windschitl, 2002). To assess both the pedagogical content and sociocultural knowledge on which teachers rely, we need to determine how teachers have come to know what they know. While some of the ES content may be learned before teachers begin teaching, much of it is learned after. Teachers are expected to be continuously learning and adapting their knowledge to facilitate a variety of classes (Abell, 2007). Yang and others (2020) found that content area credits positively correlate
with increased subject knowledge and while teachers may have degrees in other areas, many teachers earn credits through in-service courses or professional development. These teacher-learning opportunities are often defined by the grade level being taught because the higher the grade level, the greater the expertise and subject knowledge needed (Grangeat, 2015). Science education standards require teachers at higher levels to understand and communicate more sophisticated disciplinary core ideas and crosscutting concepts and support more advanced science and engineering skill development (National Research Council, 2012). A teacher’s college degree will affect their content knowledge and understanding of emerging science because of their connection to the science community (Chung-Parsons & Bailey, 2019; Feser, 2020).

Teachers’ sense of belonging in the sciences emerges situationally and endures over time and across contexts (Carlone & Johnson, 2007). Sense of belonging in science has been correlated to subject matter identity (Pedretti et al., 2008; Chung-Parsons & Bailey, 2019) where the specific cultural norms, standards, and expectations unique to the field create a community of practice (Wenger, 1998). Science teachers have complex identities as both teachers and scientists (Chung-Parsons & Bailey, 2019). While teachers’ pedagogical practice provides positive exposure to science identity, it also facilitates their students’ science identity development (Pedretti et al., 2008; Balgopal et al., 2022). When the science identity is strong, research has shown that teachers are more likely to stay current with the science they teach (Pedretti et al., 2008; Chung-Parsons & Bailey, 2019). Teachers’ sense of belonging in science contributes to their desire to learn and is critical when science develops rapidly, such as in teachers’ knowledge of anthropogenic environmental change (Plutzer et al., 2016).
The socio-scientific nature of anthropogenic environmental change challenges instructional paradigms, especially when teachers’ ideological beliefs conflict with anthropogenic environmental change science (Zeidler et al., 2009). If teachers have a comprehensive understanding of Earth’s systems, including biogeochemical cycles (Soltis et al., 2021) and climate change and its associated risks (Libarkin et al., 2018), students are more likely to learn how humans are changing landscapes, hydrologic systems, and the global climate (Plutzer et al., 2016; Nation & Feldman, 2021). Teachers’ content knowledge alone is not enough because their beliefs influence instruction. Plutzer and others (2016) found that “passionate” teachers spend more time and delve deeper into anthropogenic environmental change content than their less passionate peers. While knowledge can inform beliefs, it can also be questioned and even trumped by beliefs (Plutzer et al., 2016; Nations & Feldman, 2021). Therefore, teachers’ ecological worldview is a critical component of the teaching of anthropogenic environmental change through place-based education practices.

**Theoretical Framework**

Place-based educational strategies connect learners to where they live by grounding learning in the local environment (Meichtry & Smith 2007). Place-based strategies improve academic achievement (Smith, 2017), develop students’ 21st-Century skills (Motallebzadeh, 2015), increase students’ sense of community (Zandvliet, 2012), create more sustainable communities (Semken & Brandt, 2010) and positively affect teachers, students, schools, and communities (Powers, 2004). Place-based strategies have been shown to be effective when addressing complex sustainability (Raymond et al., 2017; Brown et al., 2019; Giusti, 2019; Ryfield et al., 2019; Sterling et al., 2020) and when supported by systemic and long-term
community collaborations (Gruenewald, 2005; Parker & Vernet, 2009). Implementing place-based strategies requires that teachers have expertise in both the effective pedagogical practices and the subject matter they are teaching (Motallebzadeh, 2015).

The interactions between teachers’ experiences, sense of belonging, worldview, content knowledge, and pedagogical practices create complex relationships (Ball & McDiarmid, 1989; Helms, 1998; Abell, 2007). To better understand the nature of these relationships, we leverage two frameworks: teacher-centered systemic reform (Woodbury & Gess-Newsome, 2002) and geo-STEM learning ecosystems (Manning, 2020).

Teacher-Centered Systemic Reform (TCSR) (Woodbury & Gess-Newsome, 2002) models how a teacher’s instructional practice may change in response to pedagogical reform. This model is well suited to understanding how an individual ES teacher’s training, school setting, sense of belonging, subject knowledge, and beliefs contribute to how they direct student learning. However, TCSR is limited to how the individual instructor changes rather than the dynamics of a system. In the present study, we use Illinois teachers as a case study to develop a system-level model of the variables related to teaching anthropogenic environmental change by also applying the lens of the geo-STEM learning ecosystems (GLE) (Manning, 2020; Chapter 1).

**Teacher-centered Systemic Reform.** TCSR identifies three factors that contribute to how a teacher changes their practice: (1) personal factors, such as demographics, training, and experiences; (2) teacher thinking defined by a teacher’s knowledge and beliefs about student learning, the content, their teaching, and their desire to and belief in change, and (3) contextual factors which include how the teacher is positioned in the classroom, department, institution, and broader community (Woodbury & Gess-Newsome, 2002). Figure 10 shows how we apply TCSR to this study. Specifically, the teachers involved in this study teach Earth science in Illinois in
grades K-12. The personal factors and dimensions of a teacher’s thinking are used to evaluate what impacts their use of place-based instructional strategies.

**Figure 10.** Application of the Teacher-Centered Systemic Reform Model (adapted from Gess-Newsome et al., 2003) to current study.

**Geo-STEM Learning Ecosystem Model.** In geo-STEM learning ecosystems (GLE), community organizations develop systemic collaborations that engage learners from all walks of life, facilitate enduring and effective GLE opportunities, elevate community literacy and innovation, improve professional and community networks, and activate transformative solutions to make communities more sustainable (Manning, 2020). Figure 11 illustrates how this model is applied in this study.
We investigated how ES teachers have learned the content they teach. Traditionally, teachers’ learning of ES has been facilitated first through formal teacher training and preparation programs and later by informal collaborations with organizations that provide professional development (including state departments of education, school districts, nonprofit organizations, and postsecondary education institutions). In this study, we seek to understand how the TCSR personal factors (teachers’ chosen degrees and the number of ES credits they have earned) and TCSR contextual factors (NGSS adoption, Grade Level) impact ES teachers’ sense of belonging in science, knowledge of anthropogenic environmental change, ecological worldview, and use of place-based instructional strategies. The GLE framework provides a system-level model within which we can interpret the relationships between the variables examined in this study.
Proposed Model and Current Study

In this research, we seek to answer the question, “How do Earth science teachers’ education and teaching experience affect their sense of belonging in the sciences, knowledge of anthropogenic environmental change, ecological worldview, and use of place-based practices?” Our hypothesis is that for ES teachers to implement place-based geoscience learning experiences for their students, they need training in ES subject matter, a worldview that human action can drive better stewardship of Earth, and a sense of belonging to the geosciences. When teachers have a strong sense of belonging in the geosciences, they are more likely to invest in further geoscience learning and maintain stronger ecological worldviews, resulting in more relevant instruction about local geoscience phenomena. GLEs also support teachers’ use of place-based instructional strategies and understanding of sustainability concepts by connecting them with local geoscientists and ongoing local geoscience research (Chapter 1, Figure 2).

We investigated the possible factors contributing to teachers’ implementation of place-based instructional strategies and knowledge of anthropogenic environmental change. We used statistical path analysis to interrogate a statewide survey of ES teachers and explore which factors significantly contributed to teachers’ use of place-based instructional strategies (Figure 12). We propose that ES teachers need grade-level appropriate training through coursework and in-service credits that emphasize anthropogenic environmental change science and place-based pedagogy. Additionally, ES teachers need strong communities of practice that afford a sense of belonging in ES and strengthen ecological worldviews.
Exogenous predictor variables are those factors that explain variation in the model, shown in black on the left of the path and predicted to be associated with teacher preparation and include the grade level, discipline of degree, and number of ES credits earned. Each of these variables has been shown to contribute to teachers’ knowledge and practices. In the TCSR model, these are personal and contextual factors that impact a teacher’s thinking. In the GLE model, these are considered inputs that affect what teachers know, believe, and do. Teachers who teach higher grade levels had greater complexity of understanding of scientific concepts (National Research Council, 2012; Grangeat, 2015). Therefore, the science discipline of teachers’ degrees should affect both their content knowledge and their sense of connection to the science community (Chung-Parsons & Bailey, 2019; Feser, 2020). The number of credits a teacher earns within and beyond their degree should also contribute to their subject area knowledge (Yang et al., 2020).
Endogenous moderating variables, those for which variation is explained by one or more variables within the model, are shown in gray in the middle of the path and emerge from teachers’ preparation. These are predicted to include teachers’ ecological worldview, sense of belonging in the science community, and knowledge of anthropogenic environmental change. The preparation a science teacher receives contributes to their sense of belonging in science (Pedretti et al., 2008; Chung-Parsons & Bailey, 2019; Feser, 2020), content knowledge, and worldview (Plutzer et al., 2016; Libarkin et al., 2018; Nation & Feldman, 2021; Soltis et al., 2021). In the TCSR model, these variables would be a part of a teacher’s thinking and in the GLE model these variables are outcomes, products of teachers’ training, culture, and setting. All of which affect their teaching practices (Balgopal et al., 2022).

The endogenous outcome variable is teachers’ use of place-based strategies which is shown on the right side of the path diagram. In this case, teachers’ use of place-based strategies is a suitable outcome variable because it results from teacher pedagogical content knowledge shown to improve student ES knowledge and skills (Meichtry & Smith, 2007; Motallebzadeh, 2015 Smith, 2017), students’ sense of community (Zandvliet, 2012; Semken & Brandt, 2010), and students’ understanding of sustainability (Raymond et al., 2017; Brown et al., 2019; Giusti, 2019; Ryfield et al., 2019; Sterling et al., 2020). In the GLE model, the use of place-based strategies is an outcome that results from teachers’ understanding of how people’s interactions with the local environment provide relevant learning opportunities for their students (Chapter 1).
Methods

Research Design

Two hundred forty-five Earth science teachers from Illinois voluntarily participated in a state-wide survey composed of questions from existing instruments and exploratory questions (Appendix A). The survey was distributed through alumni lists of Illinois STEM teacher training programs; newsletters from state science teachers’ associations, nature centers, and the state P-20 council; and the social media platforms of the National Earth Science Teachers Association and the NGSS Earth Science Storyline writing groups. Teachers receiving the survey announcement were encouraged to pass the survey link on to other ES teachers in the state. The first 200 teachers who completed the survey received a ten-dollar gift card.

Data Collection. The Qualtrics survey was open for two weeks. It was composed of seven sections in the following order: (1) teachers’ experience learning and teaching ES, (2) teachers’ implementation of place-based strategies, (3) teachers’ ecological worldview (Dunlap et al., 2000; Dunlap, 2008), (4) teachers’ content knowledge of anthropogenic environmental change (Libarkin et al., 2018; Soltis et al., 2021), (5) teachers’ sense of belonging in science (Feser, 2020), (6) teachers’ funds of knowledge, and (7) teachers’ demography. A thorough description of teachers’ performance on the individual scales is reported in Chapter 2. Teachers’ funds of knowledge were not included in this study.

Measure 1 - Teacher Educational Experiences. We asked nine questions to better understand teachers’ training and experiences in both learning and teaching ES. Five questions were asked about how ES is taught, including the amount of time teaching ES, grade level at which ES is taught, type of course (stand-alone, integrated, mandatory, elective, dual/college credit), and type of school (public, charter, magnet, or private). Four questions focused on their
college degrees, including field and level of degrees and an estimated number of ES credits earned.

**Measure 2 - Teachers’ Use of Place-Based Instructional Strategies.** To learn how teachers describe their use of place-based strategies we developed three 5-point Likert-scale items that assessed how teachers connect students to relevant, local ES phenomena in their course design. These questions align with components of NGSS ESS2, ESS3, and ETS1 (See Appendix B for specific alignments). Responses ranged from strongly disagree to strongly agree with a midpoint value of neither agree nor disagree. The items were: (1) “Earth science is relevant to my students”, (2) “I use Illinois-specific examples when teaching Earth science”, and (3) “My students collect and/or analyze Illinois-specific Earth science data.” The values reported here are the sum of the scores for all items. The reliability of the three items (α = 0.714) was acceptable for exploratory research (Tavakol & Dennick, 2011). The value of alpha, if individual items are removed are as follows: (1) α = 0.705; (2), α = 0.597; (3), α = 0.555.

**Measure 3 - Teachers’ Ecological Worldview.** We used the New Ecological Paradigm Scale, Revised (Dunlap et al., 2000; Dunlap, 2008; Stern et al., 1995) to assess teachers’ ecological worldview. This five-factor, 15-item, 5-point Likert-scale instrument has been tested internationally with a variety of populations. Responses ranged from strongly disagree (1) to strongly agree (5) with a midpoint value of neither agree nor disagree (3). In previous studies, Cronbach’s alpha values range from 0.73-0.86 depending upon the sample with which it was used (Dunlap et al., 2000; Dunlap, 2008; Harraway et al., 2012; Gomera et al., 2013; Reyna et al., 2018; Sanchez-Dominguez et al., 2021). The instruments are considered internally consistent (Arcury, 1990; Noe & Snow, 1990; Bernstein, 2020) tapping into a wide range of worldview facets and offering a balance of positive and negative items. We administered all five factors to
assess teachers’: (1) accepting the possibility of an ecological crisis, (2) rejecting the idea that humans are exempt from the impacts of an ecological crisis, (3) accepting that the balance of nature is fragile, (4) rejecting the idea that humankind is the central or most principal element of the universe, and (5) accepting limits to the growth of human civilization. (See Appendix B for how these factors align to NGSS.) The values (ranging from one to five) for each item were averaged to generate scores, with a high score indicating a more positive ecological worldview (Carifio & Perla, 2008; Gaito, 1980; Norman, 2010). The reliability of the total scale (α = 0.740) was acceptable for exploratory research (Konting et al., 2009).

Measure 4 - Teachers’ Knowledge of Anthropogenic Environmental Change. To assess teachers’ understanding of anthropogenic environmental change, we selected eighteen multiple-choice questions from existing instruments previously used with U.S. undergraduates. Questions were selected that correlated to NGSS-ESS2 Earth’s Systems and NGSS-ESS3 Earth and Human Activity (Appendix B). Thirteen questions were included from the Climate Change Concept Inventory (Libarkin et al., 2018) and assessed teachers’ understanding of greenhouse gas compositions, processes, and functions in recent atmospheric temperature changes. Five questions from the Biogeochemical Cycles & the Earth System Concept Inventory (Soltis et al., 2021) assessed teachers’ understanding of the carbon, nitrogen, and phosphorus cycles, all of which have been disrupted by human activities (Rockström et al., 2009; Kumar et al., 2018). Each question was worth one point, with a maximum score of 18 on this measure of teachers’ knowledge of anthropogenic environmental change.

Measure 5 - Teachers’ sense of belonging in science. To evaluate teachers’ sense of belonging in science, we modified a scale developed to assess teachers’ sense of belonging in science (Feser, 2020). The original instrument is a 5-factor scale with 21 5-point Likert scale
questions. In this study, redundant items were eliminated and others were modified to simplify language resulting in 5 questions. The scale was reduced to minimize participant fatigue.

Responses ranged from strongly disagree (1) to strongly agree (5) with a midpoint value of neither agree nor disagree (3). The Likert scale items summed and averaged. The reliability of the 5 questions (α = 0.712) is within the acceptable range for exploratory research (Konting et al., 2009) and comparable to Feser’s preliminary results α = 0.72 (Feser, 2020).

Measure 6 - Demographic Information. Demographic questions were placed at the end of the survey to reduce stereotype threat (Pennington et al. 2016; Spencer et al., 2016). Following the recommendations of Fernandez and others (2016), we asked multiple choice questions inquiring about teachers’ age range, gender identity, and racial and ethnic identities. Gender and racial/ethnic identity questions included short text response options to allow participants to accurately self-identify.

Data Analysis. Results from the entire Qualtrics survey data were downloaded into Microsoft Excel and cleaned by removing responses that were incomplete, redundant, came from outside of Illinois (teachers indicated the zip code of their school), indicated the teachers taught multiple grade levels (to prevent counting 15 individual responses multiple times), and did not pass the filter questions (one text response and one multiple-choice response).

Using IBM®-SPSS Statistics (v. 29.0), missing values were specified, variable types were classified and described, and correlation tables were generated. The variables (i.e., parameters) include teachers’ college degrees, the estimated number of ES credits earned, the grade level at which they teach ES, their use of place-based educational strategies, and teachers’ scores on the scales for knowledge of anthropogenic environmental change, teachers’ ecological
worldview measured by the New Ecological Paradigm, Revised, and Sense of Belonging in Science.

Given the number of variables assessed, we evaluated response outliers as those beyond 2 standard deviations on the knowledge of the anthropogenic environmental change scale. Because all outliers were evenly distributed between the different grade levels, they did not skew the results and we did not remove them. Upon evaluation of ES teachers’ education, experiences, knowledge of anthropogenic environmental change, ecological worldview, sense of belonging in science, and use of place-based practices, we found strong correlations between multiple survey components. Seeking to untangle the relationships between these, we used IBM®-SPSS AMOS (Arbuckle, 2019) to conduct a statistical path analysis mapping the relationships (Streiner, 2005). Kline (2015) and Field (2013) determined the acceptable sample size to parameter ratio in a path analysis is at least 10-20 participants per parameter. This study had a ratio of 35, with a sample size of N=245 and seven parameters. We bootstrapped the resulting model to determine direct, indirect, and total effects.

Results

Descriptive Statistics

The sample was composed of responses from 245 self-identifying Earth science (ES) teachers from a midwestern U.S. state (Chapter 2, Figure 5). The majority of the teachers were between the ages of 26-45 (91%), male (59%) and White (83%) (Table 7). Figure 5 (Chapter 2) shows that teachers work in a mix of urban, suburban, and rural schools. Table 7 shows that teachers work in a mix of elementary, middle, and high schools. Teachers identified their schools as traditional public (n=148), public magnet (n=39), charter (n=28), and private schools (n=30).
Teachers had diverse backgrounds in their ES training with respect to the discipline of their degrees and the number of ES credits earned.

Table 7
Demographics and education of ES teachers by grade level that they teach.

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</tr>
<tr>
<td>0-11</td>
<td>7</td>
<td>16.28</td>
<td>21</td>
</tr>
<tr>
<td>12-18</td>
<td>29</td>
<td>67.44</td>
<td>58</td>
</tr>
<tr>
<td>19+</td>
<td>7</td>
<td>16.28</td>
<td>7</td>
</tr>
</tbody>
</table>
Path Analysis Development

We selected grade level, number of ES credits, and degree discipline as exogenous predictor variables in the path analysis because they pre-date or underpin some of the endogenous variables, such as place-based practices and knowledge of anthropogenic environmental change. Table 8 shows the means, standard deviations, and Cronbach alpha values for the endogenous moderating variables: scales and subscales for sense of belonging in science, ecological worldview, and scores on the instrument assessing teacher’s knowledge of anthropogenic environmental change. Table 8 also shows the mean, standard deviation, and alpha for the endogenous outcome variable, teachers’ use of place-based strategies. Alpha values are acceptable for all scales (Konting et al., 2009).

Table 8

Means, standard deviations, and Cronbach’s alpha for this study’s scales and subscales.

<table>
<thead>
<tr>
<th>Scale</th>
<th>Subscale</th>
<th>Mean</th>
<th>SD</th>
<th>Alpha</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sense of Belonging (5)</td>
<td>I feel…</td>
<td>3.79</td>
<td>0.492</td>
<td>0.712</td>
</tr>
<tr>
<td></td>
<td>connected to science researchers (5)</td>
<td>3.76</td>
<td>0.981</td>
<td>0.630</td>
</tr>
<tr>
<td></td>
<td>recognized by science researchers (5)</td>
<td>3.82</td>
<td>0.963</td>
<td>0.724</td>
</tr>
<tr>
<td></td>
<td>I have something to contribute to the science research community (5)</td>
<td>3.78</td>
<td>0.950</td>
<td>0.664</td>
</tr>
<tr>
<td></td>
<td>a sense of wellbeing around science researchers (5)</td>
<td>3.91</td>
<td>0.854</td>
<td>0.660</td>
</tr>
<tr>
<td></td>
<td>I can trust science researchers (5)</td>
<td>3.69</td>
<td>1.082</td>
<td>0.633</td>
</tr>
<tr>
<td>Ecological Worldview (5)</td>
<td></td>
<td>3.32</td>
<td>0.517</td>
<td>0.740</td>
</tr>
<tr>
<td></td>
<td>Possibility of an eco-crisis (5)</td>
<td>3.56</td>
<td>0.773</td>
<td>0.721</td>
</tr>
<tr>
<td></td>
<td>Humans are not exempt from an eco-crisis (5)</td>
<td>3.16</td>
<td>0.693</td>
<td>0.744</td>
</tr>
<tr>
<td></td>
<td>The Balance of Nature is Fragile (5)</td>
<td>3.26</td>
<td>0.663</td>
<td>0.743</td>
</tr>
<tr>
<td></td>
<td>Humans are not central to the Universe (5)</td>
<td>3.25</td>
<td>0.777</td>
<td>0.732</td>
</tr>
<tr>
<td></td>
<td>Human civilization growth is limited (5)</td>
<td>3.35</td>
<td>0.677</td>
<td>0.731</td>
</tr>
<tr>
<td>Anthropogenic Environmental Change (18)</td>
<td></td>
<td>7.84</td>
<td>3.32</td>
<td>0.675</td>
</tr>
<tr>
<td>Use of Place-based Strategies (15)</td>
<td></td>
<td>11.22</td>
<td>2.36</td>
<td>0.714</td>
</tr>
</tbody>
</table>
The Pearson correlations for all the study variables (Table 9) indicate that teaching a higher grade level was correlated with having an advanced degree ($p < 0.001$), more ES credits ($p = 0.007$), and the use of place-based instructional strategies ($p = 0.019$). Having an advanced degree was correlated with a higher number of ES credits ($p < 0.001$) and a stronger sense of belonging in science ($p = 0.019$). Teachers’ earned ES credits correlated with their use of place-based instructional strategies ($p < 0.001$). Teachers’ sense of belonging in science was significantly correlated with their knowledge of anthropogenic environmental change ($p < 0.001$), ecological worldview ($p < 0.001$), and use of place-based instructional strategies ($p < 0.001$). Teachers’ ecological worldview and use of place-based instructional strategies were also significantly correlated ($p < 0.001$).

<table>
<thead>
<tr>
<th></th>
<th>Grade</th>
<th>D</th>
<th>Credits</th>
<th>SBS</th>
<th>AEC</th>
<th>EWV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Degree Discipline (D)</td>
<td>0.363***</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ES Credits (Credits)</td>
<td>0.170**</td>
<td>0.370***</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sense of Belonging in Science (SBS)</td>
<td>-0.008</td>
<td>0.150*</td>
<td>-0.043</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anthropogenic Environmental Change (AEC)</td>
<td>-0.009</td>
<td>0.083</td>
<td>0.101</td>
<td>0.320***</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Ecological Worldview (EWV)</td>
<td>0.053</td>
<td>0.053</td>
<td>-0.005</td>
<td>0.405***</td>
<td>0.471***</td>
<td>1</td>
</tr>
<tr>
<td>Use of Place-based Education Strategies (PBE)</td>
<td>-.150*</td>
<td>-0.059</td>
<td>-0.167**</td>
<td>0.695***</td>
<td>0.312***</td>
<td>0.417***</td>
</tr>
</tbody>
</table>

* $p < 0.05$. ** $p < 0.01$. *** $p < 0.001$
Direct effects of the exogenous and endogenous predictor variables (grade level, degree discipline, ES credits, sense of belonging in science, knowledge of anthropogenic environmental change, and ecological worldview) on the moderating (sense of belonging in science, knowledge of anthropogenic environmental change, and ecological worldview) and outcome variable (use of place-based instructional strategies) were determined from IBM®-SPSS AMOS output (Table 10). Indirect and total effects were calculated by conducting a bootstrap analysis of 200 samples at bias-corrected intervals of 90 (full analysis of effects can be found in Appendix C).

Table 10

<table>
<thead>
<tr>
<th>Effect (β)</th>
<th>Direct β</th>
<th>Indirect β</th>
<th>Total β</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>On Sense of Belonging</td>
<td></td>
<td></td>
<td></td>
<td>0.023</td>
</tr>
<tr>
<td>Of Degree</td>
<td>0.15*</td>
<td>0.15*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>On Anthropogenic Environmental Change</td>
<td></td>
<td></td>
<td></td>
<td>0.122</td>
</tr>
<tr>
<td>Of Degree</td>
<td>-0.01</td>
<td>0.049*</td>
<td>0.039*</td>
<td></td>
</tr>
<tr>
<td>Of ES Credits</td>
<td>0.118</td>
<td>0.118</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Of Sense of Belonging</td>
<td>0.325***</td>
<td>0.325***</td>
<td></td>
<td></td>
</tr>
<tr>
<td>On Ecological Worldview</td>
<td></td>
<td></td>
<td></td>
<td>0.297</td>
</tr>
<tr>
<td>Of Degree</td>
<td></td>
<td>0.057</td>
<td>0.057</td>
<td></td>
</tr>
<tr>
<td>Of ES Credits</td>
<td></td>
<td>0.045</td>
<td>0.045</td>
<td></td>
</tr>
<tr>
<td>Of Sense of Belonging</td>
<td>0.282***</td>
<td>0.124*</td>
<td>0.406***</td>
<td></td>
</tr>
<tr>
<td>Of Anthro Env Change</td>
<td>0.382***</td>
<td>0.382***</td>
<td></td>
<td></td>
</tr>
<tr>
<td>On Use of Place-based Strategies</td>
<td></td>
<td></td>
<td></td>
<td>0.532</td>
</tr>
<tr>
<td>Of Degree</td>
<td></td>
<td>0.104*</td>
<td>0.104*</td>
<td></td>
</tr>
<tr>
<td>Of GL</td>
<td>-0.133**</td>
<td></td>
<td>-0.133**</td>
<td></td>
</tr>
<tr>
<td>Of ES Credits</td>
<td>-0.125**</td>
<td>0.014</td>
<td>-0.111**</td>
<td></td>
</tr>
<tr>
<td>Of Sense of Belonging</td>
<td>0.618***</td>
<td>0.081**</td>
<td>0.699***</td>
<td></td>
</tr>
<tr>
<td>Of Anthro Env Change</td>
<td>0.058</td>
<td>0.058*</td>
<td>0.116*</td>
<td></td>
</tr>
<tr>
<td>Of Ecological Worldview</td>
<td>0.152**</td>
<td></td>
<td>0.152**</td>
<td></td>
</tr>
</tbody>
</table>

* p < 0.05. ** p < 0.01. *** p < 0.001
The total effect size of the variables examined in this model explained 53.2% of the variance in teachers’ use of place-based strategies (Table 10). Teachers’ sense of belonging in science ($\beta = 0.699$, $p < 0.001$) was significant at the $p < 0.001$ level. Predictors with significance at the $p = 0.01 - 0.001$ level included ecological worldview ($\beta = 0.152$, $p = 0.004$), grade level ($\beta = -0.125$, $p = 0.003$) and ES credits ($\beta = -0.133$, $p = 0.005$). Predictors with significance at the $p = 0.05 - 0.01$ level included teachers’ knowledge of anthropogenic environmental change ($\beta = 0.116$, $p = 0.040$) and the discipline of their degree ($\beta = 0.104$, $p = 0.037$) (Appendix C). The negative effects of grade level and ES credits on teachers’ use of place-based strategies indicate that the use of place-based strategies decreased at higher grade levels and amongst teachers with more ES Credits.

**Path Model**

The hypothesized path analysis model (Figure 12) was modified based on significant correlations and effect sizes (both direct and indirect). Paths that were not significant or had an impact of less than 0.01 were removed resulting in the path analysis model shown in Figure 13. This path maintains covariance paths between grade level, degree discipline, and ES credits. It also includes variance paths assessing the effects of grade level on teachers’ use of place-based strategies; degree discipline on teachers’ sense of belonging in science and knowledge of anthropogenic environmental change; ES credits on knowledge of anthropogenic environmental change and use of place-based strategies; sense of belonging in science on ecological worldview, knowledge of anthropogenic environmental change, and use of place-based strategies; knowledge of anthropogenic environmental change on ecological worldview and use of place-based strategies; and ecological worldview on use of place-based strategies.
Figure 13. Path Analysis Model. Dashed lines indicate a negative direct effect. Solid lines indicate a positive direct effect. Lines are weighted to highlight significance. * $p < 0.05$. ** $p < 0.01$. *** $p < 0.001$.

**Model Fit Summary**

The model fit was evaluated using IBM®-SPSS AMOS (Arbuckle, 2019; Streiner, 2005). The ratio of chi-square (9.7) to degrees of freedom (7) is acceptable at 1.386 (Marsh & Hocevar, 1985; Kline, 2015). The goodness of fit index is 0.993, indicating an excellent fit (Hu & Bentler, 1998; Kline, 2015). The Root Mean Square Error of Approximation is 0.039, where ≤ 0.05 demonstrates an excellent fit (MacCallum, et al., 1996).

**Discussion**

Factors measured in this study suggest that teachers were more likely to implement place-based strategies when they had a strong sense of belonging in science, a scientific understanding
of anthropogenic environmental change, and a positive ecological worldview. While having a degree in ES did not correlate to the use of place-based strategies, there were significant indirect effects if the degree was associated with a strong sense of belonging in science. Surprisingly, teachers with more ES credits and those who teach higher grades are less likely to implement place-based strategies (Woodbury & Gess-Newsome, 2002; Motallebzadeh, 2015). To provide context to these results, it is important to clarify how the measured variables may have affected teachers’ values of implementing place-based strategies.

Effect of Sense of Belonging in Science on Place-based Strategies

The effect of sense of belonging in science on use of place-based strategies was significant ($\beta = 0.699$, $p < 0.001$) and primarily direct ($\beta = 0.618$, $p < 0.05$) (Table 10). Sense of belonging in science was directly affected by degree ($\beta = 0.150$, $p < 0.05$). This relationship is supported by other researchers who describe how a sense of belonging in science is increased when teachers attain science degrees. Feser (2021) described how teachers who have earned STEM degrees express stronger connections to the science community. After earning their STEM degrees, teachers report feeling more supported by alma maters and STEM professional networks (Balgopal et al., 2022). Chung-Parsons and Bailey (2019) identified how teachers with strong sense of belonging in science maintain stronger science identities, leading them to teach ES in ways it is conducted in industry and research: authentic, inquiry-based, and driven by relevant questions. Science teachers who have experienced inquiry-based teacher training programs that emphasize place are more likely to incorporate place-based strategies in their own classrooms (Lowenstein et al., 2018). Correlations were not significant between sense of belonging in science and the number of ES Credits earned and sense of belonging in science and
the grade level taught. Thus, while sense of belonging in science and having a science degree was important for implementing place-based strategies, the specific number of ES credits and grade level teachers taught was not.

**Effect of Knowledge of Anthropogenic Environmental Change on Use of Place-based Strategies**

The total effect of teachers’ knowledge of anthropogenic environmental change on use of place-based strategies was ($\beta = 0.116, p < 0.05$), suggesting that teachers’ knowledge of anthropogenic environmental change was important to their use of place-based strategies. Other researchers have identified similar patterns, but the direction of causality is not clear. Danielsson and others (2014) reported that teachers connect their ES knowledge to their own place-based learning experiences. Others have found that positive place-based experiences increase teachers’ content knowledge inspiring them to provide those experiences to students (Atwood & Atwood, 1996; Trend, 2000). Gosselin and others (2016) identify how implementing place-based strategies led to an increase in teachers’ geoscience content knowledge. They attribute this to deepening connections between teachers, students, and local science experts. Gosselin’s connection of sense of belonging in science to anthropogenic environmental change and place-based strategies may also explain the effect of teachers’ sense of belonging in science on their knowledge of anthropogenic environmental change ($\beta = 0.325, p < 0.001$) that we see in our results. Because half of the effect of teachers’ knowledge of anthropogenic environmental change on place-based strategies was indirect ($\beta = 0.058, p < 0.05$), we also examined the effects of teachers’ knowledge of anthropogenic environmental change on the other moderating factor, ecological worldview.
Effect of Ecological Worldview on Use of Place-based Strategies

The effect of ecological worldview on use of place-based strategies was direct ($\beta = 0.152$, $p < 0.01$), confirming Masterson and others (2017), who found that ecological worldviews are closely tied to teachers’ use of place-based strategies. The development of an individual’s ecological worldview is complex, developing over a lifetime of experiences with nature as well as knowledge gained through both formal and informal education (Vollerberg et al., 2004). Our results agree with this premise, as ecological worldview is affected by both teachers’ knowledge of anthropogenic environmental change ($\beta = 0.382$, $p < 0.001$) and their sense of belonging in science ($\beta = 0.406$, $p < 0.001$). Our results also underscore how worldviews and ideologies may explain why teachers did not implement place-based strategies if they lack a sense of belonging in science and do not have strong knowledge of teachers’ knowledge of anthropogenic environmental change. Without a sense of belonging in science, having an ES degree did not appear to affect teachers’ use of place-based strategies. This finding is congruent with other researchers who have found that people with STEM degrees have an increased awareness of global economics and climate crises (Harraway et al., 2012; Rideout 2014) but their worldview and political ideologies dictate risk perception of environmental change (Mayer et al., 2013; Hamilton 2011; Kahan, 2012). Our results do not indicate that the discipline of teachers’ degrees or the number of ES credits impacted teachers’ ecological worldview. This may be explained by a lack of in-depth understanding of the Nature of Science as applied to ES (Lewis, 2008) because most teachers have learned ES content after they have started teaching (Wilson, 2018; Wise, 2010).
Effect of Teachers’ Education and Experience on Use of Place-based Strategies

We found that teachers who have STEM degrees were more likely to implement place-based strategies ($\beta=0.104$, $p < 0.05$). The effect was indirect and associated with sense of belonging in science (Degree on sense of belonging in science: $\beta=0.150$, $p < 0.05$), confirming the findings of Feser (2021) and Balgopal and others (2022). However, there appears to be a difference between having a STEM degree and earning ES credits. Credits alone inversely predicted the implementation of place-based strategies ($\beta=-0.125$, $p < 0.01$). This result may be explained by previous research that shows teachers’ lack of knowledge and skills in place-based strategies are barriers to its implementation (Ernst, 2007, 2012; Meighan & Rubenstein, 2018).

While some teachers feel unprepared to implement place-based strategies, others face structural barriers, especially in high school settings. In higher grades, we found that use of place-based strategies was less likely to be implemented ($\beta=-0.133$, $p < 0.01$). Others have found that barriers to place-based strategies include a lack of funding, transportation, and administrative support, along with concerns for student safety and achievement expectations (Dillon et al., 2006; Meighan & Rubenstein, 2018; Waite, 2020). These, along with potential interference with students’ class and assessment schedules may be the greatest limitations to implementing place-based strategies at the high school level.

Study Limitations

This study attempted to examine a set of factors that influence teachers’ practice. However, results may be limited by the survey design and distribution as well as the path analysis. What follows is a description, explanation, and the impacts of those limitations.
**Survey Design.** The survey was designed to investigate whether a variety of ES teacher characteristics predict teachers’ use of place-based strategies. The place-based strategies measured consisted of only three questions and were generated by the research team. Our goal was to determine if ES teachers were helping students connect their learning to where they live. We did not investigate teachers’ personal sense of place (Semken & Freeman, 2008), place-attachment (Williams & Vaske, 2003), or place-meaning (Young, 1999). More research is needed to understand how a teachers’ sense of place develops, how it affects their use of place-based educational strategies, and how teachers’ sense of place affects students’ learning.

No pre-existing concept inventory existed that specifically addresses teachers’ knowledge of anthropogenic environmental change. To circumvent this, we combined 5 questions from Soltis and others (2021) on biogeochemical cycles and 13 questions from a concept inventory measuring climate change understanding by Libarkin and others (2018). Both concept inventories are relatively new and have been tested on a limited population. The biogeochemical cycle questions were tested on undergraduates and the climate change questions have been used with undergraduates and the general public. This study presents results of the questions with a population of ES teachers.

**Survey Distribution.** The distribution of the survey may have introduced some limitations due to non-response bias, sampling bias, and recall bias (Bhattacherjee, 2012). We attempted to reach as many of the region’s ES teachers as possible through a variety of means including alma mater newsletters, professional association listservs, and professional social media platforms. However, we cannot be sure that we reached all ES teachers in the state. Sampling bias may have been introduced as completion of the survey was voluntary and there was an incentive for completion by the first 200 teachers. Recall bias may exist as teachers may
not remember what they have learned about teachers’ knowledge of anthropogenic environmental change. Furthermore, the survey was given at the end of the school year when teachers are very busy.

**Data Analysis.** Streiner (2005) cautions that a well-fitting path model does not prove that the model is correct or that the model predicts cause and effect relationships. In this study, we generated a path model based on extant literature and theory (Stage et al., 2004). The proposed model includes those variables where correlations are significant (see Table 9). There may be models that better predict teachers’ use of place-based strategies if other variables are measured (Pedhazur, 1997).

**Implications**

Teachers who reported using place-based geoscience learning experiences held degrees in STEM which contribute to a strong sense of belonging in science, a more positive ecological worldview, and a better understanding of the science of anthropogenic environmental change. The use of place-based strategies was less likely to be implemented in high schools and by those who had taken more ES credits. These patterns have both theoretical and practical implications.

**Theoretical Implications.** We found no research on how the development of ES teachers’ knowledge of anthropogenic environmental change, ecological worldview, and sense of belonging in science affects their use of place-based strategies. Our understanding of these variables has been facilitated through the lenses of Teacher-Centered Systemic Reform (TCSR) model (Gess-Newsome et al., 2003; Figure 10) and the geo-STEM learning ecosystem (GLE) model (Chapter 1, Figure 11).
We mapped the measured characteristics to the TCSR’s contextual factors, personal factors, and teacher thinking, to investigate the implementation of use of place-based strategies by individual teachers. For the contextual factors, Illinois is a state that has adopted the NGSS but lacks a cohesive implementation plan for the ES standards. We found a teacher’s use of place-based strategies is predicted by the discipline of their degree, not the number of ES credits they have earned (personal factors). The discipline of their degree contributes to a teacher’s thinking which includes their sense of belonging in science, knowledge of anthropogenic environmental change, and ecological worldview. The TCSR implies that a teacher’s sense of belonging in science and ecological worldview must be well-developed for them to implement place-based strategies and teach anthropogenic environmental change as described by the NGSS.

The GLE model predicts how systemic collaborations can affect the widespread implementation of place-based strategies. Within the GLE model, there are connections between teachers and their degree-granting institutions. ES licensure programs and faculty teaching ES courses to pre-service teachers have the capacity to better prepare them to teach NGSS by fostering a strong sense of belonging in science and encouraging positive ecological worldview which contribute to teachers’ knowledge of anthropogenic environmental change and place-based pedagogy. A strong sense of belonging in science is the result of positive professional relationships between ES teachers and geoscience faculty. A positive ecological worldview results from faculty’s use of place-based strategies focused on building teachers’ knowledge of anthropogenic environmental change. By identifying levers that affect teachers’ knowledge of anthropogenic environmental change, sense of belonging in science, and ecological worldview, we may be able to foster sustainability education congruent with the NGSS.
Additional regional studies are needed to better understand teachers’ knowledge of anthropogenic environmental change. This may include the development of a concept inventory that specifically addresses people’s understanding of anthropogenic environmental change happening in the region where teachers work. Possible avenues of research may use mixed-methods educational research to examine ES teachers’ funds of knowledge, professional networks, and the potential of GLE in affecting teachers’ sense of belonging in science, understanding of local anthropogenic environmental change, and implementation of place-based strategies.

We were not able to find research on the development of ES teachers’ ecological worldview, critical to their use of place-based strategies of anthropogenic environmental change (Plutzer et al., 2016). While prior research does suggest potential feedback between a teacher’s own place-based experiences, their use of place-based strategies with their students, and the teacher’s ecological worldview, sense of belonging, and knowledge of anthropogenic environmental change (Atwood & Atwood, 1996; Danielsson et al., 2014; Gosselin et al., 2016), more research is needed to identify how experiences (i.e., transformative, field-based, research) may affect teachers’ learning and practices (Pugh, et al., 2010). Researchers need better tools to assess teachers’ use of place-based strategies, especially understanding how a teacher’s sense of place develops (Semken & Freeman, 2008) through place-attachment (Williams & Vaske, 2003) and place-meaning (Young, 1999); and how teachers’ sense of place affects students’ learning.

**Practical Implications.** In this study, we found that sense of belonging in science is a strong predictor of ecological worldview, knowledge of anthropogenic environmental change, and use of place-based strategies. Teacher training and teacher professional development programs may be able to cultivate teachers’ sense of belonging in science, ecological worldview,
knowledge of anthropogenic environmental change, and place-based practices through GLE that establish teacher networks with degree-granting programs, community organizations, and other ES teachers.

If academic programs offering degrees in ES encourage interested students to pursue careers in teaching, they will affect future teachers’ sense of belonging in science (Feser, 2020) and may give researchers a chance to clarify the relationships between teachers’ sense of belonging in science and their complex science and educator identities (Chung-Parsons & Bailey, 2019). If we want teachers who implement place-based strategies, they need to be trained in place-based pedagogy and practices. This includes accessing local field sites for students to conduct field studies, incorporating available regional geoscience data into lessons, and connecting students to local and regional geoscience issues and research. Training teachers to connect with the science communities near their schools supports students’ perceptions of possible careers in geosciences and demonstrates the relevance and rigor of geosciences. GLE also support teachers’ use of place-based strategies and understanding of sustainability concepts by connecting them with local geoscientists (Chapter 1).

Given the NGSS’ emphasis on the science of sustainability and resilience (National Research Council, 2012), it is critical that ES teachers be prepared to teach Earth systems and processes within the context of Earth’s history, physical and Earth science of anthropogenic environmental change, and the economics and risks of Earth system-human interactions. Emphasizing these components of ES research will increase teachers’ awareness of the connections between global economics and environmental crises (Hamilton 2011; Kahan, 2012; Harraway et al., 2012; Mayer et al., 2013; Rideout 2014). This will also contribute to the development of teachers’ value of sustainable, resilient, and restorative solutions leading to a
more positive ecological worldview (Zelezny et al., 2000; Vollerberg et al., 2004; Prevot et al., 2018).

There is a need for long-term support for teachers of NGSS (Darling-Hammond et al., 2017; Nilsen & Iveland, 2022). Once educators are in the teaching workforce, providing research experiences that emphasize ES discoveries will support teachers’ understanding of NGSS and develop teacher leaders. When PD and advanced degree programs emphasize research in place-based pedagogy, anthropogenic environmental change content, and the creation of ES education research collaborations, students, local communities, and the STEM workforce will benefit (Atwood & Atwood, 1996; Ernst, 2007, 2012; Gosselin, et al., 2016; Meighan & Rubenstein, 2018).

**Conclusions**

The NGSS places significant emphasis on sustainability and anthropogenic environmental change from K-12 in the Earth Systems Science discipline area (Appendix B). In the context of a state adopting the NGSS but lacking a cohesive plan to address ES standards, we have found that the teaching of these topics via place-based strategies may depend on an individual ES teacher’s sense of belonging in science, which is affected by their education, experiences, and context. This, in turn, affects their knowledge of anthropogenic environmental change, ecological worldview, and the use of place-based strategies. The stronger an ES teacher’s sense of belonging in science, the more likely they will have a positive ecological worldview, continue to learn emerging ES content and use place-based strategies. Beyond an individual teacher, we found connections between teachers and their degree-granting institutions. Collaborations between teacher licensure programs and STEM departments have the capacity to instill a sense
of belonging in science and ecological worldview which contribute to teachers’ knowledge of anthropogenic environmental change and developing place-based pedagogy, necessary to teach NGSS.
CHAPTER 4: DESCRIBING EARTH SCIENCE TEACHERS’ SUPPORT NETWORKS WITH QUALITATIVE INTERVIEWS AND SOCIAL NETWORK ANALYSIS

Introduction

There is a lack of Earth science (ES) degree-holding teachers in the U.S. and many teachers assigned to teach ES have not received the training needed to support their work (Banilower et al., 2018; Plutzer et al., 2016; Sullivan et al., 2014; Wilson, 2018). The 2018 report from the National Survey of Science and Mathematics Education (Banilower et al., 2018) states that 5% of middle school STEM teachers and 15% of high school STEM teachers have degrees in ES, and 26% of all middle and high school STEM teachers have never taken ES coursework. In their 2018 report on the Status of the Geoscience Workforce, the American Geosciences Institute (Wilson, 2018) referenced the National Science Foundation’s 2015 National Survey of College Graduates and found that only 3% of the reporting Secondary STEM teachers have degrees in the geosciences. This means that many of the teachers assigned to teach ES do not have degrees in the discipline.

The shortage of degree-holding ES teachers is confounded by a lack of training in emerging ES research critical to understanding how to sustain and regenerate human and natural systems. Sullivan and others (2014) and Plutzer and others (2016) found that teachers have not been trained to address the complexities of climate concepts described by the Next-Generation Science Standards (NGSS). Manning and LaDue (in review) confirmed this for ES teachers in
Illinois and found that many of these teachers did not understand biogeochemical cycles essential to teaching about sustainability science, an emphasis of the NGSS.

Developing a community of practice that supports ES teachers would encourage more relevant and rigorous instruction of NGSS Earth and Space Science (Kelley et al., 2020). To be relevant to teachers and students, these communities of practice need to be focused on learning of geoscience, technology, and engineering issues unique to the location or place (Semken et al., 2017). We call such communities of practice geo-STEM learning ecosystems (Manning, 2020) which are a type of STEM learning ecosystem (Traphagen & Traill, 2014). Geo-STEM learning ecosystems (GLE) bring together community organizations to 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 (Manning & LaDue, in review). GLEs are composed of interconnected networks and are more effective if they include diverse ranges of people, link to people and groups that may otherwise not be connected and are allowed to evolve over time (Ibarra & Hunter, 2007). The goal of this case study is to examine a group of teachers using mixed methods Social Network Analysis to characterize the existing connections between teachers and their support systems (Froehlich et al., 2020; Thomas et al., 2019) and identify lever points within an emerging GLE to make it more impactful (Cross et al., 2006; Penuel et al., 2009; Quardokus Fisher et al., 2019).

**Communities of Practice and Social Network Analysis**

Communities of practice are defined as a community of people focused on developing expertise in a particular domain to develop a shared set of practices (Wenger et al., 2002). In
GLEs, the community consists of scientists, teachers, and others who are invested in promoting ES as locally relevant and focused on solutions. The domain is ES and includes geology, hydrology, oceanography, atmospheric science, Earth systems, and the science of natural resources and sustainability. The practices are the collection of resources, experiences, methodologies, and pedagogy that support ES education and solutions to local geo-STEM issues that inspire learners to participate in geo-STEM fields. From the perspective of teachers, this community of practice is needed because there are few ES teachers, they are isolated from each other, and many have not received the training they need to address the Next-Generation Science Standards for Earth and Space Science (NGSS-ESS). Members in a GLE can work together to create and share knowledge across their network (Cross et al., 2001) through purposeful interactions that generate ties stronger than what may be present in less intentional associations (Wenger, 1998). By examining how individuals interact with each other in an existing network, we may be able to identify the roles played by potential members in an emerging GLE (Yousefi Nooraie, et al., 2020).

SNA consists of theories and methods that identify, visualize, and analyze relationships between “actors”, the human and non-human entities that makeup a community (Milgram, 1967; Borgatti, 2005). Social network analysis is an approach to study the functions and structures of social relationships (Prell, 2012). In social network analysis, we conceptualize actors as nodes and the connections between nodes as ties. Within a network, centrality measures indicate the importance of nodes and ties relative to each other (Wasserman & Faust, 1994). Centrality has been defined in a variety of ways including degree, betweenness, eigenvector, closeness, reach, and reach efficiency (Table 11). Identifying these types of centrality for actors of interest help us
determine which actors are local hubs, boundary spanners, information brokers, and network leaders.

The tools offered by SNA enable us to study the relationships and structural features of social networks (Wellman, 1983). Scholars have adopted SNA methodologies to explore and understand CoP (Huysman et al., 2003; Ma et al., 2019). While SNA uses graph theory to quantitatively describe and reveal social structures and functions within a CoP (Burt, 1992; Huysman et al., 2003; Parker et al., 2001; Quardokus & Henderson, 2015), qualitative methods, such as surveys and interviews, have been shown to be effective in making sense of the relationships between the actors (Kelley et al., 2020; Thomas et al., 2019). Combining qualitative methods and SNA, produces more nuanced information for network visualization, analysis of relationships, and the structure and function of a CoP (Freeman et al., 1998; Freeman, 2000; Froehlich et al., 2020; Yousefi Nooraie, et al., 2020).

When describing the structure of a CoP, Wenger (1998) suggests they might exist as a core-periphery structure. CoP members' positions differ according to their levels of participation; insiders participate fully, some members participate at the periphery or margins, and outsiders observe but do not participate. This layered structure describes levels of participation, but it does not identify the roles played by different actors, such as local hubs, boundary spanners, and information brokers, all of which can be identified with SNA metrics (Cross et al., 2006).

Furthermore, it does not clarify how participation in the community supports individuals' operations in their current roles or facilitates strategic individual growth (Cross & Thomas, 2008; Liou & Daly, 2020). Combining SNA metrics and qualitative data can help identify nodes that have high levels of expertise but may not be central to the network. These peripheral specialists
do not seek out others in the network, but they provide information, resources, and fresh perspectives (Braithwaite et al., 2009; Cattani & Ferriani, 2008; Cross & Prusak, 2002).

Table 11

SNA metrics with their definitions and implications to the network (Brass & Burkhardt, 1992; Bonacich & Lloyd, 2001; Freeman, 1979, 2002; Hanneman & Riddle, 2011; Prell, 2012).

<table>
<thead>
<tr>
<th>Metric</th>
<th>Definition</th>
<th>Implication</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>the sum of the node and its neighbors</td>
<td></td>
</tr>
<tr>
<td>Degree Centrality</td>
<td>the number of ties connected to a node</td>
<td>High degree centrality indicates a local hub. Even if it is not the most connected node to the whole network, a local hub is very involved in the network.</td>
</tr>
<tr>
<td>Betweenness Centrality</td>
<td>the number of times a node lies on the shortest path between two other nodes</td>
<td>High betweenness nodes control the flow of information and can act as boundary spanners or gate keepers. They are intermediaries in the network and are likely aware of what is going on in multiple smaller networks.</td>
</tr>
<tr>
<td>Eigenvector Centrality</td>
<td>the number ties from the focus node to other local nodes of interest</td>
<td>High eigenvector centrality measures both the importance of an actor and the importance of their neighbors, indicating network leaders. Even if an actor lacks strong local influence, they have direct connections to influential network nodes.</td>
</tr>
<tr>
<td>Closeness Centrality</td>
<td>the distance between each node from all other nodes</td>
<td>Individuals with high closeness centrality are information brokers, individuals who connect otherwise unconnected actors and fill network holes. They are aware of what is happening in the network and spread information to the rest of the network.</td>
</tr>
<tr>
<td>Reach Centrality</td>
<td>the proportion of the network that can reach the node within two steps</td>
<td>A node with high reach spreads information through close contacts</td>
</tr>
<tr>
<td>Reach Efficiency</td>
<td>the reach divided by size (number of neighboring nodes)</td>
<td>A node with high reach efficiency is less connected but gains more exposure through each direct relationship</td>
</tr>
</tbody>
</table>
Using SNA to Investigate Geo-STEM Learning Ecosystems

In their SNA of a large, state-wide STEM learning ecosystem that included 316 organizations, Liou and Daly (2020) found that the PK-12 educational sector was not well represented. Leaving that sector out of STEM learning ecosystems limits effectiveness, growth, and participation. They recognized a need to understand the small networks critical to the success of the larger ecosystem. The present study fills this gap. We seek to characterize a small network of Illinois ES teachers who participated in a collaborative virtual workshop and identify nodes that have high impact within the network. During this workshop, teachers interacted with each other, geoscience education researchers, and local scientists and engineers. The goal was to initiate a community of ES teachers who could work together and learn about local ES issues. We investigated the Geo-STEM learning ecosystem created through this workshop by posing the following research questions: (1) How do ES teachers characterize their professional networks? and (2) What does SNA reveal about the ES teachers’ learning ecosystem?

Methods

Paradigm and Approach

We anchor this research in the interpretivist paradigm (Thanh & Thanh, 2015) in which we sought to learn about a group of Earth science teachers’ experiences with and perceptions of their professional networks (Willis, 2007). This is a case study that was based on multiple interactions with teachers by asking open-ended questions designed to explore and understand the nature of their networks (Lodico et al., 2010). Our data rely on teachers’ interpretations of their networks as socially constructed entities that are intended to support their work of teaching and learning (Thomas, 2003).
To determine each teacher’s network boundaries and connections, we utilized a realist strategy, in which participants defined their network, including the people, organizations, and resources they determined to be relevant to their professional network (Knoke & Yang, 2008). We sought transparency by making our intentions explicit from the beginning and reiterated these with each point of contact, as described below (Schröter et al., 2018). Our approach was also mutable, as teachers had the opportunity to make changes to their networks during the member-checking interviews discussed later (Kozinets, 2002).

**Mixed Method Case Study using Thematic Content and Social Network Analyses**

In this research, network nodes or actors were defined as the people, organizations, and resources that an ES teacher regularly accessed for support in their work. The teachers were nodes referred to as the “actors” and the people, organizations, and resources that they identified as part of their network were the “alters”. The actors and alters are nodes connected to each other by ties. While ties may be positive or negative, directed or undirected, and weighted or unweighted, in this analysis, we qualified ties as undirected. In some cases, the teachers in this study knew each other prior to the workshop; therefore, some alters were also actors depending upon the teacher of interest in the relevant analysis. Because we could not interview all the alters for each actor, we assumed that ties were reciprocal (undirected) and existed even if only one member of the pair reported the tie (Crossley et al., 2015).

**Context**

In the summer of 2021, we hosted a 2-day virtual workshop for Illinois Earth science teachers to learn about local critical zone and sustainability science (Kumar et al., 2018). All
participants received a $200 stipend. During the workshop, teachers generated network maps in response to the prompt, “Create a map that links you to the people, organizations, and events that brought you to this workshop?” While these maps did not fully represent teachers’ geo-STEM networks, they introduced the concept of network mapping and provided a starting point for later investigations of teachers’ ES support networks.

When the workshop was over, teachers attended webinars during the 2021-2022 and 2022-2023 school years. These webinars supported teachers’ collaborative creation of NGSS storylines (Reiser et al., 2021) about local sustainability issues and phenomena. In the winter of 2022, all twenty workshop participants were invited to be interviewed about the networks that support their teaching of Earth science and thirteen people volunteered. Interviewed teachers received an additional $50 stipend.

In the winter of 2023, ten of the interviewed teachers participated in member-checking interviews where they were asked to give feedback on interview summaries, codebooks, and egonets. Teachers were asked, 1) “Do you see anything you would like to add, take away, or change?” 2) “Does this work accurately reflect the network that supports your teaching of Earth science?” and 3) “Does this work accurately represent our interview?” The following research is based on the interviews with these ten teachers.

**Sampling Strategy**

All ten research participants were volunteers; therefore, the sampling strategy is non-probabilistic, limiting the likelihood that the sample represents the population of Illinois Earth science teachers (Bhattacherjee, 2012). However, the goal was to understand the networks of ES teachers in the workshop, so the goal was not to study all ES teachers in Illinois. The participants
taught in middle or high schools and in rural, suburban, and urban schools from across Illinois, resulting in a data set that contained diverse networks that intersect with each other.

**Ethical Issues-Human Subject Research/IRB**

This research was approved by the Northern Illinois University (NIU) Division of Research and Innovation Partnerships, Office of Research Compliance, Integrity and Safety Institutional Review Board, Record Number HS21-0305. Interactions were exclusively online for teacher convenience and safety during the COVID-19 pandemic. Participants completed forms consenting to the use of their data collected during the summer workshop and for both the first and follow-up interviews. Interview transcripts were anonymized and saved as protected files on a secured device. Teachers’ names have been changed to maintain the anonymity of participants and members of their networks are identified only by initials.

**Data Collection Methods**

We collected two types of data for this study: teacher-created network maps and interview data. During the virtual workshop, we introduced network mapping by asking teachers to use Jamboard to create a map of the people, organizations, and opportunities that led to their participation in the workshop (Figure 14). Teachers received feedback on these maps from both peers and workshop facilitators and had the opportunity to make changes. These maps diagrammed subjective mental pictures of a subset of each teacher’s network (Henneberg et al., 2006; Wallman, 1984), describing their individual understanding of the relationships, interactions, and interdependencies that affected their decision to participate in the workshop (Henneberg et al., 2006). These maps guided the development of an interview protocol in which
we inquired about the networks that support their teaching of ES and as a tool during those interviews (Emmel & Clark, 2008).

Our goal was to create an interview protocol that would reveal the human and nonhuman resources teachers access when they had questions about ES and to explore how they interact with those resources. Because we wanted teachers to define their own network, interview questions were open-ended (Pahl & Spencer, 2004). Questions were posed to elicit names of

Figure 14. Screen capture of a network map created during the virtual workshop.
people and other entities to which they have some connection. Because name-generating surveys have been found to limit recall (Brewer, 2000), we used semi-structured interviews to create a list of the participant’s contacts who fit our criteria. This allowed for follow-up questions, clarification, and narratives that described the nature of the connections that are not typically described in name-generating surveys (Carpentier & Ducharme, 2005).

Early versions of the protocol contained twelve primary questions and twenty follow-up questions. The initial protocol was piloted with three people, one former teacher who now facilitates teacher preparation and two ES teachers who were not part of the study group. Pilot subjects provided critical feedback on question clarity, accuracy of language, and organization and flow of the interview. With this information, the protocol was shortened by eliminating questions that strayed beyond the scope of the study. Some follow-up questions were consolidated. The final interview protocol included ten questions with twenty-two additional follow-up questions (Table 12).

We conducted interviews on Zoom. For each transcript and recording, pseudonyms were assigned to all teachers to protect their identity. The people mentioned in the interviews are identified only by their initials. The video and audio recordings were saved on a secure laptop and backed up on an external drive kept secure in a locked cabinet. Interview duration ranged from 27-52 minutes, with an average duration of 45 minutes.

**Researcher Characteristics**

While all research is informed by the identities, experiences, values, and biases of the researchers, in qualitative research we identify how these both inform and limit our analyses and interpretations. This positionality is a critical axiological assumption (Creswell, 2013).
Table 12

List of questions included in the final interview protocol.

1. Describe how you have learned the Earth science content you teach.
   a. Can you give me some examples of these experiences?
   b. How did you find these opportunities to learn Earth science?
   c. Were most of these experiences before or after you were working in the classroom?
   d. Can you discuss the most helpful professional development that has supported your teaching of Earth science concepts?

2. Do you remember the last time you taught something in the Earth sciences that was new to you?
   a. Can you give me some examples?

3. When you encounter new and/or unknown ideas in the Earth sciences, who or where do you turn to get your questions answered?
   a. How did you first find these trusted resources?
   b. How often do you access these resources? Examples?
   c. What do these resources provide? Examples?
   d. How do you know you can trust them to present the most accurate science?
   e. Are there any other places you turn to seek answers to your questions? (repeat until they are done)

4. Once you have found the information and resources, how do you enact it in your classroom?
   a. Can you give me some examples?

5. Are there Earth scientists in your local community that you consider resources?
   a. Can you give me some examples?
   b. How do you interact with them?
   c. Can you tell me more about how these people are resources?
   d. Have you reached out to any of the scientists from our workshop or webinars?

6. What STEM teaching/learning organizations do you access/belong?
   a. What do these organizations offer you?
   b. What are some specific examples of how these organization affect your work?
   c. How involved in the organization are you?

7. We have talked a lot about the different resources that you access to support your work with students. Is there anything more you would like to say about how these resources support your professional growth?

8. If money, time, space, etc. were not barriers, what kinds of resources (human and otherwise) do you wish you had access to?
   a. How would you access these resources?

9. Can you describe your role in the school or community?
   a. How many other teachers (STEM or otherwise) are there?
   b. Can you describe the sense of community there?
   c. How connected to STEM industries, businesses, or organizations are you?

10. Do you have anything to add or any questions you would like to ask?
Author 1 is a white, nontraditional Ph.D. candidate in a geoscience education research lab. Prior to pursuing a Ph.D., Author 1 was a secondary STEM teacher, spending six years teaching in a diverse urban middle school and 19 years in a mostly white, affluent suburban high school. Author 1 grew up in a remote, rural community in the western U.S. and was a first-generation college student who earned B.S. and M.S. degrees in geology.

In this study, most participants are female, and all are white secondary Earth science teachers. Author 1 has insider status because she is a white female with experience teaching Earth science in diverse urban middle schools and a suburban high school. Like many of the participants, she taught through the transition to the Next Generation Science Standards (NGSS Lead States, 2013) and during the COVID-19 pandemic.

This research was conducted through a project in which participants learned about critical zone science and sustainability in the Midwestern region (Kumar et al., 2018). As an outcome, participants created NGSS storylines (Reiser et al., 2021) that address sustainability issues in the urban, suburban, and rural communities where they teach. Author 1 has outsider status because she is not from the Midwest and has never taught in a rural school. Other factors that may contribute to outsider status include her strong pro-environmental beliefs about the importance of living sustainably. Furthermore, she welcomes the perspectives of those who have been traditionally excluded from science, technology, engineering, and mathematics communities. While some participants may share the same socio-scientific mindset, others may not.

The other two authors served as advisors to the first author in the project development, data collection, and analysis phases. Author 2 served as Author 1’s graduate advisor and identifies as White and upper-middle class. She has several years of high school ES teaching experience and conducts research on ES learning. In addition to advising the research, Author 2
assisted in the development of the codebook through a process of inter-rater analysis. Author 3 served on Author 1’s graduate committee and identifies as White. Author 3 contributed primarily to the network analysis and did not interact with participants. She taught K-12 mathematics and science classes (but not ES) for three years, is currently in a faculty developer role and formerly was an associate professor, and studies scientists and faculty social networks across STEM.

**Data Analysis Methods**

Data analysis had two components: thematic content analysis of interviews and social network analysis.

**Thematic Content Analysis of Interviews.** In the late spring and summer of 2022, audio recordings were transcribed using Otter.ai. Transcripts were checked for accuracy by simultaneously listening to the recordings while reading and correcting the AI-generated transcripts. Coding of transcripts was conducted between November 2022 and January 2023. Our coding strategy utilized content analysis of the transcript narratives (Saldaña, 2023) to better understand the evolution, structure (Froehlich et al., 2020), and relational qualities (Carpentier & Ducharme, 2005) of the networks that support their teaching of ES.

To build trustworthiness in the findings, Author 1 engaged colleagues in the NIU Visualization and Geoscience Education Research Lab to conduct inter-rater coding and development of the codebook (Syed & Nelson, 2015). Through multiple iterations, content analysis led to the development of a codebook. Coders kept memos throughout the process, recording reflections on the analysis, methods, dilemmas, conflicts, and their states of mind (Bogdan & Biklen, 2007). Initially, the codebook was a list of teachers’ contacts and resources (alters) and descriptions of where alters worked and how often they were being accessed. Further
analysis resulted in fuller descriptions of alters and descriptions of interactions as positive or negative. Working with inter-raters, codes were streamlined to decrease redundancy. Codes specifically identified social network nodes and the quality (+/-) of connections or ties. Alters were color-coded to identify proximity to a teacher (school, community, district, state, organization, college/university, and industry). Some alters were identified in multiple categories (a former professor who provides professional development opportunities). Using Excel, the codebook of the classified nodes was organized into a spreadsheet. The spreadsheet was shared with the inter-raters who used it to code three of the interviews.

Upon completing the content analysis and coding of each interview, inter-raters compared and discussed similarities and differences to better define and describe nodes and ties. The most significant changes were for those nodes that played multiple roles in the professional support system of the teacher. On the third transcript, inter-raters reached a level of agreement of 94%. The rest of the interviews were coded by Author 1.

Using the codebook and content analyses, Author 1 summarized each teacher’s school setting, training and professional development in ES, their participation in organizations and associations that support ES teaching, the ES resources they relied on, and the challenges they faced when teaching ES. Quotations were used as evidence in these summaries (Saldaña, 2023).

From the codebooks and summaries describing individual teachers’ networks, preliminary individual network maps (egonets) were diagrammed using Microsoft PowerPoint (Hogan et al., 2007). Alters were visually grouped to indicate the context of their relationship with the actor. Alters that had multiple roles were indicated by tie thickness and were placed to show overlap in groups, positive relationships were indicated with solid ties, and negative relationships were shown with dashed ties (Figure 15).
Once each dataset (codebooks, summaries, and egonets) was drafted, they were shared with the corresponding teacher interviewee. To improve accuracy (Knaub et al., 2018) and provide transactional validation (Cho & Trent, 2006), teachers were invited to participate in follow-up member-checking interviews to provide feedback and correct mistakes (Candela, 2019). Author 1 used Zoom to share her screen, taking notes directly on the codebooks, summaries, and egonets in real-time so that participants could ensure that these products
reflected their perceptions of their own network (Koelsch, 2013). These follow-up interviews were recorded and transcribed on Zoom.

**Social Network Analysis.** To understand the structure of the network of teachers we interviewed, we used social network analysis to map the networks described in interviews with the teachers. Initially, we created individual egonets for each teacher. We found the teachers were connected to each other through the people, programs, and resources they described in their interviews. To better understand the interconnections between the interviewed teachers, we constructed a single social network map and analyzed the full network of all the interviewed teachers.

To create the full network map, we organized the information about the people, organizations, and resources from each codebook into a separate new Excel Workbook, within which, two sheets were created. First, the “Elements” sheet listed all the teachers we interviewed (Egos) and people, organizations, and resources (Alters) that emerged from those interviews. The Elements sheet had four columns: (1) “Label” where all nodes were listed; (2) “Type” where nodes were identified as people, organizations, or resources: (3) “Sector” which identified where the node functions or is accessed; and (4) “Description” lists information about the node provided by the teacher. The second sheet, “Connections” listed all ties identified from the interviews. The Connections sheet had four columns: (1) “From” listed all of the actors and alters, (2) “To” listed the nodes that those actors and alters are connected, (3) “Type” indicates if the tie is positive or negative, and (4) “Description” lists any other shared information about the tie. The Excel workbook was imported into Kumu.io (Kumu, 2023), and using the Big Data Template, a comprehensive social network map was generated and saved as ILEST-SNA. All nodes were set as “floating”, and ties were set as “undirected”.
SNA metrics (Table 11) were calculated using the functions within Kumu. Following Freeman (1979) and Brass and Burkhardt (1992), we determined the roles individual teachers played in the network. Local hubs were teachers with high levels of degree centrality and were very involved in the network. Boundary spanners were identified by high betweenness centrality, acted as intermediaries in the network, were likely aware of what was going on in multiple smaller networks, and controlled the flow of information in the network. Network leaders were identified by high eigenvector centrality, indicating direct connections to influential network nodes. Information brokers were individuals with high closeness centrality indicating they were connected to otherwise unconnected actors and filled network holes.

Limitations

The authors recognize that this study is limited by sampling bias, informant bias, and researcher bias. Because the sampling strategy was non-probabilistic, we cannot assume that the sample fully represents the population of Illinois ES teachers. Half of the teachers we interviewed have ES degrees and all are certified to teach ES in the state of Illinois. Three teachers have earned degrees in the environmental sciences, suggesting that they may have the content knowledge needed to teach NGSS-ESS sustainability concepts. This suggests that our sample over-represents teachers with degrees and coursework in ES when compared to national data on ES teacher’s degrees (Banilower et al., 2018; Wilson, 2018).

During the interviews, every effort was made to make the teacher participants comfortable. However, the study is limited by possible informant bias where those interviewed may have chosen to not reveal all their connections or inadvertently overlooked certain network members (Knoke & Yang, 2008). All three of the authors are white females who worked as
secondary STEM teachers and are actively involved in educational research focused on ES issues. These commonalities limit our collective experience which influences the questions we asked and our interpretation and synthesis of the research findings.

**Transferability**

The concept of GLE is new. Similar studies in other states are needed if we seek more transferable findings. As in ecological studies, this is a case study science wherein no two studies can be identical. In our attempts to initiate a GLE that supports teachers, we recognize that each GLE will be unique, dependent upon place, people, and resources. These findings reflect the work of Hecht and Crowley (2020), who found that application and adaptation to different locations is effective with considering the local and regional ES challenges.

**Results**

**Participant Descriptions**

Ten teachers from a variety of settings were interviewed for this project, nine women and one man (Table 13). All participants were White. Five teachers had degrees in ES and all teachers were certified to teach ES in Illinois. One teacher was also certified in two other states. All teachers are current or past members of the National Science Teaching Association and Illinois Science Teaching Association. One teacher is a member of the National Association of Geoscience Teachers, two teachers are members of the National Earth Science Teachers Association. All teachers participated in the virtual professional development program designed to support the teaching of critical zone science in Illinois.
Table 13
Participant descriptions, organized by degree.

<table>
<thead>
<tr>
<th>Pseudonym</th>
<th>Setting</th>
<th>Degree</th>
<th>Other Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sam</td>
<td>Suburban</td>
<td>B.A. Psychology, Gifted Education</td>
<td>National Geographic Certified; Science Olympiad Coach; Teaches Earth and integrated sciences</td>
</tr>
<tr>
<td></td>
<td></td>
<td>M.Ed. Elementary Education</td>
<td></td>
</tr>
<tr>
<td>Wanda</td>
<td>Rural</td>
<td>B.A. American Sign Language</td>
<td>Worked in informal environmental education; participated in R/V Joides Resolution School of Rock and multiple geology field experiences for teachers; teaches a mandatory one-semester Earth science course</td>
</tr>
<tr>
<td>Cassie</td>
<td>Rural</td>
<td>B.S. Biology</td>
<td>Only Earth science &amp; biology teacher at her school; severe weather spotter</td>
</tr>
<tr>
<td>Joselin</td>
<td>Suburban</td>
<td>B.S. Biology</td>
<td>Teaches biology and Earth science; works with teacher candidates from local college</td>
</tr>
<tr>
<td>Zena</td>
<td>Rural</td>
<td>B.S. Wildlife Biology</td>
<td>Has worked in multiple states; participated in R/V Joides Resolution School of Rock and multiple Earth science PD; Teaches Environmental and Life sciences</td>
</tr>
<tr>
<td></td>
<td></td>
<td>M.S. Biology</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>M.Ed. Science Curriculum and Instruction</td>
<td></td>
</tr>
<tr>
<td>Opal</td>
<td>Urban</td>
<td>B.S. Geology</td>
<td>Attended environmental and hydrogeology field camps; worked in the water quality sector and now teaches Earth, environmental, and life sciences</td>
</tr>
<tr>
<td>Stella</td>
<td>Suburban</td>
<td>B.S. Geology</td>
<td>Attended geology field camp; participated at EGU-GIFT and R/V Joides Resolution School of Rock; Teaches year-long Earth and environmental sciences</td>
</tr>
<tr>
<td>Jamie</td>
<td>Urban</td>
<td>B.S. Environmental Science</td>
<td>Worked for state archeological survey; attended environmental and hydrogeology field camps; teaches physical science at school with academy tracks</td>
</tr>
<tr>
<td></td>
<td></td>
<td>M.S. Hydrogeology</td>
<td></td>
</tr>
<tr>
<td>Katie</td>
<td>Suburban</td>
<td>B.S. Geology</td>
<td>Attended environmental and hydrogeology field camps; worked as an environmental consultant and now teaches Earth and environmental sciences</td>
</tr>
<tr>
<td></td>
<td></td>
<td>M.S. Environmental Geosciences</td>
<td></td>
</tr>
<tr>
<td>Price</td>
<td>Suburban</td>
<td>B.S. Environmental Science and Restoration Ecology</td>
<td>Attended environmental and geology field camps; worked School’s literacy coach; Teaches Earth and environmental sciences, dual-enrollment geology</td>
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Teachers’ Networks: Interviews

Colleagues. Every teacher discussed how their colleagues were critical to their success in teaching ES. Colleagues are defined here as other teachers in their schools who supported them and their work with students. Four teachers described these colleagues as mentors, while six teachers referred to peers. Joselin describes the value of having a mentor with ES knowledge despite not having formal ES training of her own:

I did have a teacher who ... was so brilliant. He had, like, all the content knowledge for Earth science. Like, you know, he didn't even need a book. He just had it all. You show him any rock, any mineral, he knew what it was, you know? He was someone that I would go ask when I had questions. – Joselin

For those who had degrees in ES (n=5), having ES mentors enabled them to identify quality resources and teaching strategies at the beginning of their careers. For example, Price describes his cooperating teacher mentor as “having a lot of really, really cool resources”.

Every teacher interviewed (n=10) talked about the value of working with other teachers (i.e., peers) to design and implement ES curriculum. In many cases, these were the “go to” resources when teachers had questions about ES content, teaching strategies, and assessment. For teachers with little background in ES, these colleagues were critical to their success. For example, Wanda describes how her peer mentored her in learning the ES content:

I never took ES in high school or college, so I started learning from a colleague... She came like five years ago and is why we started having Earth science. I started learning from her, like, literally running to her room, like she would teach us the lessons in advance. ... I was just like a student, and she was my teacher.

Cassie describes how she collaborated with a peer teacher in her building that she knew from her licensure program: “If there were things I didn't understand, I would walk in and say, okay, so J, tell me about this”. Joselin described how she was self-taught, pre-internet and when teachers “relied entirely on other teachers for your material”.
These in-school colleagues also supported teachers who had degrees in ES. Teachers reported (n=3) that these colleagues clarified their understanding of science concepts, co-developed strategies to engage students, and created better activities and assessments. For example, Price explains how a colleague helped him recognize why a lab was not working:

But then I was just in the office with my environmental science teacher, and she goes, “Oh, like, I used to do that lab. But I don't do it anymore.” Because I guess the science is totally bogus on it and she gave me a resource. There was a bunch of physics teachers breaking it down saying that, like, it's such a more complex system, that it's not just like this enclosed, here's your carbon dioxide in the glass thing, throw a heat lamp on it, and it's going to heat up more. There was so much more at play and a lot of teachers were saying like, you can kind of fudge it, and it kind of works, but if you're really looking for the science behind it, like, it doesn't quite add up to why that's happening. So I ended up not doing the lab at all for it.

Beyond casual interactions, Stella describes how a 17-year veteran teacher would collaborate to look up information and they ended up combining their courses: “he's been doing this for so long, so he's very knowledgeable… And we actually combined the two courses [Earth and Environmental Sciences]... I really appreciate collaboration and the ideas he has are great.”

In contrast, three teachers reported that some colleagues were not supportive or did not give great advice. For example, Joslyn reported that a senior colleague was resistant to revising the curriculum to implement the NGSS. This was echoed by Jamie who observed that newer teachers were more open to curricular innovation:

I hate to say this, but it seems like the younger teachers that have more recently come out of college seemed to have more research-based information. And say things less often like, “Well, this is just the way we've always taught.” It's like, “Well, I like to keep up to date and things.” So yeah, it's good to talk to A next door who's just a little bit younger than me.

**Professional Learning Communities (PLCs).** At some point in their career, all the interviewed teachers participated in professional learning communities (PLC), where they built connections that affected their teaching of ES. PLCs are school or district groups of teachers and
administrators who meet on a regular basis. Members of a PLC are often grouped by content area, grade-level teams, or shared interests. PLC members work together to make decisions about curriculum, analyze student data, learn research-based practices, or address issues around student wellness.

Teachers found most PLCs gave them the opportunity to make meaningful connections with other teachers from around their school or district. Opal described how PLCs feel safer than larger faculty meeting spaces: “I'm still kind of like a fly on the wall when we have big faculty meetings, …but within our curriculum groups, we have really great PLCs and discussions.” Joselin discussed how PLCs are spaces where teachers can learn new ways of teaching, collaborate, and support each other:

> We're looking at other people's ideas and think, “Wow, okay, well, I never would have done that, you know, but it works.” So a lot of times we do that in our PLC, we’ll say, “Okay, we need an idea for this. We know this lab hasn't worked for a while, let's go look for something to satisfy this component. Everybody, bring your ideas next week,” and then we go through them and we figure out, you know what we're gonna do.

Three teachers felt the PLCs in which they were assigned to participate lacked focus and direction, failing to support teachers new to a school. While she continues to stay in touch with some of the teachers in a previous school, Cassie felt like other teachers in the ES PLC did not take the curriculum seriously,

> So the first school that I worked in, … they really didn't have a curriculum, I go to the ES PLC, and I'd be like, “Okay, so I've never taught ES, where do I go?”, and their whole theory in life is that, you know, “Well, teach what you enjoy and what you think the kids are going to enjoy.” And I'm like, “No, I need a scope and sequence”. I can't just randomly teach things.

At the District level, teachers’ perceptions of PLCs were mixed. Four teachers described how PLCs were very helpful, providing connections between teachers who felt isolated. Price
discussed how these PLCs provide space to check in and support each other, “We meet like, … once every other week, … usually just touching base, seeing how things are going, planning out some activities like labs.” Stella described how her district Earth and environmental sciences PLC was able to acquire district-level support for purchasing lab materials and improving teachers’ content knowledge:

My colleague and I were working with our sister school and the two teachers there… and one of the teachers there, … actually found all these labs, and a lot of them are chemistry based, which for me, I was like, “Oh, no.” It was definitely my worst of the sciences. Now I am so grateful to have been able to learn more chemistry.

**Administration.** All the teachers interviewed considered school administrators to be influential components of their networks. For most teachers, principals and assistant principals were considered helpful facilitators of teachers’ professional growth (n=4) and ensuring departments were appropriately staffed (n=3). For example, Stella felt more successful because her administrators supported teachers’ work to improve their content knowledge and support students’ ES learning: “My school is incredibly supportive when it comes to buying new resources such as labs. …When I went overseas and to a few of these conferences, my school was incredibly supportive and helped out with that.”

For teachers like Sam, who did not have a background in ES and felt like she needed that expertise to support ES instruction, school administrators facilitated the hiring of an ES teacher: “We went to admin and said, ‘Whoever we replace KK with has to be an ES person. Because we have physical science, general science and two biology people.’ So they found someone that had a master's in geology.”
In many situations, however, school administrators did not support teachers’ efforts to inspire students in ES (n=3) or limited teachers’ professional opportunities (n=4). The administration at Cassie’s rural school discouraged field trips:

He's like, “[In the city] you had access to museums, and like government labs and things like that…You had access to field trips that took you to all those places. These kids don't have that access, because half of the field trip time would be, you know, driving to wherever we were going.”

Joselin did not feel like she could count on school administrators to communicate teacher-leadership opportunities, forcing her to do her own research. Joselin was interested in supporting pre-service and early career teachers but was not able to do so until a new administrator prioritized working with the local teacher-preparation program at the local university:

I learned about professional development schools in my master’s program and I was like, “Huh, I wonder if [we are] one?” Because it would make sense with the university’s teaching program being what it is, and low and behold, we were, but I never knew about it until it became more important to an assistant principal at our school.

As with school-level administrators, teachers’ perceptions of district and state-level administrators were mixed (n=5). For example, Sam described how important community support was to district administrators' decision-making, “We have a reputation for being really good in the sciences and…the community feels strongly about the kids doing well in science and they let the district know that.” Joselin discussed how frequent turnover in district administration degrades teachers’ trust in district personnel and initiatives:

The turnover that we've had in our school district: we have had administrator after administrator after administrator. And you know, the same thing with curriculum coordinators and superintendents. You don't get anybody who invests in relationships …You start to see some things, really exciting things, happen and then all of a sudden, administrators leave. And now you're back to the beginning again, that, that's really heartbreaking.
**Community Organizations.** Participants (n=8) described the support they received from members in their community. Some of these community connections were well-established, others were emerging. These connections included those with both the for-profit and nonprofit sectors.

Four teachers discussed how local businesses and industries supported ES teachers by offering grants, sending volunteers to support extra-curricular efforts, and hosting professional development. Some of these connections were small but meaningful efforts. Zena discussed how local industries provided financial support for expanding students’ opportunities in Earth and environmental science courses, “I did get a grant from a local business, like, an energy company, … to dive deeper into energy [industries’] need to diversify into renewables.” Sam described how large and small local businesses support her school’s long-standing Science Olympiad program by providing volunteer coaches: “We've had Northrop Grumman in doing things, …like for Science Olympiad, I've got a couple of coaches from them and I've got a guy who runs his own electrical business who comes in and coaches Science Olympiad.” Stella’s school had a Girls in STEM camp that leveraged similar connections, inviting STEM professionals to “talk to and teach girls about STEM and their companies and what they do.”

Wanda and Zena both took advantage of the professional development and student field experiences offered by a nearby National Wildlife Refuge that is an Environmental Protection Agency (EPA) Superfund site designated for post-Cold War munitions manufacturing. Zena described how the manufacturer hosted field experiences for teachers to learn about Superfund designation: “They built bombs and artillery during wartime. And there was a lot of dumping and pollution in the area. They still have like bunkers there, so they're going to take us to view parts
that are usually restricted.” Wanda discussed how she accessed the site with her students and built upon those field experiences in class:

We take our students, and they give us a tour and talk about, like, all of the waste that was left over from military activity there and like what they've been doing to try to remediate it. And we're gonna go through a little like mini unit on different sites locally.

Wanda also described how community relationships with local industries affected how students and parents thought about scientific issues.

We live in a really rural community that has had a lot of pushback with, like, COVID and climate change. … we have like, a lot of coal mining in our area … but they're going more to solar and natural gas … and I've noticed a shift in the amount of pushback from teaching climate change.

However, not all relationships with local industries have been maintained. Joselin described how shifts in public opinion regarding the corporate models of agricultural biochemical companies have discouraged her from collaborating with those organizations: “We used to have a big connection with [large agriculture corporation], but after all that we’ve learned about them, I really don’t want to have a relationship with them.”

Five teachers discussed their connections with non-profit organizations that host public events, provide local resources and volunteers, and support students’ career goals. Katie found value in the local Farm Bureau, “I went to like the county Farm Bureau, for a presentation on soils. It was a good reminder of how important soils are to our state and the rest of the world.”

Wanda valued field experiences provided by a local ES professional association:

The mining and aggregate summer program, they taught us … actual content … and activities that you could use in the classroom…. So I have a bunch of samples from there, a lot of pictures and video clips, things that I can use in my classroom. They also have grants every year so any teacher that's been in the program can apply for the grants.
While these experiences benefited teachers, Price described how he has become cautious about inviting guest speakers to his classroom. He emphasized that the presenter needs to be able to connect with students:

CNT worked with one of our environmental science teachers in the past and they brought some stuff in to work with students, but it was tough. He ... just wanted to kind of lecture to a bunch of high school kids. And it was like, super boring. ... I respected the content that he was sharing, but ... the delivery was a big disconnect.

Three of the teachers work in schools with academies or pathway programs where community organizations provide places for students to shadow professionals and learn about different careers. Unfortunately, none of these ES teachers were able to identify how these programs connect students to ES careers. Jamie described her work with local public servants and service organizations: “Students work with like local police and fire departments. And ... the local homeless shelter and food bank for service. ... But no, there’s no options for like Earth or environmental careers.” Opal was frustrated that the similar lack of opportunities for her students was limiting their sense of career options:

They want students to start focusing on like, a path, and it's specific to the area, you're not going to see a lot of geologists or environmental scientists ... they're focusing on these kids’ socioeconomic status. The purpose of the career pathway is to have seniors graduate with professional license certification.

**Colleges and Universities.** Colleges and universities provided multiple important opportunities for teachers to cultivate and maintain their networks. These relationships began when teachers were college students and began to meet with and interact with their professors. When those relationships were maintained, teachers continued to take advantage of opportunities to do research, interact with former professors and their graduate students.

**Geoscience Faculty.** Four teachers who were certified at the same university mentioned one particular ES professor who was working with teachers to install small monitoring wells at
schools, provide data sets, and support interactions between the university, teachers, and their students. Katie stated that, “With [my former professor], we’re installing monitoring wells at our campus to get kids thinking about where their water comes from.” And Opal is hoping that getting students working with the same professor will be “…at amazing opportunity …that could open up new pathways for them.” Price explained that the same professor “...was my advisor for my thesis and we stay in touch.” And Jamie agreed that she would pursue the same professor when looking for scientific data for a lesson.

Teacher Preparation Faculty. Teacher preparation programs continue to impact teachers well into their careers. Teachers discussed that they reach out to faculty, teachers from their cohorts, and the cooperating or mentoring teachers with whom they trained. Jamie stated that, “When I am teaching something new, I sometimes reach out to my old cooperating teacher.” Opal described how she continues to, “reach out to [my teacher preparation professor] on all things NGSS, … he's given me so many resources on how to apply the practices.” Stella discussed how “Forest has been awesome at just providing resources since I graduated seven years ago. And it’s because of her I have ever had the opportunity… to network at all.”

Wanda described how the education and outreach program at a local university supported her learning of ES. During a professional development event, the university offered teachers from all disciplines to participate in learning new content.

They had a professional development day specifically for geology. I learned a lot that day, …and they were promoting a geology program for teachers to take courses so that you would be certified to … teach dual-credit geology classes. There were a lot of activities that we could bring directly into our classroom. And I think those were the most helpful, like, teach me something, but then also teach me how I can, like, give me an activity that goes directly into my classroom.
Three teachers were actively working with college and university programs designed to support teachers' implementation of standards and developing teacher-leaders. Sam discussed the training she and her colleagues received in the early stages of implementing NGSS: “For three years, the [university outreach] group was training us, and we really worked together. Like, so you had four or five teachers working on a problem instead of each in your own classroom. Yeah, that was really powerful.”

Both Wanda and Zena participated in a Noyce Master Teacher program associated with an Illinois university. Wanda described how this program encouraged her to take risks and try new approaches to teaching ES content:

Noyce has pushed me to do things and incorporate labs and content and techniques that I never would have considered if I had not been a part of it. It has been definitely like, probably one of the things that has pushed me in my career, the most. I wouldn't have … done any of the things … the lessons stretching my students, pushing my students … I've met and collaborated with teachers from different schools in the area.

Through the Noyce program, Wanda actively collaborated with Zena. Zena described how working with other teachers in the Noyce program encouraged her to integrate new content into her courses: “My focus is biology because it’s my main course … it makes me want to add more ES into my biology and vice versa.” Zena also explained how Noyce was helping her to develop into a leader, “Part of the program is to kind of push you to be a leader outside of your classroom, which I also appreciate, because it's, it's hard to go seek out yourself.”

Membership in Associations and Organizations. Next, we review how teachers perceived the effects of professional associations and organizations on their networks. All the teachers we interviewed (n=10) maintained memberships in professional associations. All were current or past members of the National Science Teaching Association and the Illinois Science Teaching Association. Only a few were members of ES-specific organizations or associations,
such as the National Association of Geoscience Teachers (n=1) or the National Earth Science Teachers Association (n=2). All of these groups provided support for teachers in a variety of ways including conferences, publications, and web-based resources. Two teachers have taken on leadership positions in these groups.

Conferences inspired and invigorated teachers. Cassie described how attending NSTA conferences made her feel like part of a larger community, “You're with like-minded people, that are super excited about the things that you're super excited about, … I can go there and …geek out with people and you leave and you're just super excited about teaching again.” Stella participated at a variety of conferences and described how they benefited her teaching, “NSTA, ISTA, yeah, whenever I attend one of those, I collect all the information, I get these big ideas… especially the EGU-GIFT workshop in Vienna, Austria.” Jamie learned about NAGT’s Earth Educators Rendezvous and joined the organization because, “It inspired me because I was able to see a lot of different ES teachers and realize that I could still, like take data and do research, even as a teacher, and to think critically about what the best way is to teach from the research side.”

Journals and publications from these organizations inspired teachers to try new approaches in their classrooms. Thanks to a subscription for teachers in his school, Price benefitted from labs and activities described in NSTA’s journal for high school teachers, “We get the Science Teachers from NSTA, like the magazine, in our department, …and I really value some of the ideas from there.” Joselin agreed, stating, “The NSTA journal, so they have a good mix of physical, Earth, and life science ideas in there. I have tried and true things that work in the classroom.”

As members, teachers were grateful that NSTA resources are also available online. Joselin described her use of these, “If you go on their website, and you can search for different
labs, or different activities, and you know, it's all there at your fingertips … it's an infinite resource, but it can be overwhelming.” Opal accessed NSTA’s website as a source of professional development, “from NSTA, a great organization, those fantastic webinars, listening to just different points of views, it’s great professional development.”

These organizations also provided teachers with opportunities to become leaders in science education. Wanda was excited to shift her relationship with the state science teachers’ association from receiver to leader, “I’m in ISTA, starting in a couple of weeks I’ll be a regional director on the board and I imagine that will be fun, I'm excited for that.”

**Government Entities.** Government entities provided a wide array of resources that support teachers, ranging from local to global. County and state-level governments managed outdoor learning environments, provided accurate and accessible reading and graphical materials for teachers to learn from and share with students, and web-based resources such as maps and real-time and archived data.

Two teachers discussed how they accessed local government entities to support their students. When Zena moved to a new school in a rural, agricultural area, she, “reached out to the county ag extension person, …for resources for like, agriculture-specific types of things.” Sam’s students did not have access to natural spaces on campus. This encouraged her to reach out to a local forest preserve, “to do like a bio blitz ever year, they have elk and eagles, and it’s pretty close… my thinking was that it wouldn't be like a big deal to do, and it could be something that could be ongoing.”

While local governments provided opportunities to work with local people and organizations, State and Federal agencies supported teachers’ acquisition and use of ES articles, data sets, and interactives. Katie had her students, “use the state Geological Survey site to learn
about sinkholes and subsidence. The writing is good, and my students can understand it.” Opal found that state-level resources were more relevant to students, “I like to have them compare data on the Illinois EPA and the US EPA sites. Especially in my environmental science class. And getting them to look at air quality and other local pollution issues. Students actually care about that.”

All of the teachers considered resources from Federal science agencies to be trustworthy and accurate, referencing at least one scientific government agency as a provider of maps, data, infographics, reading material, or models. With her students, Jamie emphasized the trustworthiness of the data, “NOAA, USGS, I trust these …and students can follow the data source it back to where it comes from, like, that's what I want … I want to give my students data, and they they're gonna figure it out.” Price had a similar sentiment, “when we're building data sets or …like readings, I am looking for the primary sources and then it ends up being a lot of where we're getting info from is … governmental type of sites, like USGS.”

Wanda described her rationale and instructional design process when using these resources to build students’ skills and knowledge:

I like USGS, NOAA, National Park Service because they have data sources. I always start with, “What is my goal for students to learn today? What do I want them to take away?” And like, I come up with like the answer first. And then like, “Okay, well, what did they need to get to that answer?” And kind of work backwards and give them like, “Okay, well, they will need this dataset,” or like, “They'll need to be able to ask this question.”

In addition to data, Sam described how she used reading material and imagery when designing her storylines, “This Dynamic Planet from the USGS helped me build my storyline about plate tectonics and it actually became like story time for the kids.”
Three teachers discussed their experiences participating in trainings offered by federal government agencies. These trainings improved their content knowledge, impacted their practices with students, and changed their perceptions of themselves as scientists. Zena described how she was able to learn ES content, “I did do a training …with NOAA, it’s their Ocean Explorer training and I learned a lot about how like, the deep ocean geology affected ecosystems. It was really cool.”

During a field excursion hosted by the National Park Service, Wanda was able to conceptually connect Earth history, plate tectonics, and climate change:

I saw the stromatolites in Glacier National Park. And I knew that they were fossils. But I didn't understand what they were, they're like bacteria, fossils of bacteria. … And I wanted to tie in, in Glacier stromatolite fossils, like with, like, in the mountains, like, why are they there? Because we use Glacier National Park to talk about climate change… And then it hit me, “construct an argument based on evidence about the simultaneous coevolution of Earth's system.”

After participating in a research experience for teachers funded by the National Science Foundation, Stella’s perspective of herself as a scientist changed:

I applied and was accepted for the School of Rock on the Joides Resolution … What was the most beneficial for me is we were actually doing the hands-on work, essentially, that the scientists do, so that we experienced it … And for me, …I learned so much, and being able to share that experience and talk about, “okay, this is, this is what the scientists are doing,” …And I was like, okay, this is why science is awesome.

**Physical Resources.** Three teachers discussed the role of physical resources in their work, including labs, textbooks, and popular press books. Stella described how commercial labs designed to address NGSS can be useful resources because they are revised regularly and provide teachers with opportunities to work together to learn new science concepts.

The packets that [Flinn and Carolina] send us, the teacher resources are phenomenal … with just so much background information, …I'm learning so much just by reading through these and talking them over with my colleagues … And we’re getting rid of the
Earth science book we had, we just don’t need it, especially with the readings for the labs.

Stella was not the only teacher who mentioned how static textbooks are becoming less useful and relevant. Cassie was frustrated with her textbook’s inconsistent and out-of-date content, “It still has Pluto as a planet. And it still talks about, in one part, like the mantle … being solid, and one part talks about it being liquid, and it just doesn't make any sense.”

Teachers explained how popular press books written about ES had a different, more positive role than textbooks. Wanda explained how she and her students were engaged in learning about ES through good storytelling:

I was reading *The Story of the Earth in 25 Rocks* with my students and the author, he wants to tell the story about how twenty-five rocks and outcrops have changed like the way we all think about the planet. And by the way, my students found it really really interesting.

**Online Resources.** The Internet has revolutionized teachers’ access to resources (this study was conducted prior to the release of Chat GPT). Here we identify online resources as the diverse collections of data, text, imagery, videos, and curricula available on the Internet. Teachers described using online resources to learn the ES content they teach, manage their work, and engage students in ways that would be impossible without online resources.

*Google and all its tools.* Google was an essential resource for every teacher interviewed. Teachers described using the Google search engine to look up concepts to improve their understanding or find lesson plan ideas. Price described how Google was easy, fast, and reliable, “For contenty [sic] stuff, … if it's like a process we're looking to do, or something where it's a central idea, like a lot of times, it'll be just the Google search and, you know, see what pops up.” Zena taught her students to recognize reliable content when searching on Google by modeling
critical thinking, “I show them how I put things into Google, and then I kind of look for certain locations, like .gov and .edu. and then find the sources of the information, data and all that.”

Google apps were accessible to all students and teachers used these to create content and teach skills. Jamie described she was using Google apps to teach basic data analysis, “I went through how to make a spreadsheet, then a graph. And I showed them how to make one in Google Sheets, which felt like quite the accomplishment, and they were like, ‘why haven’t we already learned this?’” Zena used Google Slides to curate information and create content for her students, “I'll like, pull information and diagrams from a bunch of websites and put it all into Google Slides. So that … they can have something to refer back to when they’re working.”

Wikipedia. Teachers (n=5) had mixed perspectives on Wikipedia, some thinking that it was not trustworthy, and others found it to be a good starting point for learning new ideas. As someone who did not receive formal training in the ES, Wanda found Wikipedia as a good place to start when she is learning new content, “Sometimes when I can't understand things, I go to Wikipedia first, …and then I go to the resources Wikipedia refers to … Like, what's the point of reading if you don't understand the half of what's in there?” Stella supported her students in a similar way, “I learned in college that Wikipedia is okay, but don't just read the article, go to the sources at the bottom and use those sources to bring you to the actual research.” Opal conveyed a different perspective and discouraged her students from using Wikipedia, “We're gonna use credible resources, right? So, we're not doing Wikipedia, I'm not going to have them use a site that just anyone can generate.”

Science Education Sites. When using web browsers to research different topics or discover new sources of information on social media, teachers found sites that provided content that is very useable and high-quality. Four teachers referred to Paul Anderson’s sites, Bozeman
Science and The Wonder of Science, as useful, evolving, and reliable. Joselin stated, “Paul Anderson has great websites…where you can look up the specific cross-cutting concept or DCI or performance expectation and get ideas from other teachers … and over time, it’s getting even better because it’s still developing.”

Seven teachers stated that they are no longer using physical textbooks and rely on resources online. While Opal’s whole school has agreed to use CK-12, a customizable open-source content and technology platform for K-12 teachers and students (CK-12 Foundation, 2023), Zena has more flexibility and uses a combination of web-based references:

I use CK 12, Concord Consortium, Earth Labs from SERC. I did also teach environmental science … and for that, I used … Annenberg’s Habitable Planet as a resource, and it had a lot of good teacher-facing stuff.

Sam explained how both National Geographic and Science Olympiad resources were accessible, reliable, and motivating to her students. She described using online materials from these groups’ websites:

Like when it's all of a sudden, ‘Oh, you need to teach plate tectonics, here’s our dynamic planet stuff.’ Or, ‘What are we doing for hydrology?’ Check the Sci-Oly site…My educator certification project for NatGeo was ES related because I was sort of seeking ways to excite Midwestern kids about plate tectonics and earthquakes and volcanoes. From that, I learned that anything off of NatGeo is going to be is going to be good.

**Online Communities.** In addition to resources, teachers find community online. Online communities are made up of people with shared interests, whose collaborations are guided by agreed-upon norms and supported by computer technology (Jones & Preece, 2006). For the ES teachers we interviewed, these communities connect them to other like-minded educators. For example, Sam described how, “The biggest, like jump in finding resources and networking is … the internet … now, not only can I find stuff, I can seek out other teachers who are also exploring.”
Google Certified Teacher Program. Teachers (n=4) used Google Classroom, a learning management system, to create, organize, and assign student work. Opal described how becoming a Google Certified Teacher improved her practice through networking with others, “I’m doing professional development within Google Classroom and becoming Google certified. I am finding my people. And the students have Chromebooks so everything that we’re doing is supported and works together.”

Social Media. Teachers (n=6) described how social media has created significant opportunities for them to build their networks by interacting with other like-minded teachers and organizations. Six teachers stated that different social media platforms were important to their professional growth. Along with Facebook groups and X (formerly known as Twitter), organizational forums and community pages have connected teachers with others who are interested in similar topics and grade levels. Sam described her activity on multiple social media platforms:

There's like a Facebook group for I-quest teachers. And then through that group, I made a friend … and we literally, the first time we met sat and talked for six hours about, about teaching science, you know? And then, you know, there's my NAT-GEO Group, where I get to see what everyone else is doing. There's just so many groups online. Like there's two middle school science teachers’ groups that I'm part of online and just get some, you know, some ideas from them.

Wanda was very active in multiple Facebook groups focused on science education: “I’m in lots of ES education and adventure Facebook groups, and then … groups like the Illinois biology storylines. We get help from there all the time for biology.” The biology storyline group inspired her to create a Facebook group focused on creating ES storylines, “That’s how we found each other!”
While social media was a great place to meet other ES teachers and enthusiasts, teachers described how it can also be overwhelming and distracting. Price explained that he was feeling like he needs to pull back from social media,

I'm trying to give it up for the new year, but Twitter was a really good resource for me for… geoscience news or recent publications. There's some cool threads around and then, for me, it turns into, like dig and dig into the research and like, find out some more cool stuff about it, and then building like what we think we can use in the class. I used to rock out on the Facebook… because … people in the department were posting cool activities, but yeah, I've given up on Facebook.

As a National Geographic Certified Educator and Science Olympiad coach, Sam values the communities of teachers she has found with both organizations.

I've also been trained [with National Geographic] and found joys through connections with other teachers. One of my NatGeo friends does ESRI GIS programming, which also hooked me into the Illinois geographic society and looking at, like, the NatGeo mapmaking apps, and then adding a research piece, that all engages kids so differently…SciOly coaches training is rejuvenating, like not just challenging me to learn new things but also just a fun group of educators who want to make learning more fun for everyone.

In summary, we found that teachers’ questions about ES are first directed to knowledgeable close colleagues, reliable online resources (e.g., government science agencies, science communication and education sites), and known scientists. Government science agencies were accessed to find data, maps, and textual information. Science faculty at colleges and universities were important resources for teachers. Faculty at alma maters and nearby institutions were considered knowledgeable and reliable sources of information, answering content questions, and explaining new research. Professional development programs offered by college programs were considered ideal because teachers found them to be rigorous, relevant, and research based. When designing learning activities, these teachers worked with colleagues and content-specific PLCs and online groups, frequently accessing science education resource sites
(e.g., SERC, NSTA, Concord Consortium, National Geographic) to find lesson and unit plans they could modify for their needs. State and national science teacher associations and organizations supported teachers’ professional development and access to physical and online resources. Community organizations provided relevant and local support for both teachers and students through field trips, guest speakers, and classroom resources.

**Social Network Analysis of Teachers’ Networks**

Analysis of individual teachers’ egonets showed that prior to the workshop all the teachers were either connected directly or were separated by only one degree and connected through teacher organizations, colleges and universities, social media, and providers of resources and professional development. Cassie, Jamie, Joselin, Katie, Opal, Price, and Stella knew or knew of each other through their professional educator licensure program, in which Joselin is now a mentor and instructor. Wanda and Zena met each other through a state university’s Noyce Master Teacher program. Five teachers learned about the workshop through Wanda’s Facebook ES group. Three teachers participated in the Joides Resolution School of Rock. All the teachers used data, maps, and information from Federal science agencies (e.g., USGS, NPS, NOAA, NASA, EPA).

As an example of these interconnections, Sam’s egonet (Figure 16.A) had the fewest number of ties of any of the teachers in the network. However, if we stepped out one degree (Figure 16.B), we observed that Sam was connected to all the other teachers in the network. These connections were facilitated by online communities on social media; educational resource providers Concord Consortium, NGSS, and PBS; and scientific resource providers such as the
Figure 16. Participant Sam’s egonet (A) and her egonet showing one degree of separation (B).
USGS and Illinois State Geological Survey. Likewise, Sam connects all the other teachers in the network to organizations such as Science Olympiad, National Geographic, and Esri. Given the observed ties between people, organizations, and resources, we constructed a single social network map that portrays the interconnections between the interviewed teachers (Figure 17).

Social network metrics (Table 1) define the roles played by teachers and the alters that connect them. These roles include local hubs, boundary spanners, network leaders, and information brokers. Based on the social network metrics calculated for the teachers in this network, we can compare the likelihood of the teachers acting in these roles (Figure 18).

In this network, teachers who function as local hubs were Zena, Price, Opal, and Jamie. In their interviews, these teachers described being actively engaged in multiple PLCs in their schools and districts, indicating that PLCs are a way to foster local hubs in a network. Many teachers described their ties with the Illinois Science Teachers Association and university faculty, these two groups also emerged as local hubs in the SNA.

Zena, Price, Jamie, Opal, Katie, and Wanda were the most likely to function as boundary spanners, acting as information bridges or gatekeepers to others in the network. With the exception of Wanda, these teachers worked as scientists prior to teaching. All of them participated in a wide variety of professional development within and outside of their districts and described how their experiences informed their contributions to their content area PLCs. These teachers described ties to both the science education and industry sectors (e.g., science education associations, USGS, environmental consulting). In this network, teachers who were boundary spanners sought out a variety of professional development experiences beyond their schools and districts. Other entities that emerged as boundary spanners were university faculty, Google, NSTA-NGSS, USGS, and NOAA.
Figure 17. Social network map based on interviews with ten teachers. Teachers are shown as blue circles. See the legend for the symbols representing the people, organizations, and resources that these teachers relied upon.
Joselin, Stella, Cassie, and Jamie were the network leaders. Prior to the workshop, these five teachers knew each other, having all been certified through the same teacher training program at which Joselin is an instructor and mentor. All of these teachers described how they were supported by frequent meaningful interactions with science education faculty and how these interactions helped them support other teachers. Therefore, in this network, the network leaders are those people who have strong ties to faculty members who contributed to their science teacher training. Other entities that emerged as network leaders include those same faculty members, USGS, NOAA, and NSTA/ISTA.

In this network, the teachers who functioned as information brokers were Zena, Jamie, Joselin, and Wanda. At the time of the interviews, these four teachers were either working in or

<table>
<thead>
<tr>
<th>Centrality Predicted Behavior</th>
<th>Jamie</th>
<th>Joselin</th>
<th>Zena</th>
<th>Price</th>
<th>Katie</th>
<th>Opal</th>
<th>Wanda</th>
<th>Stella</th>
<th>Cassie</th>
<th>Sam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local Hub</td>
<td></td>
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<tr>
<td>Boundary Spanner</td>
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<tr>
<td>Network Leader</td>
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<tr>
<td>Information Broker</td>
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</tbody>
</table>

Figure 18. Visualization of social network metrics comparing the ten teachers in this network. Yellow indicates greater likelihood that the teacher played the specified roles. Purple indicates a lesser tendency to play these roles.
had just finished teacher training programs that encouraged outreach and collaboration with people outside of their schools and districts. As participants in a Noyce Master Teacher program, Zena and Wanda described how they were being challenged to reach out to their local communities, participate in conferences, and collaborate with teachers from around their region. Joselin’s role as an instructor and mentor in a teacher training program provided opportunities to share information from one cohort to the next, supporting connections between pre-service and in-service teachers. In her interview, Jamie talked about how she had recently finished her certification program where she realized that by working with local science agencies, community organizations, and universities, she would be able to enrich her teaching. Other information brokers in this network included the USGS, NOAA, and NSTA/ISTA.

**Discussion**

This study investigated the social networks of teachers engaging in a community of practice (Wenger, 1998). The community of practice was made up of teachers who came together to learn about local ES research and then work together to create NGSS Storylines addressing local sustainability issues. Through analysis of individual interviews, we sought to understand how these Illinois ES teachers characterized their individual professional networks (egonets). We then used Social Network Analysis to investigate the ES teachers’ learning ecosystem as a single whole network.

**How do ES teachers characterize their professional networks?**

As described by the teachers, their individual professional networks have two functional characteristics, (1) the people and structures that supported them in their current roles
(operational networks), and (2) the people and organizations who facilitated teachers’
professional growth (strategic networks) (Cross & Thomas, 2008; Liou & Daly, 2020).

Teachers’ operational networks consisted of close school colleagues, school and district
PLCs, university faculty, and online resources. While Cassie and Wanda, were the only ES
teachers in their schools, they were able to identify at least one other science colleague in their
schools or districts who supported them. In other cases, teachers (Katie, Sam, Stella, and Zena)
worked closely with one other ES teacher, indicating operational dyads (Daly, 2012; Prell,
2012). Other teachers (Price, Opal, Joselin, and Jamie) had multiple close ES colleagues
suggesting that some individual networks may have had characteristics of cliques (Liou & Daly;
2014, 2020; Prell, 2012). Similar to the findings of Prenger and others (2019), the teachers in this
study (Price, Opal, Joselin, Jamie, and Sam) who participated in multiple high-functioning PLCs
described how these groups broadened their networks and created more awareness of ES
resources and ES professional development opportunities. The teachers in this study reported
that college faculty in their networks were knowledgeable and reliable sources of information,
they were comfortable asking questions about ES content and emerging research. This supports
the findings of Smith and others (2016), who studied partnerships between K-12 teachers and
university faculty, and found that such partnerships updated teachers’ content knowledge,
improved access to resources, and introduced innovative thinking in K-12 and college teaching.
The last component of teachers’ operational network was online resources. All the teachers in
this study described how they regularly access science education and science websites. For
example, these ES teachers’ reliance on raw data from government agencies (USGS, NOAA,
NASA, EPA, FEMA, NPS) was ubiquitous. This contrasts with Rosenberg and others (2022)
national survey of 330 K-12 science teachers which found that 70% of the teachers in their study preferred data that had been formatted for educational users.

Teachers’ strategic networks were made up of those people and organizations that facilitated professional growth (Cross & Thomas, 2008; Liou & Daly, 2020). In this study, teachers’ strategic networks were diverse, existing outside of their schools and districts and made up of university faculty, science teacher associations, and federally funded programs. Teachers (Cassie, Jamie, Joselin, Opal, Sam, Stella, Wanda, and Zena) described how professional development programs offered by university faculty were considered ideal because they were rigorous, relevant, research-based, and opened doors to new opportunities. This finding supports Sullivan and others’ (2014) call for scientist-led professional development. Similar to Howe and Stubbs (2003), we found that state and national science teacher associations provided teachers (Jamie, Price, Opal, Stella, Wanda, and Zena) access to new physical and online resources, professional development, and opportunities to develop leadership skills. Teachers (Stella, Wanda, and Zena) who had the opportunity to participate in federally funded programs (e.g., Joides Resolution School of Rock, National Park Teacher Expeditions) referred to these programs as “life-changing” and described how they met other like-minded teachers and scientists who they are continuing to communicate. This supports the findings of Karston (2019) who recommended expanding programs that engage teachers in geoscience research.

All the teachers in this study identified barriers within their networks that they needed to navigate. These barriers (e.g., unproductive PLCs, unsupportive administrators) have been recognized by others (Coburn & Russell, 2008; Daly et al., 2010; Moolenaar et al., 2012) to limit teachers’ willingness to work with others, contributing to the mindset of “close my door and do my own thing” (Katie). Despite these barriers, these teachers sought out the parts of their
network beyond the school walls to find the inspiration and support they needed. Like the teachers in the study by Jones and Preece (2006) we found that teachers gained needed support from online communities, PD opportunities where they met and interacted with like-minded colleagues, or college faculty who provided encouragement.

**What does SNA reveal about the ES teachers’ learning ecosystem?**

Through social network analysis we found that the ES teachers in this study were connected prior to the workshop. Following the descriptions by Freeman (1979) and Brass and Burkhardt (1992), we identified a variety of roles in the network. Zena, Price, Opal, and Jamie were local hubs who accessed and communicated resources or information to other teachers in their communities. These same four, along with Katie, acted as boundary spanners in this network, where they mediated the flow of information and resources between other actors. They were also able to synthesize information from different parts of the network. Joselin, Stella, Cassie, Jamie, and Opal acted as network leaders, and even if they lacked strong local influence, they had direct connections to influential network nodes. Jamie, Zena, Joselin, and Wanda were the information brokers, aware of what was happening in the network and spreading information both locally and to the rest of the network. All these teachers described how both their direct and indirect connections enabled them to share information, resources, and support.

When trying to characterize the role of other parts of this network, we recognized that the personal connections made between teachers, ES education resource providers and government agencies were limited. While we did not map the directionality of these relationships, teachers characterized the interactions as one-directional: they were receiving something from the agencies. While government agencies and ES education resource providers contributed expertise
and resources to the network, they connected teachers to each other indirectly. Therefore, their efforts were both essential and peripheral to this network (Cross et al., 2006; Wenger, 1998).

**Implications**

In this mixed-methods social network analysis, we attempted to understand how Illinois ES teachers characterized their individual professional networks and use SNA to investigate the ES teachers’ learning ecosystem as a single whole network. In doing so, the results have implications for the development of GLEs.

The individual networks of the ES teachers in this study were connected by colleges and universities, local organizations, resource providers (science education and government agencies), and social media. To develop GLEs that support larger networks of ES teachers, the present study suggests it is important to: (1) maintain communication with former students, cultivate connections with local organizations; (2) identify those teachers who are boundary spanners and information brokers to spread information through both local and network channels; (3) connect with ES teachers through group pages on social media platforms (Chester et al., 2018); and (4) resource providers (both government agencies and science education resource providers) can leverage teachers’ use of resources to support the development of GLEs.

SNA may be effective in identifying the evolution of GLE by mapping the same networks more than once (Assimakopoulos & Yan, 2006). Many of the factors that cause GLE and CoP to evolve, be sustained, or disappear may be related to network disruptions and feedbacks (Cross et al., 2006). Hence, a similar study performed again in the future with the same group of teachers would be valuable.
If applying these methods in other locations with a different group of teachers, it would be important to consider what local ES issues are relevant to teachers and their students (Hecht & Crowley, 2020). Further studies could compare the methods presented in this research to the ecosystem approaches from other disciplines (Falkner et al., 2018). Other theoretical lenses that may be useful in studying GLE include the social capital (Burt, 2000; Penuel et al., 2009), self-efficacy (Bandura, 1997), and identity (Chung-Parsons & Bailey, 2019) of teachers and other participants in a GLE and of teachers to create and utilize networks.

The breadth of needs in this small teacher network was diverse and our research indicates that further investment in this emerging GLE would support the teaching of ES. A GLE would cultivate a community of educators and professionals, deepen teacher content knowledge, demonstrate the relevance of ES to students, and introduce students to ES careers through field and research experiences.
CONCLUSION

In Chapter 1, I examined how the term “learning ecosystem” is used in a variety of disciplines and identified the inputs, processes, and outcomes in these different branches of research. Through the lenses of social constructivism, the Bioecological Model, and Activity Theory, I defined geo-STEM learning ecosystems as place-based communities of practice focused on transdisciplinary solutions to local geoscience problems. Three examples of authentic collaborations were used to demonstrate how GLEs can transform the geosciences and communities by leveraging transdisciplinary expertise. To better understand how GLEs develop and are sustained, I recommend transdisciplinary research efforts 1) study the mechanisms that perpetuate positive GLEs outcomes, 2) assess how place influences GLEs, and 3) examine GLEs through other theoretical lenses. Future research could refine how we describe GLE boundaries, compare GLEs in different contexts, and examine the role of disruptions and feedbacks.

Chapter 2 was an analysis of a survey that assessed the attributes of 245 Illinois Earth science teachers’ personal and enacted pedagogical content knowledge (PCK) when teaching NGSS sustainability concepts. My hypothesis, that teachers’ learning context (e.g., school type, grade level) would predict their personal and enacted PCK, was not supported. I found that teachers trained in ES did not have the requisite content knowledge to teach NGSS sustainability concepts. However, having a degree did correlate to their sense of belonging in science which was correlated to their content knowledge, ecological worldviews, and use of place-based practices. These results suggest that 1) ES teachers’ worldview would benefit from training that
emphasizes environmental advocacy and action, 2) ES teachers’ sense of belonging would be strengthened through professional connections with scientists, and 3) ES teachers would be better prepared to teach NGSS sustainability concepts if their college coursework and professional development were aligned with the pedagogy and specific expectations of the NGSS. We were not able to assess teachers’ actual use of place-based strategies and more research is needed to understand the factors that contribute to teachers’ sense of place, place-attachment, and place-meaning. Future research should examine the role of teachers’ identity in ES. To develop a generalizable understanding of how content knowledge, worldview, and sense of belonging in science develop, change, and affect student learning in general, data is needed from other states. There is much to learn about the efficacy of teachers’ understanding and use of NGSS disciplinary core ideas, science and engineering practices, and crosscutting concepts related to sustainability.

Chapter 3 builds on our findings in Chapter 2 using a path analysis to examine the same data through the lenses of the Teacher-Centered Systemic Reform model and the geo-STEM learning ecosystem model. The path analysis quantified the effects of teachers’ training and experiences on their sense of belonging in science, knowledge of anthropogenic environmental change, ecological worldview, and use of place-based teaching strategies. This confirmed the findings in Chapter 2: that having a STEM degree did not predict teachers’ understanding of anthropogenic environmental change or ecological worldview. However, having a STEM degree did predict teachers’ sense of belonging in science and, indirectly, their use of place-based strategies. Teachers’ sense of belonging in science also predicted their knowledge of anthropogenic environmental change and ecological worldview. More research is needed to
identify the levers that drive these factors if fostering sustainability education congruent with the NGSS is a goal in teacher preparation and professional development. Future research should 1) investigate how different types of research experiences (e.g., field-based, laboratory) may transform teachers’ learning and pedagogical practices; 2) assess teachers’ understanding of how anthropogenic environmental change is affecting the regions where they teach; and 3) examine how teachers’ funds of knowledge, professional networks, and the potential of GLE affect teachers’ sense of belonging in science, understanding of local anthropogenic environmental change, and implementation of place-based strategies. Researchers need better tools to assess teachers’ sense of place, teachers’ use of place-based strategies, and how these affect students’ learning.

In Chapter 4, I used a combination of interviews and social network analysis to investigate how ten Illinois Earth science teachers describe and access their networks. All these teachers participated in a 2-day virtual workshop learning about critical zone science, place-based educational strategies, and building a network that supports them. When analyzing the interviews, I found that teachers sought support from a variety of human and non-human sources, including colleagues, professional learning communities, local community groups, government agencies, science education organizations, and college and university faculty. Combining these findings with social network analysis reveals the roles that teachers play in their networks. Many of the teachers who are local hubs are also boundary spanners. They also participated in a wide variety of professional development opportunities and described themselves as active participants in Professional Learning Communities (PLCs). It is interesting to note that these same teachers worked as scientists prior to teaching. Teachers who are strong network leaders
were closely connected to their local colleges and universities, were aware of professional
development opportunities, and described how they distribute information to others. The teachers
who act as information brokers were not only aware of what was happening in the network, they
also shared information with close contacts, like PLCs, through broader channels such as social
media, and they took on roles in their communities to raise awareness about ES curriculum.
More research is needed to understand how to support teachers in developing and maintaining
networks that support their personal well-being and their professional lives. While it was clear
that teaching is both demanding and fulfilling, it was not clear how teachers are leveraging their
network to support their future work and meet their professional goals. We learned that when
teachers seek out diverse learning experiences, they develop a network that is broad, dynamic,
and diverse.

Geo-STEM learning ecosystems that are designed to support ES teachers have the
potential to create meaningful change in the geoscience community. Creating place-based
communities of practice that bring together scientists and teachers addresses several challenges
that emerged from this research. When teachers interact with scientists, they are more likely to 1)
develop a sense of belonging in science, which leads to 2) gains in content knowledge, 3)
ecological worldviews that value sustainability, and 4) increased use of place-based practices.
Teachers who have worked as scientists and engage in a wide variety of professional
development opportunities support other teachers by connecting them with resources. Teachers
who have close ties to colleges and universities function as network leaders, distributing
information and supporting research-based practices. By cultivating GLE with ES teachers, the
geoscience community has an opportunity to increase teachers' awareness of and participation in the geosciences.
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APPENDIX A

SURVEY QUESTIONS
**Experiences learning and teaching Earth science (TE)**

| TE1 | Which of the following best describes your experience teaching Earth & Space Science? (Choose all that apply.) (1=Taught ESS in last 3 yrs; 2=will teach next year; 3=NA) |
| TE2 | At which level do / will you teach Earth & Space Science? (Choose all that apply.) (1=k-5, 2=6-8, 3=9-12) |
| TE3 | Where I teach, Earth & Space Science is ... (choose all that apply) (1=standalone, 2=integrated into other courses, 3=mandatory, 4=elective, 5=college/dual) |
| TE4 | Which best describes the school where you teach? (1=public, 2=public charter, 3=public magnet, 4=private) |
| TE5 | What is the zip code where you teach? |
| TE6 | What is the highest level of education that you have completed? (1=Bachelor, 2=Bachelor+, 3=Masters, 4=Masters+, 5=Doc/Prof) |
| TE7 | How many credits of earth sciences coursework (astronomy, atmospheric sciences, ocean sciences, geology, physical geography) did you complete for your endorsement / professional educator license? (1=0-11, 2=12-18, 3=+19) |
| TE8 | Do you have a bachelor's degree in a science field? (=IF(cell=11,1,0)) (Coded as non-science degree) |
| TE9.a | Which of the following best describes your science major? If you had multiple majors, please indicate those. - Selected Choice (1=Astronomy, 2=Atmospheric Sciences, 3=Biology, 4=Chemistry, 5=Geology, 6=Ocean Science, 7=Physical Geography, 8=Physics) (Coded Biology, Chemistry, Physics as science-not ES) (Coded Astronomy, Atmospheric Sciences, Geology, Ocean Sciences, and Physical Geography as ES Major) |
| TE9.b | Which of the following best describes your science major? If you had multiple majors, please indicate those. - Other - Text |

**Place-based Education Practices (PBE)**

| PBE1 | Indicate the degree to which you agree or disagree with the following statements. - Earth science is relevant to my students |
| PBE2 | Indicate the degree to which you agree or disagree with the following statements. - I use Illinois-specific examples when teaching Earth science |
| PBE3 | Indicate the degree to which you agree or disagree with the following statements. - My students collect and/or analyze Illinois-specific Earth science data. |

1=SA, 2=A, 3=NA or DA, 4=DA, 5=SDA (must be reverse coded)(=6-[ ])

(Continued on following page.)
### Ecological Worldview (as measured by the New Ecological Paradigm Scale, Revised by Dunlap et al., 2000)

| NEP1 (L2G1) | Indicate the degree to which you agree or disagree with the following statements. - We are approaching the limit of the number of people Earth can support. |
| NEP2 (AA1) (R) | Indicate the degree to which you agree or disagree with the following statements. - Humans have the right to modify the natural environment to suit their needs. |
| NEP3 (BofN1) | Indicate the degree to which you agree or disagree with the following statements. - When humans interfere with nature it often produces disastrous consequences. |
| NEP4 (AEx1) (R) | Indicate the degree to which you agree or disagree with the following statements. - Human ingenuity will ensure that we do not make Earth unlivable. |
| NEP5 (EC1) | Indicate the degree to which you agree or disagree with the following statements. - Humans are seriously abusing the environment. |
| NEP6 (L2G2) (R) | Indicate the degree to which you agree or disagree with the following statements. - Earth has plenty of natural resources if we just learn how to develop them. |
| NEP7 (AA2) | Indicate the degree to which you agree or disagree with the following statements. - Plants and animals have as much right as humans to exist. |
| NEP8 (BofN2) (R) | Indicate the degree to which you agree or disagree with the following statements. - The balance of nature is strong enough to cope with the impacts of modern industrial nations. Increased |
| NEP9 (AEx2) | Indicate the degree to which you agree or disagree with the following statements. - Despite our special abilities, humans are still subject to the laws of nature. |
| NEP10 (EC2) (R) | Indicate the degree to which you agree or disagree with the following statements. - The so-called "environmental crisis" facing humankind has been greatly exaggerated. |
| NEP11 (L2G3) | Indicate the degree to which you agree or disagree with the following statements. - Earth is like a spaceship with very limited room and resources. |
| NEP12 (AA3) (R) | Indicate the degree to which you agree or disagree with the following statements. - Humans were meant to rule over the rest of nature. |
| NEP13 (BofN3) | Indicate the degree to which you agree or disagree with the following statements. - The balance of nature is very delicate and easily upset. |
| NEP14 (AEx3) (R) | Indicate the degree to which you agree or disagree with the following statements. - Humans will eventually learn enough about how nature works to be able to control it. |

(Continued on following page.)
<table>
<thead>
<tr>
<th>NEP15 (EC3)</th>
<th>Indicate the degree to which you agree or disagree with the following statements. - If things continue on their present course, we will soon experience a major ecological catastrophe.</th>
</tr>
</thead>
<tbody>
<tr>
<td>I=SA, 2=A, 3=N A or DA, 4=DA, 5=SDA (non-R must be reverse coded)(=6- [ ] )</td>
<td></td>
</tr>
</tbody>
</table>

- Limits to Growth questions 1, 6, 11 (Reverse coded 11)  
- Anti-anthropocentrism questions 2, 7, 12 (Reverse coded 2, 12)  
- Balance of Nature questions 3, 8, 13 (Reverse coded 8)  
- Anti-exemptionalism questions 4, 9, 14 (Reverse coded 4, 14)  
- Ecocrisis questions 5, 10, 15 (Reverse coded 10)  

**Knowledge of Anthropogenic Environmental Change (measured with questions on biogeochemical cycles (BGC) by Soltis, 2020 and climate change (CC) by Libarkin and others, 2018)**

| AEC-BGC1 | Increased temperature can cause what change in the carbon cycle?  
  
a) *weathering drawing down carbon*  
b) Increased volcanic activity increasing carbon dioxide levels  
c) *Increased ice melting moving carbon to the deep ocean*  
d) Increased photosynthesis results in an increase in carbon dioxide  
e) I do not know.  

| AEC-BGC2 | Phosphorus differs from Nitrogen in_________.  
  
a) Nitrogen is a critical nutrient to plant life and phosphorus is toxic  
b) *Nitrogen in an important component of the atmosphere and phosphorus is not*  
c) Microbial activity is essential for moving Phosphorus, but not nitrogen  
d) Nitrogen is typically locked in rocks and minerals, whereas phosphorus can be found in variety of settings  
e) I do not know.  

| AEC-BGC3 | Excess nitrogen introduced to a body of water is likely to_________.  
  
a) Poison living things  
b) Change the temperature of the body of water  
c) *Initially increase primary productivity*  
d) Significantly modify the pH of the water  
e) I do not know.  

(Continued on following page.)
### APPENDIX A (Continued)

| AEC-BGC4 | Photosynthesis moves carbon from the ____________ to the ____________.
|----------|---------------------------------------------------------------|
|          | a) Biosphere to Atmosphere
|          | b) *Atmosphere to Biosphere*
|          | c) Hydrosphere to Biosphere
|          | d) Geosphere to Atmosphere
|          | e) I do not know.

| AEC-BGC5 | Atmospheric Nitrogen can be taken up and used by living organisms through ...
|----------|-----------------------------------------------------------------------------|
|          | a) Respiration
|          | b) Photosynthesis
|          | c) *Microbial Activity*
|          | d) Diffusion
|          | e) I do not know.

| AEC-CC1 | How much incoming sunlight do greenhouse gases absorb?
|---------|-----------------------------------------------------------------------------|
|         | a) *Greenhouse gases absorb almost no incoming sunlight.*
|         | b) Greenhouse gases absorb about half of the incoming sunlight.
|         | c) Greenhouses gases absorb most incoming sunlight.
|         | d) I do not know.

| AEC-CC2 | Which is the best definition of a positive feedback loop in the climate system?
|---------|-----------------------------------------------------------------------------|
|         | a) A change in the climate system leads to a response that benefits climate change.
|         | b) A change in the climate system leads to a response that slows down climate change.
|         | c) *A change in the climate system leads to a response that speeds up climate change.*
|         | d) A change in the climate system leads to a response that harms climate change.
|         | e) I do not know.

| AEC-CC3 | Which of the following is the best definition of a greenhouse gas?
|---------|-----------------------------------------------------------------------------|
|         | a) An atmospheric gas that is produced as plants grow.
|         | b) *An atmospheric gas that absorbs infrared radiation.*
|         | c) An atmospheric gas that produces acid rain.
|         | d) An atmospheric gas that absorbs ultraviolet radiation.
|         | e) I do not know.

| AEC-CC4 | Which is the most common form of radiation given off by Earth's surface?
|---------|-----------------------------------------------------------------------------|
|         | a) The Earth’s surface mostly gives off visible radiation.
|         | b) *The Earth’s surface mostly gives off infrared radiation.*
|         | c) The Earth’s surface mostly gives off ultraviolet radiation.
|         | d) Earth’s surface does not give off radiation.
|         | e) I do not know.

(Continued on following page.)
### APPENDIX A (Continued)

<table>
<thead>
<tr>
<th>AEC-CC5</th>
<th>Which of the following statements about atmospheric temperature changes over the past million years is most accurate?</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>a) Air temperature change over the past million years is slightly due to natural processes and mostly due to human activities.</td>
</tr>
<tr>
<td></td>
<td>b) <em>Air temperature change over the past million years is mostly due to natural processes and slightly due to human activities.</em></td>
</tr>
<tr>
<td></td>
<td>c) Air temperature change over the past million years is about equally due to natural processes and human activities.</td>
</tr>
<tr>
<td></td>
<td>d) Air temperature change over the past million years has not occurred whether due to natural processes or human activities.</td>
</tr>
<tr>
<td></td>
<td>e) I do not know.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>AEC-CC6</th>
<th>Which of the following will occur if the amount of ice floating in the ocean decreases?</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>a) More sunlight will be reflected back into space and Earth’s temperature will decrease.</td>
</tr>
<tr>
<td></td>
<td>b) <em>Less sunlight will be reflected back into space and Earth’s temperature will increase.</em></td>
</tr>
<tr>
<td></td>
<td>c) More sunlight will be reflected back into space and Earth’s temperature will increase.</td>
</tr>
<tr>
<td></td>
<td>d) Less sunlight will be reflected back into space and Earth’s temperature will decrease.</td>
</tr>
<tr>
<td></td>
<td>e) I do not know.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>AEC-CC7</th>
<th>How does sunlight affect the temperature on Earth?</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>a) Sunlight warms the air directly, but the air does not warm the land.</td>
</tr>
<tr>
<td></td>
<td>b) Sunlight warms the land directly, but the land does not warm the air.</td>
</tr>
<tr>
<td></td>
<td>c) Sunlight warms the air directly, and the air warms the land.</td>
</tr>
<tr>
<td></td>
<td>d) <em>Sunlight warms the land directly, and the land warms the air.</em></td>
</tr>
<tr>
<td></td>
<td>e) I do not know.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>AEC-CC8</th>
<th>Which of the following statements about atmospheric temperature change over the past 50 years is most accurate?</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>a) <em>Atmospheric temperature change over the past 50 years is slightly due to natural processes and mostly due to human activities.</em></td>
</tr>
<tr>
<td></td>
<td>b) Atmospheric temperature change over the past 50 years is mostly due to natural processes and slightly due to human activities.</td>
</tr>
<tr>
<td></td>
<td>c) Atmospheric temperature change over the past 50 years is about equally due to natural processes and human activities.</td>
</tr>
<tr>
<td></td>
<td>d) Atmospheric temperature change over the past 50 years has not occurred whether due to natural processes or human activities.</td>
</tr>
<tr>
<td></td>
<td>e) I do not know.</td>
</tr>
</tbody>
</table>

(Continued on following page.)
### APPENDIX A (Continued)

<table>
<thead>
<tr>
<th>Question ID</th>
<th>Text</th>
</tr>
</thead>
</table>
| AEC-CC9     | Which of the following contributes to the transfer of thermal energy from place to place around the Earth?  
|             | a) The movement of ocean water but not the movement of air.  
|             | b) The movement of air but not the movement of ocean water.  
|             | c) Both the movement of ocean water and the movement of air.  
|             | d) Neither the movement of ocean water nor the movement of air.  
|             | e) I do not know.  |
| AEC-CC10    | Which of the following best describes how plants take in carbon dioxide?  
|             | a) Plants take in carbon dioxide from rain.  
|             | b) Plants take in carbon dioxide from sunlight.  
|             | c) Plants take in carbon dioxide from air.  
|             | d) Plants take in carbon dioxide from soil.  
|             | e) I do not know.  |
| AEC-CC11    | Which of the following would most likely occur if the oceans stopped absorbing carbon dioxide?  
|             | a) Carbon dioxide in the atmosphere would remain the same.  
|             | b) Carbon dioxide in the atmosphere would increase.  
|             | c) Carbon dioxide in the atmosphere would decrease.  
|             | d) I do not know.  |
| AEC-CC12    | Which is the best description of the differences between climate and weather?  
|             | a) Climate does not change over time, and weather does change over time.  
|             | b) Climate changes over time, and weather does not change over time.  
|             | c) Climate changes over long periods of time, and weather changes over short periods of time.  
|             | d) Climate changes over short periods of time, and weather changes over long periods of time.  
|             | e) I do not know.  |
| AEC-CC13    | What information do ice cores from glaciers contain about Earth? (Choose all that apply.)  
|             | a) Ice cores contain information about Earth’s air temperature.  
|             | b) Ice cores contain information about Earth’s seasonal precipitation.  
|             | c) Ice cores contain information about Earth’s carbon dioxide concentration.  
|             | d) Ice cores contain information about Earth’s daily weather events.  
|             | e) I do not know.  |

(Continued on following page.)
### Teachers’ Sense of Belonging in Science

<table>
<thead>
<tr>
<th>SBS1</th>
<th>Indicate the degree to which you agree or disagree with the following statements. - I feel connected to people who conduct scientific research.</th>
</tr>
</thead>
<tbody>
<tr>
<td>SBS2</td>
<td>Indicate the degree to which you agree or disagree with the following statements. - I feel recognized by people who conduct scientific research.</td>
</tr>
<tr>
<td>SBS3</td>
<td>Indicate the degree to which you agree or disagree with the following statements. - I feel like I have something to contribute to the scientific research community.</td>
</tr>
<tr>
<td>SBS4</td>
<td>Indicate the degree to which you agree or disagree with the following statements. - Select &quot;Somewhat disagree&quot;.</td>
</tr>
<tr>
<td>SBS5</td>
<td>Indicate the degree to which you agree or disagree with the following statements. - I feel a sense of well-being when I am around people who conduct scientific research.</td>
</tr>
<tr>
<td>SBS6 (R)</td>
<td>Indicate the degree to which you agree or disagree with the following statements. - I feel like I want to disappear into the background when I am with people who conduct scientific research.</td>
</tr>
<tr>
<td>SBS7</td>
<td>Indicate the degree to which you agree or disagree with the following statements. - I trust people who conduct scientific research.</td>
</tr>
</tbody>
</table>

Delete SBS4; 1=SA, 2=A, 3=N A or DA, 4=DA, 5=SDA (must be reverse coded)(=6-[ ]) Drop SBS6 (Feser, 2021)

### Teachers’ Funds of Knowledge

<table>
<thead>
<tr>
<th>TFK1</th>
<th>Imagine your student asks you a question about an Earth and environmental science topic that you do not know how to answer. You want to find out the answer by the next class. Where would you seek an answer?</th>
</tr>
</thead>
<tbody>
<tr>
<td>TFK2.a</td>
<td>Do you subscribe to any listservs, email lists, or social media feeds related to science education? - Selected Choice</td>
</tr>
<tr>
<td>TFK2.b</td>
<td>Do you subscribe to any listservs, email lists, or social media feeds related to science education? - Yes, I subscribe to the following - Text</td>
</tr>
<tr>
<td>TFK3.a</td>
<td>To which, if any, professional societies do you belong? (Choose all that apply.) - Selected Choice</td>
</tr>
<tr>
<td>TFK3.b</td>
<td>To which, if any, professional societies do you belong? (Choose all that apply.) - Other (please enter) - Text</td>
</tr>
<tr>
<td>TFK4.a</td>
<td>When I need to design or redesign an Earth and/or environmental course, I seek out professional development opportunities offered by... (Choose all that apply.) - Selected Choice</td>
</tr>
<tr>
<td>TFK4.b</td>
<td>When I need to design or redesign an Earth and/or environmental course, I seek out professional development opportunities offered by... (Choose all that apply.) - Professional Societies (please indicate which ones) - Text</td>
</tr>
</tbody>
</table>

(Continued on following page.)
APPENDIX A (Continued)

<table>
<thead>
<tr>
<th>TFK4.c</th>
<th>When I need to design or redesign an Earth and/or environmental course, I seek out professional development opportunities offered by... (Choose all that apply.) - Other - Text</th>
</tr>
</thead>
</table>

**Teacher Demographics**

<table>
<thead>
<tr>
<th>D1</th>
<th>Which of the following age ranges do you fall into? (1=20-25, 2=26-35, 3=36-45, 4=46-55, 5=56-65, 6=+65)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D2.a</td>
<td>How do you describe your gender identity? (Choose all that apply.) - Selected Choice (1=male, 2=female, 3=genderqueer, 4=agender, 5=trans, 6=cis)</td>
</tr>
<tr>
<td>D2.b</td>
<td>How do you describe your gender identity? (Choose all that apply.) - Other, not listed - Text</td>
</tr>
<tr>
<td>D3.a</td>
<td>With which racial and ethnic group(s) do you identify? (Choose all that apply.) - Selected Choice (1=NAM/AMIN, 2=As, 3=B/AfAm, 4=Hisp/lat/span, 5=midEast/NAf, 6=PIs/NHi, 7=White)</td>
</tr>
<tr>
<td>D3.b</td>
<td>With which racial and ethnic group(s) do you identify? (Choose all that apply.) - Other race or ethnicity not listed above - Text</td>
</tr>
</tbody>
</table>

TE = Teacher Experience  
PBE = Place-based Education  
NEP = New Ecological Paradigm  
EWV = Ecological Worldview  
L2G = Limits to Growth  
AA = Anti-anthropocentrism  
BofN = Balance of Nature  
AEx = Anti-exemptionalism  
EC = Ecocrisis  
AEC = Anthropogenic Environmental Change  
BGC = Biogeochemical Cycle  
CC = Climate Change  
SBS = Sense of Belonging in Science  
TFK = Teachers’ Funds of Knowledge  
D = Demographics
APPENDIX B

NGSS-SURVEY CROSSWALK
A Crosswalk connecting questions on Anthropogenic Environmental Change and Sustainability to the NGSS

<table>
<thead>
<tr>
<th>Survey Questions</th>
<th>NGSS Performance Expectation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Place-base Education (PBE)</strong></td>
<td></td>
</tr>
<tr>
<td>ES is relevant</td>
<td>K-ESS2-1; K-ESS3-2, 3; 4-ESS1-1;</td>
</tr>
<tr>
<td>Use of local examples</td>
<td>MS-LS1-5; MS-ESS2-2, 5, 6; MS-ESS3-2; HS-ESS2-2; HS-ESS3-4; HS-ETS1-1</td>
</tr>
<tr>
<td>Students collect and analyze local data</td>
<td></td>
</tr>
<tr>
<td><strong>Anthropogenic Environmental Change (AEC)</strong></td>
<td></td>
</tr>
<tr>
<td>Carbon Cycle</td>
<td></td>
</tr>
<tr>
<td>Increased temperature can cause what change in the carbon cycle?</td>
<td></td>
</tr>
<tr>
<td>A.) <em>Increased weathering drawing down carbon</em></td>
<td></td>
</tr>
<tr>
<td>B.) <em>Increased volcanic activity increasing carbon dioxide levels</em></td>
<td></td>
</tr>
<tr>
<td>C.) <em>Increased ice melting moving carbon to the deep ocean</em></td>
<td></td>
</tr>
<tr>
<td>D.) <em>Increased photosynthesis results in an increase in carbon dioxide</em></td>
<td></td>
</tr>
<tr>
<td>Photosynthesis moves carbon from the __________________ to the __________________.</td>
<td></td>
</tr>
<tr>
<td>A.) Biosphere to Atmosphere</td>
<td>MS-LS1-6; MS-LS2-3; HS-LS1-5,6;</td>
</tr>
<tr>
<td>B.) Atmosphere to Biosphere</td>
<td>HS-LS2-4, 5; HS-ESS2-6, 7</td>
</tr>
<tr>
<td>C.) Hydrosphere to Biosphere</td>
<td></td>
</tr>
<tr>
<td>D.) Geosphere to Atmosphere</td>
<td></td>
</tr>
<tr>
<td>Which of the following best describes how plants take in carbon dioxide?</td>
<td></td>
</tr>
<tr>
<td>A. Plants take in carbon dioxide from rain.</td>
<td>MS-LS1-6; MS-LS2-3; HS-LS1-5,6;</td>
</tr>
<tr>
<td>B. Plants take in carbon dioxide from sunlight.</td>
<td>HS-LS2-4, 5; HS-ESS2-6, 7</td>
</tr>
<tr>
<td>C. <em>Plants take in carbon dioxide from air.</em></td>
<td></td>
</tr>
<tr>
<td>D. Plants take in carbon dioxide from soil.</td>
<td></td>
</tr>
<tr>
<td>E. I do not know.</td>
<td></td>
</tr>
</tbody>
</table>

(Continued on following page.)
APPENDIX B (Continued)

Which of the following would most likely occur if the oceans stopped absorbing carbon dioxide?

| A. Carbon dioxide in the atmosphere would remain the same. | MS-LS2-3; HS-LS2-5; HS-ESS2-2, 6, 7; HS-ESS3-6 |
| B. *Carbon dioxide in the atmosphere would increase.* |
| C. Carbon dioxide in the atmosphere would decrease. |
| D. I do not know. |

**Phosphorus Cycle**

Phosphorus differs from Nitrogen in…

| A.) Nitrogen is a critical nutrient to plant life and phosphorus is toxic |
| B.) *Nitrogen in an important component of the atmosphere and phosphorus is not* |
| C.) Microbial activity is essential for moving Phosphorus, but not nitrogen |
| D.) Nitrogen is typically locked in rocks and minerals, whereas phosphorus can be found in a variety of settings |

**Nitrogen Cycle**

Excess nitrogen introduced to a body of water is likely to…

| A.) Poison living things |
| B.) Change the temperature of the body of water |
| C.) *Initially increase primary productivity* |
| D.) Significantly modify the pH of the water |

Atmospheric Nitrogen can be taken up and used by living organisms through…

| A.) Respiration |
| B.) Photosynthesis |
| C.) *Microbial Activity* |
| D.) Diffusion |

(Continued on following page.)
### Feedback Loops

Which is the best definition of a positive feedback loop in the climate system?

<table>
<thead>
<tr>
<th>Option</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>A.</td>
<td>A change in the climate system leads to a response that benefits climate change.</td>
</tr>
<tr>
<td>B.</td>
<td>A change in the climate system leads to a response that slows down climate change.</td>
</tr>
<tr>
<td>C.</td>
<td>A change in the climate system leads to a response that speeds up climate change.</td>
</tr>
<tr>
<td>D.</td>
<td>A change in the climate system leads to a response that harms climate change.</td>
</tr>
<tr>
<td>E.</td>
<td>I do not know.</td>
</tr>
</tbody>
</table>

**HS-ESS2-1, 2; HS-ESS3-4**

### Earth’s Energy Balance

How does sunlight affect temperature on Earth?

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A.</td>
<td>Sunlight warms the air directly, but the air does not warm the land.</td>
</tr>
<tr>
<td>B.</td>
<td>Sunlight warms the land directly, but the land does not warm the air.</td>
</tr>
<tr>
<td>C.</td>
<td>Sunlight warms the air directly, and the air warms the land.</td>
</tr>
<tr>
<td>D.</td>
<td>Sunlight warms the land directly, and the land warms the air.</td>
</tr>
<tr>
<td>E.</td>
<td>I do not know.</td>
</tr>
</tbody>
</table>

**MS-ESS2-6; HS-ESS2-2, 4; HS-PS4-4**

Which of the following contributes to the transfer of thermal energy from place to place around the Earth?

<table>
<thead>
<tr>
<th>Option</th>
<th>Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>A.</td>
<td>The movement of ocean water but not the movement of air.</td>
</tr>
<tr>
<td>B.</td>
<td>The movement of air but not the movement of ocean water.</td>
</tr>
<tr>
<td>C.</td>
<td>Both the movement of ocean water and the movement of air.</td>
</tr>
<tr>
<td>D.</td>
<td>Neither the movement of ocean water nor the movement of air.</td>
</tr>
<tr>
<td>E.</td>
<td>I do not know.</td>
</tr>
</tbody>
</table>

**MS-ESS2-6; HS-ESS2-2, 4**

(Continued on following page.)
### APPENDIX B (Continued)

<table>
<thead>
<tr>
<th>Question</th>
<th>Options</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Which is the most common form of radiation given off by Earth's surface?</td>
<td>A. The Earth’s surface mostly gives off visible radiation.</td>
<td>MS-ESS2-6; HS-ESS2-4; HS-PS4-4</td>
</tr>
<tr>
<td></td>
<td>B. <em>The Earth’s surface mostly gives off infrared radiation.</em></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C. The Earth’s surface mostly gives off ultraviolet radiation.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>D. Earth’s surface does not give off radiation.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>E. I do not know.</td>
<td></td>
</tr>
<tr>
<td>Which of the following is the best definition of a greenhouse gas?</td>
<td>A. An atmospheric gas that is produced as plants grow.</td>
<td>MS-ESS3-5; HS-ESS2-4; HS-ESS3-6</td>
</tr>
<tr>
<td></td>
<td>B. <em>An atmospheric gas that absorbs infrared radiation.</em></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C. An atmospheric gas that produces acid rain.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>D. An atmospheric gas that absorbs ultraviolet radiation.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>E. I do not know.</td>
<td></td>
</tr>
<tr>
<td>How much incoming sunlight do greenhouse gases absorb?</td>
<td>A. <em>Greenhouses gases absorb almost no incoming sunlight.</em></td>
<td>MS-ESS3-5; HS-ESS2-4</td>
</tr>
<tr>
<td></td>
<td>B. Greenhouses gases absorb about half of the incoming sunlight.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>C. Greenhouses gases absorb most incoming sunlight.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>D. I do not know.</td>
<td></td>
</tr>
</tbody>
</table>

(Continued on following page.)
Which of the following will occur if the amount of ice floating in the ocean decreases?

- A. More sunlight will be reflected back into space and Earth’s temperature will decrease.
- B. Less sunlight will be reflected back into space and Earth’s temperature will increase.
- C. More sunlight will be reflected back into space and Earth’s temperature will increase.
- D. Less sunlight will be reflected back into space and Earth’s temperature will decrease.
- E. I do not know.

Climate Change

Which is the best description of the differences between climate and weather?

- A. Climate does not change over time, and weather does change over time.
- B. Climate changes over time, and weather does not change over time.
- C. Climate changes over long periods of time, and weather changes over short periods of time.
- D. Climate changes over short periods of time, and weather changes over long periods of time.
- E. I do not know.

Which of the following statements about air temperature change over the past million years is most accurate?

- A. Air temperature change over the past million years is slightly due to natural processes and mostly due to human activities.
- B. Air temperature change over the past million years is mostly due to natural processes and slightly due to human activities.
- C. Air temperature change over the past million years is about equally due to natural processes and human activities.
- D. Air temperature change over the past million years has not occurred whether due to natural processes or human activities.
- E. I do not know.
Which of the following statements about global warming over the past 50 years is most accurate?

A. Global warming over the past 50 years is slightly due to natural processes and mostly due to human activities.

B. Global warming over the past 50 years is mostly due to natural processes and slightly due to human activities.

C. Global warming over the past 50 years is about equally due to natural processes and human activities.

D. Global warming over the past 50 years has not occurred whether due to natural processes or human activities.

E. I do not know.

What information do ice cores from glaciers contain about Earth? CHOOSE ALL THAT APPLY.

A. Ice cores contain information about Earth’s air temperature.

B. Ice cores contain information about Earth’s seasonal precipitation.

C. Ice cores contain information about Earth’s carbon dioxide concentration.

D. Ice cores contain information about Earth’s daily weather events.

E. I do not know.

Ecological Worldview (EWV)

Limits to Growth

We are approaching the limit of the number of people Earth can support

Earth has plenty of natural resources if we just learn how to develop them.

Earth is like a spaceship with very limited room and resources.

(Continued on following page.)
APPENDIX B (Continued)

<table>
<thead>
<tr>
<th>Anti-Anthropocentrism</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Humans have the right to modify the natural environment to suit their needs</td>
<td>K-ESS2-2; K-ESS3-3; 3-LS4-4; HS-LS2-7; HS-LS4-6; HS-ESS3-1, 2, 3, 4, 5, 6</td>
</tr>
<tr>
<td>Plants and animals have as much right as humans to exist.</td>
<td></td>
</tr>
<tr>
<td>Humans were meant to rule over the rest of nature.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Balance of Nature</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>When humans interfere with nature it often produces disastrous consequences</td>
<td></td>
</tr>
<tr>
<td>The balance of nature is strong enough to cope with the impacts of modern industrial nations.</td>
<td>5-ESS3-1; MS-ESS3-3, 4; HS-LS2-7; HS-LS4-6; HS-ESS3-1, 2, 3, 4, 5, 6</td>
</tr>
<tr>
<td>The balance of nature is very delicate and easily upset.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Anti-Exemptionalism</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Human ingenuity will insure that we do not make Earth unlivable.</td>
<td>K-ESS2-2; K-ESS3-1, 2, 3; 4-ESS3-2, 5-ESS3-1; MS-ESS3-2, 3, 4; HS-ESS3-1, 2, 3, 4, 5, 6</td>
</tr>
<tr>
<td>Despite our special abilities, humans are still subject to the laws of nature.</td>
<td></td>
</tr>
<tr>
<td>Humans will eventually learn enough about how nature works to be able to control it.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Likelihood of an Ecological Crisis</th>
<th></th>
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<td>Humans are seriously abusing the environment.</td>
<td>K-ESS2-2; K-ESS3-1, 2, 3; 4-ESS3-2, 5-ESS3-1; MS-ESS3-2, 3, 4; HS-ESS3-1, 3, 4, 5, 6</td>
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<td>The so-called &quot;environmental crisis&quot; facing humankind has been greatly exaggerated.</td>
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<td>If things continue on their present course, we will soon experience a major ecological catastrophe.</td>
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Number of Occurrence of Each NGSS-Performance Expectation aligned with Survey

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APPENDIX C

EFFECT SIZES AND SIGNIFICANCE
Bootstrap Confidence (Group number 1 - Default model)
Bias-corrected percentile method (Group number 1 - Default model)
90% confidence intervals (bias-corrected percentile method)
Scalar Estimates (Group number 1 - Default model)

Correlations: (Group number 1 - Default model)

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Standardized Regression Weights: (Group number 1 - Default model)

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Squared Multiple Correlations: (Group number 1 - Default model)

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