Research on Elementary, Middle, and Secondary Earth and Space Sciences Teacher Education

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Introduction

The release of the *Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas* in 2012 and the subsequent publication of the *Next Generation Science Standards* (NGSS) in 2013 represents a new vision for K-12 science learning culminating from decades of science education reform efforts. Several aspects of the NGSS are critical to the geoscience education community. First, the NGSS place the Earth and Space Sciences (ESS) on equal footing with Life Sciences, Physical Sciences (chemistry and physics), and Engineering and Technology applications across K-12 grades. Second, the NGSS promote a vision of "three-dimensional learning" in which core disciplinary knowledge, concepts that cut across disciplines, and practices used in science and engineering are given equal prominence.

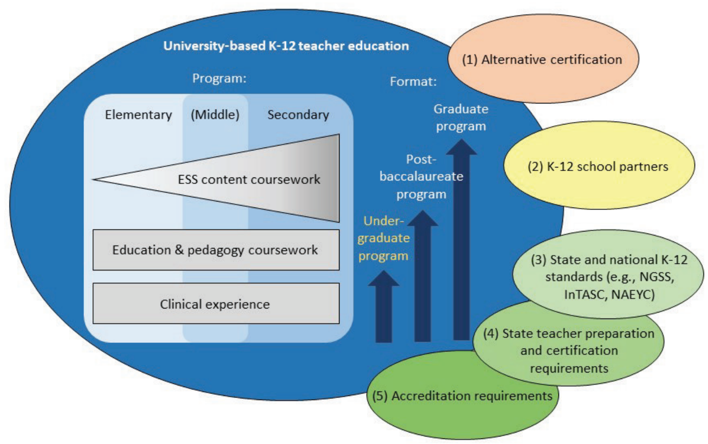

Figure 1. A generalized conceptual model of university-based K-12 teacher education in Earth and Space Sciences and key external factors that impact teacher preparation. These factors make teacher education a complex and dynamic endeavor. Research Grand Challenges and recommended strategies were developed that one part of this landscape: teacher education at the undergraduate level (shown in yellow in the model).

In order to fully engage with the vision of the *Framework for K-12 Science Education* and the *NGSS*, however, our nation needs a diverse and well prepared K-12 science teacher workforce. And in order for ESS to gain equal status with other sciences, the geoscience community must ensure that the K-12 science teacher workforce is adequately prepared to teach ESS core knowledge and practices. This is a challenging endeavor and complicated by the fact that the K-12 teacher education landscape is highly variable across institutions in terms of how much ESS content is included, how programs are structured, and how ESS fits into the larger institutional context. Figure 1 is our model of this complex landscape.

Within institutions, ESS may be part of an elementary, middle, and/or secondary teacher preparation program. Depending on the state, middle grades may be a separate certification, or may be included within elementary and/or secondary certification (shown in parentheses in the Figure 1 model). Teacher preparation programs usually have components of content-area coursework, education and pedagogy coursework, and in-school clinical experience. ESS content courses may be part of a generalized science (or education) program of study, or may be a disciplinary major or minor; in general, secondary teacher preparation programs require more disciplinary content than do elementary programs (Figure 1, width of the triangle). The quantity of education and pedagogy coursework and clinical experiences may also vary within individual programs. Program models vary from those in which the undergraduate degree leads directly to initial teacher certification, those at the post-baccalaureate level providing initial certification for candidates who already have a content undergraduate major, and those in which certification is obtained during a graduate program (such as a Master of Arts in Teaching program). Most post-baccalaureate and graduate programs are of shorter duration but are faster paced than undergraduate programs (Figure 1, arrow height).

Teacher education is also influenced by a push-pull of many external factors such as higher education and K-12 institutional pressures and priorities, changing teacher education accreditation standards, high stakes testing, state-by-state NGSS adoption, and public perception of the value of ESS. In addition, several external factors (#1-5 in the Figure 1 model) directly impact teacher education programs: Both nonprofit and for-profit organizations offer alternate routes to teacher certification (e.g., Teach for America, Teachers of Tomorrow) which may be in partnership with, or in competition with, university-based programs. Programs, especially clinical experiences, rely heavily on partnerships with K-12 districts. And teacher education programs are accountable to accrediting bodies (such as the Council for the Accreditation of Educator Preparation [CAEP]), state teacher preparation standards, and state or national standards such as the NGSS, the Interstate New Teacher Assessment and Support Consortium [InTASC], and the National Association for the Education of Young Children [NAEYC]). These factors directly influence one another, for example, accreditation requirements include national standards, and state teacher certification requirements may mirror both accreditation requirements and national standards.

Clearly, teacher education exists in a complex landscape that involve many domains of research. Here we focus on teacher education research that most directly aligns to the undergraduate teaching and learning experience (yellow text in Figure 1). Three grand challenges emerged from discussion and reflections on the existing literature and are poised to guide future research on undergraduate K-12 teacher education.

Definitions

We recognize that many states include programs of study leading to certification in preschool through grade 12 (e.g., PreK-12). In this paper we use “K-12” as the amount of Earth and Space Sciences content in preschool grades is typically minimal. The K-12 education community uses “Earth and Space Sciences” to include the disciplines of astronomy, geology, meteorology, and oceanography. In this paper, we preferentially use “Earth and Space Sciences” or “ESS” to align with the common language of K-12. We also use the term “geosciences” interchangeably with ESS in reference to college-level disciplines or coursework, or when authors we cite specifically use this term.

Grand Challenges

Grand Challenge #1. How do we attract and support a greater number of future K-12 ESS teachers who represent and can effectively engage diverse K-12 learners?
With less than 3% of secondary STEM teachers holding a geoscience degree we have a tremendous opportunity to grow the ESS teaching workforce. Yet growth of this workforce should reflect the growing diversity of K-12 learners, inclusive of gender, race/ethnicity, ability status, and more.

Grand Challenge #2. What are effective models for incorporating ESS into undergraduate K-12 teacher preparation and in providing professional development for inservice teachers?
In order to produce K-12 teachers that are well-prepared to teach ESS, we must first determine what makes teacher preparation and professional development programs successful.

Grand Challenge #3. How do we best prepare future and practicing K-12 teachers to engage in ESS to promote three-dimensional learning that involves the integration of disciplinary core ideas, science and engineering practices and crosscutting concepts?
The NGSS and Framework reflect a new vision for K-12 teaching in science and engineering. Science is an interconnected enterprise encompassing three dimensions: science and engineering practices, crosscutting concepts, and disciplinary core ideas. To effectively teach ESS, K-12 teachers need to understand not only the geoscience concepts they teach, but also the practices of geoscientists.

Grand Challenge 1:

How do we attract and support a greater number of future K-12 ESS teachers who represent the diversity of K-12 learners?

Rationale

Nationally, fewer college students are enrolling in teacher education programs, with a decline of 30% enrollment reported over the last five years (Barth et al., 2016). However, students entering teacher education programs now have stronger academic profiles (as measured by incoming SAT/ACT scores), and more entering students are completing their programs (Barth et al., 2016). Yet as many as a quarter to half of graduates of teacher preparation programs do not go into teaching (DeMonte, 2016). Retention of new teachers has also improved nationally, with 17-20% leaving the profession in the first four to five years - as opposed to older reports of nearly 50% leaving the profession within the first five years (Gray and Taie, 2015; Goldhaber, 2015; Brown, 2015). These same reports suggest that higher quality incoming teachers are retained in the profession at higher rates.

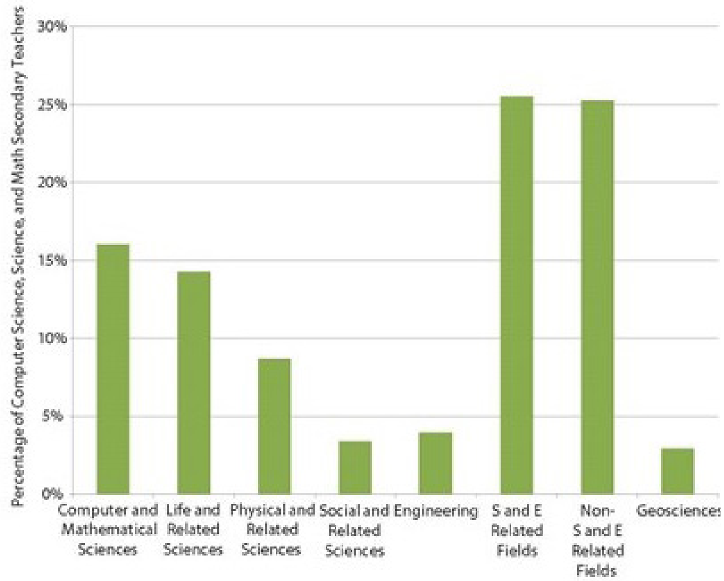

Figure 2. Percentage of secondary STEM teachers prepared in the geosciences. Reproduced from Wilson, 2016.

Amid this mixed news of national teacher preparation and retention, the ESS continue to have the least number of discipline-trained teachers within the sciences (Figure 2). Teachers of young children typically teach a wide range of content (e.g., Language Arts, math, science, and social studies) with increasing disciplinary specialization as grade levels go up. Thus elementary teachers have limited preparation in ESS content, whereas middle and secondary teachers may be prepared as content specialists. Based on analysis of data provided by the National Science Foundation, however, Wilson (2016) estimates that only 3% of secondary teachers hold a degree in the geosciences. Sixty-five percent of elementary teachers, 75% of middle school teachers, and 61% of high school teachers report taking at least one ESS course at the undergraduate level (Banilower et al., 2013). According to the same report (Banilower et al., 2013), only 28% of middle school and 30% of high school teachers have taken one or more ESS courses beyond the introductory level. Clearly, opportunity exists across all grade levels to expand the Earth and Space Science teacher workforce.

Yet growth of this workforce should reflect the growing diversity of K-12 learners, inclusive of gender, race/ethnicity, ability status, and more. Nationally, four out of five teachers are white, yet nearly 50% of school-age youth are ethnically diverse (AACTE, 2013). This issue is compounded in the geosciences, where less than 11% of bachelor’s degrees in geoscience are conferred to students of African American, Hispanic/Latino, or Native American/Alaskan race or ethnicity (Wilson, 2016). Compounding this issue, minority-serving institutions are less likely to offer degrees in the geosciences; Petcovic et al. (2016) found that only 2.5% of institutions with degree granting geoscience departments were designated as minority-serving. As yet the fraction of teacher preparation programs in ESS at minority-serving institutions remains unknown.

Research is needed to identify roadblocks that deter individuals, especially persons of color, from choosing or staying on the path to become ESS teachers. Research is also needed to identify mechanisms that are successful in both attracting individuals to K-12 ESS teaching and supporting their long-term success. This research will need to consider how pathways for entry into and persistence in ESS teaching may differ depending the grade bands that an individual intends to teach; in other words, different factors likely influence whether someone enters and persists in teaching elementary, middle, or high school grades.

There is considerable overlap between this challenge and GC#2; here the focus is on understanding how to better attract and support the individuals who make up a diverse pool of future K-12 ESS teachers, whereas GC#2 focuses on broader institutional models, partnerships, and best practices in ESS teacher education.

Recommended Research Strategies

Here we recommend short and long-term strategies that could yield insight into Grand Challenge #1 and ultimately drive forward both knowledge and practice. While short and long term strategies can both be approached immediately and simultaneously, short term strategies (#1-4) tend to focus more on synthesis of current literature, surveys of our current state of knowledge, or application of excising research to the field of teacher education. In contrast, long term strategies (#5-7) require more significant time and resource investment (such as support by external funding), focusing on more large-scale empirical students that can build the knowledge base.

1. At present, the research community lacks a baseline understanding of how individuals, especially persons of color, decide to become K-12 ESS teachers. Understanding how and when individuals decide to become K-12 ESS teachers is important foundational data to collect and compile. We call for a systematic review of existing literature that would establish our current understanding of what attracts individuals to ESS teaching. This review should encompass literature in other STEM fields in order to establish what may be unique to ESS teaching in addition to what is common with other fields. It should also highlight critical theoretical and conceptual frameworks that provide explanatory power to findings.

2. The research community also lacks a baseline understanding of what efforts in recruiting a diverse pool of students to K-12 ESS teaching have been successful. Again there is a need for systematic literature review that identifies the existing strategies for attracting students and determine what components of these are effective for underrepresented populations. Learning what external factors contribute to or inhibit interest in becoming a K-12 ESS teacher, especially among persons of color can help us move forward. We should look to other STEM

fields for examples of successful interventions as well as to the results of programs specific to ESS teacher recruitment. Along these lines, there may be a need for comprehensive evaluation of NSF-funded GEOPATHS programs that focus on ESS teacher recruitment and preparation.

3. To better understand the population of current and future K-12 ESS teachers, we suggest a survey of teacher preparation institutions that focuses on their recruitment methods. We especially would want to know how these institutions reach a diverse pool of potential applicants and the extent to which partnerships with two-year colleges and minority-serving institutions exist. It would also be useful to survey current K-12 ESS teachers to determine what other courses they teach, what certification(s) they hold, and how they describe their preparation to teach the ESS. This work could also refine our knowledge of the current and potential future demand for ESS teachers.

4. The broader K-12 teacher education community has a good understanding of what factors support the transition from preservice teacher education to inservice teaching, inclusive of teachers of color (e.g., Ingersoll & May, 2011). However this work has not been communicated within the ESS teacher education community. We call for review and synthesis of this existing literature from which researchable questions specific to K-12 ESS teacher transitions may arise.

5. The geoscience education community has done some work examining awareness of, and barriers to, underrepresented populations pursuing study and careers within the geosciences (e.g., O'Connell and Holmes, 2011; Levine et al., 2007; Huntoon & Lane, 2007; Stokes et al., 2015; Baber et al., 2010; see also references in GC#5 Access and Success). To our knowledge, no work has yet been done to identify barriers and attractors to careers in K-12 ESS teaching. Building this understanding could take an ethnographic or phenomenological approach, drawing experiences from current K-12 ESS teachers of color to identify critical experiences (e.g., Levine et al., 2007). Initial work could be followed up with broader surveys of the current K-12 STEM teaching community to identify critical experiences, incidents, or factors that lead to greater interest in ESS teaching. Conversely, these surveys could also identify factors that serve as barriers or deterrents to students interested in K-12 ESS teaching.

6. Significant research supports the notion that reformed teaching practices lead to greater retention of STEM students, especially women and students of color (e.g., Freeman et al., 2014). Is the same true for future STEM teachers? To address this question, we call for a comparative study of whether institutions with transformed STEM course design might attract and support a more diverse pool of future K-12 ESS teachers than institutions with more traditional courses.

7. We see a need for longitudinal phenomenological research that follows pre-service ESS teachers into the first few years of teaching to identify factors that contribute to thriving. This is especially important for teachers of color, who are more likely to leave the profession within the first five years than are white teachers (Ingersoll & May, 2011). Current work points to organizational factors (such as the level of collaboration and autonomy, institutional support, and pressure of high stakes testing) as driving minority teachers from the profession (Ingersoll & May, 2011). Similar to the research agenda described above, we suggest an initial qualitative study followed by broad survey research to identify widespread factors that both contribute to K-12 ESS teacher retention, and those that ultimately drive teachers to leave.

Grand Challenge 2:

What are effective models for incorporating ESS into undergraduate K-12 teacher preparation and in providing professional development for inservice teachers?

Rationale

Current and future science teachers are being asked to teach science in ways that may differ radically from the ways they learned science (Figure 3; National Research Council, 2015). In order to produce K-12 teachers that are well-prepared to teach the Earth and space sciences (ESS), we must first determine what makes teacher preparation programs successful. Teacher preparation programs across the nation vary widely across several characteristics, including (but not limited to) content, course requirement, recruitment methods, graduation and placement rates, and student demographics. This is due in part to state- and district-level differences in teaching standards, differences in the types of institutions that offer teacher preparation programs, and the grade levels for which the programs are designed (elementary, middle, secondary). For example, most teacher preparation programs are offered at four-year and Masters granting colleges and universities, but some are offered at two-year colleges. Other types of institutions, like museums and non-profits, offer masters' degrees (e.g., the American Museum of Natural History MAT in Earth and space science) as well as professional development workshops. A rigorous evaluation of teacher preparation and professional development must consider the diversity of contexts in which teacher learning takes place. It must also consider what is known about the key features that characterize effective professional development (National Research Council, 2015). Inservice teacher learning is not limited to professional development, as professional learning communities (PLCs) and instructional coaching can also contribute to teacher learning.

Recommended Research Strategies

Here we recommend short and long-term strategies that could yield insight into Grand Challenge 2 and ultimately drive forward both knowledge and practice. While short and long term strategies can both be approached immediately and simultaneously, short term strategies (#1-4) tend to focus more on synthesis of current literature, surveys of our current state of knowledge, or application of excising research to the field of teacher education. In contrast, long term strategies (#5-7) require more significant time and resource investment (such as support by external funding), focusing on more large-scale empirical students that can build the knowledge base.

1. There is a need to identify and evaluate (i.e., measure the efficacy of) existing models of teacher preparation and professional development, particularly those that specifically address the needs of elementary, middle, and/or high school pedagogical content knowledge (PCK) necessary for teaching ESS. For example, while reasoning with models is a feature of all science disciplines, it is especially important in the ESS where many processes and events occur at spatial and temporal scales that cannot be directly experienced. For example, research that focuses on ways to help teachers use models effectively with their students could be beneficial for teachers of earth and space science at all grade levels (Miller & Kastens, 2018). Information about current models of

teacher preparation and professional development that are relevant for ESS teaching could be obtained through a national survey, systematic literature review, or other mechanisms. Evaluation of existing programs should include methods for identifying their strengths and weaknesses

2. While most teacher preparation programs exist at 4YC and Masters-granting universities, some are hosted at other types of institutions, including 2YC, museums, non-profits, etc. These alternative pathways into teaching should also be identified and evaluated.

3. After existing models are identified and evaluated, additional research could be conducted to define the specific PCK and CK needed by teachers of ESS at elementary, middle, and high school, including special needs and/or underrepresented groups. This could be achieved through a literature review of research on ESS PCK and CK and would benefit from research on PCK in other science disciplines.

4. While ESS teacher preparation has unique characteristics, challenges, and opportunities, research on teacher preparation would benefit from collaboration with other science education organizations (e.g., the Association for Science Teacher Education [ASTE], the National Association for Research in Science Teaching [NARST], the National Science Teachers Association [NSTA], the National Earth Science Teachers Association [NESTA], the National Association of Geoscience Teachers [NAGT], etc.). Such a collaboration could also help teacher educators capitalize on the interdisciplinary aspects of ESS.

5. Standards and other specific requirements for initial and continued teacher licensure vary widely from state to state. Successful teacher preparation programs can remain informed of local needs and ensure that teachers are fully prepared to enter the classroom by building robust partnerships with local districts. Many teacher preparation programs actively cultivate partnerships with local school districts and typically focus on the nature and extent of clinical experiences teacher candidates have. Partnerships that simultaneously support pre-service and in-service teachers could have broad impact on the quality of ESS instruction. It is estimated that most teachers teach within 30 miles of where they grew up or went to college (Barth et al., 2016), so programs can be revised or designed with the knowledge that students enrolled in the program are very likely to teach in that region. Programs should be tailored to the unique needs and standards of ESS teaching in local districts.

6. How is "success" defined for ESS teacher preparation and professional development programs? Several metrics (e.g., recruitment of pre-service teachers into teacher preparation programs, retention, graduation rates, post-graduation employment, student learning and performance indicators, etc.) are used for measuring the success of a teacher preparation program, and so measuring "success" is a complex endeavor. Measuring the success of professional development programs for in-service teachers is equally complex. Furthermore, there are significant regional differences in teacher preparation requirements (e.g., state standards, district requirements, student populations, etc.), so direct comparison of programs is not always possible. We need to develop a methodology or tool for evaluating ESS teacher preparation programs and models, so that we can determine and implement the most effective models.

7. The success of ESS teacher preparation programs must include the long-term success of graduates after they leave the program and enter K-12 classrooms. Our evaluation of ESS teacher

preparation programs would benefit from the same type of longitudinal phenomenological research recommended above for GC#1. Successful teacher preparation programs should produce a K-12 ESS teacher workforce that teaches well, reflects the demographics of the student population, experiences low rates of attrition, among other factors. This can be evaluated best through longitudinal studies of ESS teachers as they move from teacher preparation programs into the workforce.

Grand Challenge 3

How do we best prepare future and practicing K-12 teachers to engage in ESS to promote three-dimensional learning that involves the integration of disciplinary core ideas, science and engineering practices and crosscutting concepts?

Rationale

The *Next Generation Science Standards* (NGSS Lead States, 2013) and *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas* (NRC, 2012), upon which the NGSS are based, reflect a new vision for K-12 teaching in science and engineering. Science is an interconnected enterprise encompassing three dimensions (Figure 4): science and engineering practices, crosscutting concepts, and disciplinary core ideas (NRC, 2012). Focus on an integration of the three dimensions into performance statements, or "three-dimensional learning," is based on decades of research on student learning and knowledge transfer. While not all states have formally adopted NGSS, many states have adopted standards that closely mirror NGSS. The practices, crosscutting concepts, and disciplinary core ideas of the NGSS, and the *Framework* on which it is based, have received widespread acceptance in the science education community and serve as a defacto consideration when developing any program that serves a national, if not local, audience. The geosciences education community has a great deal to gain from engagement with NGSS, or at least the concept of 3-dimensional learning, regardless its is role in state and local curricula, including but not limited to collaborations with other discipline-based science education research in the physical and biological sciences and a common language with which to discuss curricular elements across the country.

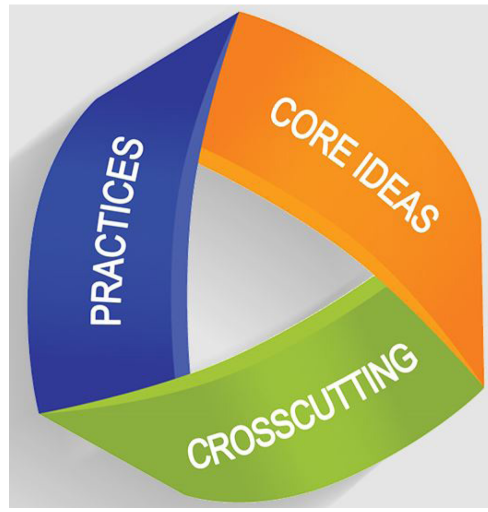

Figure 4. The NGSS recognizes that science is an interconnected enterprise encompassing three dimensions (3D): science and engineering practices, crosscutting concepts, and disciplinary core ideas (NRC, 2012). Resarch is needed on how to best prepare future K-12 teachers to engage with ESS 3D learning. Figure from NGSS at https://www.nextgenscience.org/.

To effectively teach ESS, K-12 teachers need to understand the geoscience concepts they teach. Teachers need to be able to engage in the types of instructional practices that will help students progress in their learning of ESS core ideas over time (Duschl, Maeng, & Sezen, 2011). However, K-12 science instruction as envisioned by the *Framework* is about more than teaching science content. There are important crosscutting concepts that cut across science disciplines (e.g., patterns; scale, proportion, and quantity; stability and change, etc.). Teachers must understand how these crosscutting concepts apply in the ESS and be able to embed them in instruction. The *Framework* emphasizes that science learning occurs as students engage in the practices of science and engineering (e.g., engaging in argument from evidence, developing and using models, etc.). Teachers must be able to engage in those practices themselves and be able to design instruction that will enable their students to develop facility with those practices. We know little at present about what effective three-dimensional teaching and learning looks like in ESS education or what pedagogical content knowledge (PCK) is needed to teach effectively in the unique space of ESS across K-12 (e.g., is there PCK for teaching in the field? for using big data? for visualizations?). There has been some research on students' use of model-based reasoning (e.g. Gobert, 2000; Rivet & Kastens, 2012) and argumentation (e.g. Kelly and Takao, 2002; Lee et al., 2014) in the earth and space sciences, but literature that explores how students develop facility with other science and engineering practices in K-12 classrooms is lacking. Also, while research exists on systems thinking (e.g. Raia, 2005) and thinking within and across scales (e.g. Libarkin et al., 2007), data on how students, teachers, or teacher candidates acquire crosscutting concepts is also lacking. It will be important to learn how struggles in teacher learning of ESS content, recognition of crosscutting concepts within science, and understanding of the nature of science impact instructional choices.

Recommended Research Strategies

Here we recommend short and long-term strategies that could yield insight into Grand Challenge 3 and ultimately drive forward both knowledge and practice. While short and long term strategies can both be approached immediately and simultaneously, short term strategies (#1-2) tend to focus more on synthesis of current literature, surveys of our current state of knowledge, or application of excising research to the field of teacher education. In contrast, the long term strategy (#3) requires more significant time and resource investment (such as support by external funding), focusing on more large-scale empirical students that can build the knowledge base.

1. There is a need to identify teacher education instructional models that promote three-dimensional thinking in teachers, particularly as they relate to an understanding of the nature of the ESS. This is especially important as few K-12 teachers have strong backgrounds in geoscience (Wilson, 2016). A first step is a literature review to determine what teacher education models currently in use support three-dimensional learning, either specifically in the ESS or in science education more broadly. There is some literature exploring practicing teachers' use of scientific argumentation (McNeill & Knight, 2013; Sampson & Blanchard, 2012) and model-based reasoning (Miller & Kastens, 2018), but we are not aware of studies that have investigated the development of teacher expertise with other science and engineering practices. We do not know how teachers acquire crosscutting concepts nor how to help them infuse these important themes into instruction. Once current teacher education models that promote three-dimensional thinking have been identified, we call for qualitative research that investigates specific teacher education models in the ESS to determine their effectiveness in the promoting the nature of the ESS.

2. As NGSS-aligned assessments are developed, geoscience education researchers will need to conduct a literature review of available assessments for measuring the "three-dimensionality" of classroom instruction that could be applied to ESS-specific instructional models. While many of these assessments are still in the early phases of development and evaluation (National Academies, 2018), continued research that examines the effectiveness of those models and their applicability for Earth & Space Science courses is called for.

3. K-12 student achievement in science is linked to the content and pedagogical content knowledge of their teachers (Jin et al, 2015). A review of literature on the effectiveness of conceptual change instructional approaches in ESS found far more research on astronomical phenomena than on geological ones (Mills et al, 2016). What is lacking is data that connects conceptual

change instructional practices to three-dimensional learning. Research that measures the connection between teacher education instructional models that promote three-dimensional learning in the ESS and the instructional practices K-12 teachers engage in in their classrooms will be important for both classroom teachers and ESS teacher educators.

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Figures

Figure 1:
Provenance: Heather Petcovic, Western Michigan University

Figure 2:
Provenance: Wilson, C. (2016). Status of the Geoscience Workforce 2016. American Geosciences Institute. Available from https://www.americangeosciences.org/workforce/reports/status-report

Figure 3:
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