Science & Education (2019) 28:329–366
https://doi.org/10.1007/s11191-019-00034-4

SI: NATURE OF SCIENCE

Exploring the Complexity of Students' Scientific Explanations and Associated Nature of Science Views Within a Place-Based Socioscientific Issue Context

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Abstract

In addition to considering sociocultural, political, economic, and ethical factors (to name a few), effectively engaging socioscientific issues (SSI) requires that students understand and apply scientific explanations and the nature of science (NOS). Promoting such understandings can be achieved through immersing students in authentic real-world contexts where the SSI impacts occur and teaching those students about how scientists comprehend, research, and debate those SSI. This triangulated mixed-methods investigation explored how 60 secondary students' trophic cascade explanations changed through their experiencing place-based SSI instruction focused on the Yellowstone wolf reintroduction, including scientists' work and debates regarding that issue. Furthermore, this investigation determined the association between the students' post place-based SSI instruction trophic cascade explanations and NOS views. Findings from this investigation demonstrate that through the place-based SSI instruction students' trophic cascade explanations became significantly more accurate and complex and included more ecological causal mechanisms. Also, significant and moderate to moderately large correlations were found between the accuracy and contextualization of students' post place-based SSI instruction NOS views and the complexity of their trophic cascade explanations. Empirical substantiation of the association between the complexity of students' scientific explanations and their NOS views responds to an understudied area in the science education research. It also encourages the consideration of several implications, drawn from this investigation's findings and others' prior work, which include the need for NOS to be forefront alongside and in connection with science content in curricular standards and through instruction focused on relevant and authentic place-based SSI.

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s11191-019-00034-4) contains supplementary material, which is available to authorized users.

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1 Introduction

Among the primary goals of scientists is to provide explanations about the natural world and how it works, which in turn provides the basis for science content presented in classrooms (McCain 2015; National Research Council 2012). Philosophers of science and those who study the nature of science (NOS) alternatively focus their attention toward providing accounts regarding how scientists investigate, think about, and develop explanations about nature. Current standards (NRC 2012; NGSS Lead States 2013) and science educators (e.g., Clough 2006; Hodson 2009) strongly urge that students engage in practices across a bevy of contexts and develop sophisticated and functional science content explanations and NOS understandings. Such understandings are an important part of educating scientifically literate citizens who can intelligently engage in resolving socioscientific issues (SSI, e.g., climate change, species introduction or reintroduction), which are contentious and complex scientific matters that have social implications (Herman et al. 2018; Zeidler et al. 2013; Zeidler et al. 2005). However, students do not spontaneously construct sophisticated scientific explanations and NOS views without considerable curricular and instructional support (Herman et al. 2013a,b; Osborne et al. 2004).

One way to support students in developing accurate and complex science explanations and NOS views is engaging them in real-world SSI contexts. Successful SSI resolution demands understanding and applying scientific explanations and NOS (Mitchell 2009), as well as considering sociocultural, political, economic, ethical, and other factors (Herman 2015, 2018; Herman et al. 2018; Zeidler et al. 2005). One such SSI concerns the reintroduction of wolves to Yellowstone, which entails diverse perspectives ranging from those of Native Americans that recognize the historic and sacred aspects of wolves in Yellowstone to more political and economic perspectives such as the views of ranchers' who consider wolves to be a tangible threat to livestock and livelihoods. Caught in the middle of this contentious issue are ecologists who generally recognize the environmental importance of wolves, yet debate their actual impact on the Greater Yellowstone Ecosystem and the veracity of top-down trophic cascade models to account for that impact.

This investigation focused on how students within a place-based SSI context expressed scientific explanations and NOS views about the work of this latter group—the ecologists. This builds on our prior work (Herman 2018) to explore the impact that place-based SSI instruction focused on Yellowstone wolf reintroduction had on students' trophic cascade explanations. The study reported here also examines whether and how the sophistication of students' trophic cascade explanations were associated with their NOS views—particularly those elicited when the students were prompted to think about environmental and ecological research such as that conducted on trophic cascades. This investigation did not attempt to determine the extent that students' NOS views changed through the place-based SSI instruction because those findings are reported elsewhere (Herman 2018).

2 Literature Review

2.1 Forms of Explanations

Harman (1986) considered an explanation to be "something one grasps or understands that makes things more intelligible" (p. 67). Explanations that are constructed in an attempt to better understand the natural world can include common sense accounts derived from everyday life experiences as well as those developed through scientific processes (Woodward 2014). Focusing on the latter type of explanations, constructing such accounts is among the most important aims of science—to provide clarified constructions of reality, which attempt to afford some universal applicability and ability to control or predict natural phenomena in the future (Strevens 2006). In their simplest form, the credibility of a scientific explanation relies, in part, on how it accounts for the cause of the observed natural phenomena (Mayr 1997).

The philosophical treatment of causality in science has often followed that set forth by physics, where laws, such as thermodynamics, appear to facilitate high degrees of predictability and seemingly unambiguous causal explanations for natural phenomena. However, Mayr (1982, 1997) argued that framing causality in this manner is often inappropriate for biological phenomena, because they exhibit characteristics that are often found with complex systems, such as pluralism (i.e., multiple causal explanations) and emergence (the development of novel and unpredictable factors at different hierarchical levels). Thus, as Mitchell (2009) indicated through examples from the biological sciences, complex natural systems and the relationships among their causal mechanisms are often abstruse, contextual, and unpredictable.

Bechtel (2011) critically pointed out that biological explanations sometimes exhibit a "basic account of mechanistic explanation," where they strictly treat causal mechanisms as a sequentially operating chain of factors with a clear start and finish. While Bechtel indicated that such an approach has some value as an initial step in explaining biological processes, he advocated that biological explanations must go beyond linear accounts to better portray how dynamic biological systems work. He nicely summarized this point by stating:

> As a result, researchers cannot understand the behavior of the whole mechanism by simply envisaging successive execution of operations but must seek other explanatory resources that allow them to factor in how other activity in the mechanism modulates specific operations. Instead of emphasizing sequential execution of operations, Bechtel and Abrahamsen (2005, 423) speak of the "orchestrated functioning of the mechanism." Like a player in an orchestra, an individual part may behave differently as a result of operations performed by other parts … With non-sequential organization, the operations performed by parts of the mechanism vary dynamically, depending on activity elsewhere in the mechanism, undermining the ability to understand how the mechanisms will behave simply by mentally stepping through the operations from start to termination conditions. (Bechtel 2011; p. 539, 551)

Considering these important points, biological explanations can range from those that entail blatant inaccuracies regarding how the natural world works (e.g., claiming that plants *eat* soil) to those that exhibit simplistic linear causal reasoning (i.e., "basic account of mechanistic explanation" described previously) to those that are sophisticated and complex in that they indicate the dynamic non-sequential causal relationships that occur among components of systems.

The theoretical underpinnings of this study are confined to scientific explanation theory and, therefore, do not consider argumentation theory. While both are critical scientific practices, they are not the *same* scientific practice (Braaten and Windschitl 2011; Brigandt 2016; NGSS Lead States 2013; Osborne and Patterson 2011). An explanation is "to offer a plausible causal mechanism" (Osborne and Patterson 2011; p. 8), while an argument is to defend and persuade. Scientific explanations may be generated without any attempt to defend or persuade; they serve as sense-making tools that assist students in connecting observation with theory about how and why a phenomenon occurs. However, scientific argumentation is dependent on the generated explanation because it cannot occur without a claim (i.e., the explanation) as the argument base (Zangori et al. 2013).

2.1.1 Science Content Explanations

The National Research Council (2012) advocated that theory construction is a foremost goal of science in the interest of providing explanatory accounts of the natural world. The purpose and nature of scientific explanation construction within classrooms is for students to experience science as a *way of knowing* derived from evidence that seeks to answer “how do I know?” and “why do I believe?” (Driver et al. 1994). Science content explanations accounting about natural phenomena, how and why those phenomena occur, and the underlying mechanisms (Osborne and Patterson 2011) are among the most prevalent forms of scientific knowledge (NGSS Lead States 2013). Scientific explanations presented in classrooms can range in sophistication and complexity. In their simplest form, a scientific explanation resembles what Bechtel (2011) described as the “basic account of mechanistic explanation” (i.e., simplistic linear causal reasoning of what happened and how and why it happened with pathways characterized by clear beginning and end points). The scientific explanation identifies the *cause* and *effect* (I watered the plant [cause] and the plant lived and grew [effect]) connected by the underlying mechanism (water helps plants live because water and carbon dioxide are turned into glucose during photosynthesis [mechanism]).

As the complexity and sophistication of scientific explanations increases, students begin to consider multiple generative causal relationships that may be dependent on other, sometimes simpler, explanations (Osborne and Patterson 2011; McCain 2015). In other words, a sophisticated scientific explanation can be considered a “causal story,” the narration of which requires one to identify and place the causal mechanisms and their effects in a coherent and logical order (Sandoval 2003). As indicated previously, particularly with biological science explanations, they indicate the consideration of multiple causal, and often non-sequential, relationships and emergence to better portray how dynamic systems work (Bechtel 2011). In summary, a causal story facilitates a multi-faceted understanding of how and why a natural phenomenon occurred as depicted by the fundamental ideas in science (Braaten and Windschitl 2011; de Andrade et al. 2017).

Much empirical work demonstrates that students’ responses about biological ideas, such as food chains and food webs, frequently reflect simplistic and inaccurate causal explanations. For instance, Barman and Mayer (1994) demonstrated that high school students struggled to accurately indicate how a change in one population in a food web impacts other populations in that food web. Furthermore, many students in that investigation thought that a change in one population would impact another population only if they shared a direct predator–prey relationship. Hogan (2000) showed that sixth-grade students, after one month of ecosystem instruction, typically indicated that the food web disturbance effects occurred linearly in one direction and neglected to recognize the multiple causal pathways that occur in food webs. Similarly, Gotwals and Songer (2010) investigated sixth-grade students who had experienced an instructional unit focused on developing scientific explanations in biodiversity and ecology and showed that many students after such instruction were adept at reasoning about directly connected predator–prey relationships. However, some students still struggled to determine how changes in a population influenced another population more than one trophic level away (e.g., how a change in producers would impact indirectly connected second-order consumers).

The studies profiled in the previous texts demonstrate that despite experiencing significant educational interventions focused on complex biological phenomena, students persistently employ simplistic linear causal explanations, instead of expressing more complex, multi-causal, and non-sequential explanations about concepts, such as food webs and trophic relationships. In response, one of our foci in the present investigation was to determine if secondary students' trophic cascade explanations became more sophisticated and complex after experiencing place-based SSI instruction in Yellowstone that addressed how wolf reintroduction in that area influences other natural populations. This investigative aim seems justified given that possessing sophisticated explanations about science content better equips students' engagement of the complexities of SSI at multiple scales (Zangori et al. 2017; Harlen 2015; Sadler and Fowler 2006).

2.1.2 Students' NOS Understandings and Explanations

While the glut of science teachers' efforts and standard documents have typically focused on providing science content explanations through factual assertions about the natural world and how it works, it is equally important to promote contextual accounts about how those explanations are generated and come to be accepted by scientists (i.e., NOS). There has been contention among the science education community regarding exactly how to characterize NOS (Herman et al. 2013a). Some claim that science is very nuanced and contextual and, thus, question whether a bounded construct of NOS holds value (Harding 1998; Knorr-Cetina 1999; Rudolph 2000). Others have put forward NOS tenets that, perhaps unintentionally, appear limited to epistemological considerations (Lederman 2007; McComas 2004). Still, others have advocated that NOS should take a *family resemblance* approach, where the focus should be on how diverse examples of scientific advancements and disciplines share similarities and express differences (Eflin et al. 1999; Irzik and Nola 2011). For instance, critical inquiry and self-correcting occur across the scientific fields. However, how critical inquiry and self-correcting is carried out can parallel and diverge in diverse, yet valid, ways within and across those fields. Despite these tensions, common ground exists among the field in recognizing that those who study NOS concern themselves with what science is and how it works, science's ontological and epistemological foundations, and how science and society impact one another (Clough 2006).

Our stance is that those attempting to define and understand NOS should contextually contemplate the authentic work of scientists and public engagement with science. Justifications for students deeply understanding and articulating NOS ideas across a variety of contexts pervades science education literature (e.g., Allchin et al. 2014; Clough 2006; Driver et al. 1996; Herman 2015, 2018; Hodson 2009; Kampourakis 2016; Lederman 2007), and some (McComas and Nouri 2016; Olson 2018) rightly assert that NOS should be brought to the forefront of current standards alongside other important curricular foci (e.g., science content and practices; NGSS Lead States 2013). Justifications for students learning NOS include that understanding NOS facilitates science content understanding and, more broadly, scientific literacy and democratic ways of living through socioscientific decision-making.

Several have articulated the ways that NOS should be portrayed to students so that they can develop functional scientific literacy (Allchin 2011; Allchin et al. 2014; Clough 2006, 2007; Herman 2018; Herman et al. 2013a; Matthews 2012). Providing broad-sweeping generalizations about NOS in the form of discrete tenets may not sufficiently prepare students to meaningfully understand the scientific enterprise and its achievements in a manner that aligns with scientific literacy. Rather, students require the ability to understand and apply their NOS understanding in the context of specific questions or phenomena, which enables individuals to critically engage with real-world scientific issues through exploring how claims about those issues are constructed and why they are (or are not) valid. In summary, the literature base demonstrates that students who deeply understand NOS should be able to provide contextually relevant (e.g., specific to science content and inquiry, contemporary and historical scientific cases, and SSI) interpretive analyses of scientific work, practices, and claims along multiple dimensions to include explaining the cultural facets of science, the demarcations between science and pseudoscience, and internal and external factors that influence scientific knowledge development, validity, and use (Allchin et al. 2014; Clough 2006; Herman 2015, 2018; Hodson 2009).

Of particular interest to this study is the under-investigated claim posed in the NOS literature (e.g., Lederman 2007) that an association exists between the accuracy and sophistication of students' science content explanations and NOS understanding. As described by the NOS literature, commonalities appear present when comparing how students develop sophisticated science content explanations and how scientists dynamically construct accounts about the natural world (Clough 2006; McComas et al. 1998). Helping students understand the parallels and divergences between the ways they and scientists construct ideas through NOS instruction may facilitate their interest in and learning of science (Rudolph and Stewart 1998). For instance, students should understand that theirs and scientists' accounts about trophic cascades are not static, in "final form," or developed exclusively through simple stepwise approaches. Rather, students should understand that scientists' methods and accounts about trophic cascades are guided by the complex and emergent quality of those phenomena. That is, scientists' accounts of trophic cascades are developed through a bevy of complex and novel methods, normally divergent and perpetually incomplete in some ways, subject to revision, and the basis for future investigations.

Again, similar epistemological characteristics are expressed with students' developing deep knowledge about complex science ideas and scientists' constructing accounts about the natural world. Therefore, we agree with Lederman (2007) and others who assert that students' science content and NOS understanding could be associated in some way. This relationship seems worthy of inquiry because while a number of potential explanations for any given natural phenomenon may exist, from those that are common sense to scientific ones, contextual knowledge about NOS should give insight about the virtues of well-established scientific explanations (despite their oftentimes counterintuitive nature) in comparison to other types of explanations.

2.2 SSI Contexts for Promoting Science Explanations and Their Utility

Despite the importance of helping students develop and use informed and rich explanations about science content and NOS for SSI engagement, science teaching in formal contexts (e.g., classrooms) oftentimes falls short of this paramount goal. This is largely because students can develop a static and trivial view of science ideas and NOS through classroom instruction that presents what many have referred to as "final-form science" (Clough 2006; Duschl 1990). Some science education work outside of the SSI field has substantiated this assertion through claiming that students' and teachers' NOS views are linked to their perceptions about scientific models, which are modifiable and simplified forms of explanations that enable pattern recognition and predictions about natural phenomena (Cheng and Lin 2015; Gericke et al.

2013; Grosslight et al. 1991). This work has demonstrated that science textbooks and classroom instruction present models in a way that reinforces students' developing science understandings consistent with a naïve realist epistemology. That is, the students, and oftentimes their teachers, come to believe that scientific models and explanations to be exact and immutable copies of natural phenomena. From a situated learning perspective, learning environments such as these perpetuate discrete and impoverished academic goals and work against functional scientific literacy through failing to immerse students in authentic and contextualized portrayals of how science ideas are constructed, negotiated, perceived, and used by scientists and the public sphere (Allchin 2011; Herman 2018; Sadler 2009; Sadler et al. 2007).

Alternatively, using SSI as rich contexts for academic interventions can help students deeply consider and apply fundamental science and NOS concepts when resolving scientific issues of societal importance. This is particularly the case for academic interventions that are relevant to everyday life. From this perspective, science explanations and NOS should not be divorced from the real-world SSI contexts in which they are to be used (Allchin 2011; Allchin et al. 2014; Herman 2018; Sadler 2009; Sadler and Donnelly 2006; Sadler and Fowler 2006; Sadler et al. 2007; Wong et al. 2008; Zangori et al. 2017; Zohar and Nemet 2002). Situating scientific explanation construction within the context of an SSI can motivate students to learn the underlying science in a more robust manner than what might occur without the SSI context. For example, students that learned genetics within the context of an SSI outperformed on content knowledge tests their peers who received similar content instruction without an SSI focus (Zohar and Nemet 2002). Zangori et al. (2017) have demonstrated that an SSI-based modeling curriculum focused on climate change helped students develop sophisticated science explanations about carbon cycling.

A substantial number of conceptual arguments and investigations exhibit the merits of using diverse authentic SSI contexts to promote students' NOS understanding as part of a functional scientific literacy (e.g., Allchin 2011; Allchin et al. 2014; Herman 2018; Khishfe 2012, 2014; Wong et al. 2008). We focus on the small subset of that scholarship where students were immersed in the SSI context through first-hand lived experiences. Wong et al. (2008) used the 2003 severe acute respiratory syndrome (SARS) outbreak in Hong Kong and video interactions with SARS scientists as a context to highlight several NOS ideas, such as tentativeness, theory-ladenness, and the intersection of science with sociocultural and political factors, for preservice and in-service science teachers. Through this intervention, the teachers developed a deeper understanding of authentic scientific inquiry and NOS aspects, such as the intersections between science and the sociocultural environment and technology. In a previous investigation, related to the one reported here, Herman (2018) demonstrated that sixty secondary students' NOS views (e.g., nature of science methods; role of culture for investigating and resolving SSI) became significantly more accurate and contextualized after place-based SSI instruction focused on the wolf reintroduction in the Greater Yellowstone area. During this instruction, the students visited areas where ecologists were investigating wolves' impact on the Yellowstone ecosystem with biologists who were involved in the wolf reintroduction efforts. From the wolf biologists' interactive instruction, the students learned about various science and NOS concepts, such as how ecologists' research supports competing views regarding the presence of a top-down wolf controlled trophic cascade.

In summary, SSIs can serve as ideal contexts for helping students develop robust and functional science explanations and NOS understandings. Without a functional understanding of the science that undergirds an issue and associated NOS features, people are ill-equipped to develop and argue for ways to resolve that issue (Herman 2015; Rudolph 2007; Sadler and Fowler 2006). This investigation responds to this claim through exploring how experiencing an authentic place-based SSI instructional context focused on Yellowstone wolf reintroduction can promote students' trophic cascade explanations and how those explanations associate with students' NOS views. The following questions guided this investigation:

1. How did the sophistication of students' trophic cascade explanations change through place-based SSI instruction focused on wolf reintroduction?
2. In what ways did students' post-instruction NOS views demonstrate accuracy and reference to relevant ecology research contexts and considerations (e.g., wolf reintroduction issues and trophic cascades) and correlate with the sophistication of those students' trophic cascade explanations?

In the following sections, we provide a description of the place-based SSI learning context and how we collected and analyzed data regarding the trophic cascade explanations and NOS views that students expressed during the place-based SSI instruction.

3 Methods

A triangulated mixed-methods approach was used to investigate qualitative and quantitative data sources in order to respond to this investigation's research questions (Cresswell 2014; Onwuegbuzie and Combs 2011). More specifically, qualitative data sources were prioritized and corroborated with and through quantitative data sources, analyses, and interpretation to help ensure robust findings. The participants, the place-based SSI instruction they experienced, and data collection and analysis are described in the subsequent texts.

3.1 Participants

Sixty students, males ($n = 31$) and females ($n = 29$), participated in the study. The students reside in urban and suburban (80%) and non-agricultural (15%) and agricultural (5%) rural settings and were enrolled in 7th ($n = 23$), 8th ($n = 19$), 9th ($n = 13$), 10th ($n = 4$), and 11th ($n = 1$) grades in a medium-sized city school district in Missouri that implements a uniform science curriculum. All students had previously experienced an ecosystem science curriculum, including food webs and top-down trophic cascades, as part of their 6th grade coursework. This curriculum was considered and provided a backdrop for shaping the place-based SSI instruction.

3.2 Study Context

The place-based SSI instruction occurred over the course of a week in the Yellowstone National Park and followed the design elements required for SSI instruction (see, Herman et al. 2018; Herman 2018; Zeidler et al. 2011; Zeidler and Kahn 2014). At the forefront of the SSI instruction was the contentious topic of Yellowstone wolf reintroduction and associated scientific and sociocultural themes, such as the contention among the ecological research community regarding the extent that reintroduction resulted in a wolf-controlled top-down trophic cascade and how diverse stakeholders (e.g., ranchers, Native Americans, and ecologists) perceived this controversial issue.

The instruction began with the students watching the popular video that was widely shared across social media, *How Wolves Changed Rivers* (Sustainable Human 2014), and then discussing how that video presented an over-simplified, yet emotively appealing, portrayal of the extent that wolf reintroduction caused a top-down trophic cascade. Subsequent scaffolding of SSI instruction included concrete experiences, such as videos (CBS 2007a,b; PBS 2010), field observations with wolf ecologists, readings (e.g., Marris 2014), and discussions focused on (1) the contentious historical, political, cultural, and ethical implications of wolf reintroduction and (2) the complex ecology and NOS concepts, such as how many interacting biotic and abiotic factors beyond what is represented in simple top-down trophic cascade models must be accounted for when determining wolves' impact on the Yellowstone ecosystem and how ecologists use diverse investigative approaches to account for that impact. For instance, halfway through the place-based SSI instruction, the students hiked with the author delivers summarizings, including wolf ecologists who were involved with the Yellowstone wolf reintroduction and subsequent research and education outreach efforts, to several field locations where they examined and deliberated the extent that wolves had impacted herbivores' effect on vegetative stands of willow and aspen. Appearing subsequently is an excerpt from one of the wolf ecologist's field presentations close to a research site where the impact of wolf reintroduction on the Yellowstone ecosystem is being investigated.

> There's a wolf den up here right now that's active. We can't see it, but there's a wolf pack that lives in this area, and there has been for the last 20 years. And so one of the reasons that maybe there's less elk here eating willow is because of the wolf pack … But, there's a lot of debate in the scientific community. Basically, some people are trying to say that wolves are very important to Yellowstone's landscape. And that's what we [ecologists] want—all this natural stuff occurring without a lot of interference from humans. A place where the food chain is totally intact and operating in the sense that there's top carnivores like wolves eating dominant herbivores like elk and affecting communities along the rivers like the willow. Some scientists have shown that is the case, but we're not really finding that reaction occurring in other parts of Yellowstone. Maybe it's (trophic cascade like events) occurring here, but if you go farther down Lamar Valley it's not going on there. It seems like those areas have dried out a lot and it's just not really a place where these plants can grow anymore. And so climate could be a big factor. And maybe the fact that Yellowstone's becoming a warmer and drier place all the time—because of climate change, some of these communities aren't affected in the way that we predicted from the trophic cascade's interaction. So, climate's a big one. I also mentioned flooding. One of the things that kick started this plant growth and the trophic cascade interaction going here was maybe you need a little bit of flooding to start things off. So, everything kind of gets silted over. The seeds are deposited. The willow starts growing. And then, without the elk eating it, it can grow back to being like you see it behind me. So, so maybe some big events like flooding are also a factor that affects the interaction.

The author delivers summarizings, then, proceeded to explain that since the mid-1990s (when the wolves were reintroduced), climate change has caused the frost-free growing time to be extended dramatically and has increased the availability of elks' preferred food, which are grasses. Therefore, elk pressure on young willow has diminished, thus letting stands of these plants to grow until they are unpalatable for elk. Finally, the author delivers summarizings described how ecologists studying this issue sometimes exhibit, like all scientists, a form of subjective confirmation bias where they perceive their own methods and accounts as more efficacious than those of competing research groups. However, they also explained that the peer review and consensus building processes in science work to limit these subjectivities. Table 1 presents the day-to-day place-based SSI instruction activities.

Table 1 Sequence of the place-based Yellowstone SSI instruction

Day	Experience	Salient themes
1	- Complete pre-instruction SEEDSII - Films and discussion about wolf reintroduction and trophic cascades through multiple perspectives: How Wolves Change Rivers (Sustainable Human 2014), Hunting Wolves Saving Wolves (PBS 2010), Wondering About Wolves, Wolves of Yellowstone Spur Love and Hate (CBS 2007a,b)	- Ecosystem dynamics and how top-down trophic cascade may be too simplistic for Greater Yellowstone ecosystem - Perspectives (ranchers' and scientists') and contention about wolf reintroduction - Introduce how ecologists investigate
2	- Travel through Yellowstone National Park from Jackson, WY, to Gardiner, MT - Instructor/author transfers from van to van and engages small groups of students	- Esthetic and community value of Yellowstone National Park - Cultural and ethical aspects of Yellowstone National Park management and decision-making
3	- Hike Slough Creek/Lamar Valley, observe wildlife, and learn from wolf biologists - Read/discuss—The Legend of the Wolf: Predators are Supposed to Exert Strong Control over Ecosystems, but Nature does not Always Play by the Rules (Marris 2014) and competing biologists' Yellowstone National Park trophic cascade accounts (Beschta and Ripple 2013; Kauffman et al. 2013) - Instructor/author transfers from van to van and engages small groups of students - Instructor/author delivers summarizing presentation	- How ecologists investigate nature through diverse yet valid approaches - How wolves impact the Greater Yellowstone ecosystem in diverse ways and Yellowstone trophic cascade debate among scientists - Scientific and cultural perspectives about wolf extirpation, reintroduction, and contentious environmental issue resolution - How trophic cascades/scientific models omit many factors and considerations (e.g., abiotic, biotic, sociocultural factors)
4	- Hike Mount Washburn: field discussions - Read and discuss—Wolf Ecology and Thinking Like a Mountain (Leopold 1949) - Interactive instruction at Mammoth Hot Springs Terraces about perspective-taking involved in contentious environmental issues resolution - Instructor/author transfers from van to van and engages small groups of students	- Different historical and cultural perspectives (e.g., scientific, Native American vs. Eurocentric, ecocentric and anthropocentric) regarding wolf reintroduction and ecosystem dynamics (e.g., trophic cascades) -How trophic cascade research can be used to promote diverse agendas - Moral and ethical considerations regarding wolf extirpations and reintroduction
5	- Hike Grand Prismatic, Artists Paintpots, and Old Faithful - Instructor/author engages students in small group discussions on hikes and in vans - Students gather together at the Hoodoos and share their Yellowstone experience	- Address perspectives about wildlife management and public natural resources use - Summarize major impacts from Yellowstone National Park experience - Share emerging views regarding Yellowstone National Park SSI.
6/7	- Bonfire at Teton National Park/Coulter Bay - Complete post-instruction SEEDSII - Travel to Jackson/departure	- Share emerging views regarding wolf management and Yellowstone National Park SSI

3.3 Research Instruments Used

Each student completed The Socioscientific Ecological Engagement Dimensions Survey II (SEEDSII, Appendix A) prior to and after the place-based SSI instruction that was developed, validated, and specifically used for this and a related investigation (Herman 2018) that focused on the same population. The SEEDSII presents open-ended and Likert prompts relevant to the environmental SSI of wolf reintroduction, and the current investigation is limited to analyzing students' responses to section 1, which focused on trophic cascades and food webs, and section 2, which focused on five NOS dimensions related to investigating and resolving environmental issues. The remaining SEEDSII items were not used here due to their lack of relevance to the aforementioned research questions.

Effectively engaging in the SSI of wolf reintroduction requires a complex understanding of how wolves impact trophic cascades. The robustness of the SEEDSII derives from its items being developed to align with the environmental SSI used in this investigation. Section 1 presents a food web and trophic cascade model similar to those found in many science textbooks and includes items that ask students to (1) indicate the impact of an increase in the wolf population on aspen and willow populations and (2) add anything, with explanation, that is missing that may affect the populations of the wolves, elk, aspen, and willow. Section 2 begins with a prompt that asks respondents to consider how scientists understand things in nature like the trophic cascade theory and how the environment should be managed. Then, presented are five sets of four forced Likert prompts, each accompanied by an open-ended qualitative prompt that requests respondents to express their views regarding five dimensions of the nature of ecology and environmental science research. These five NOS dimensions and the SEEDSII items that measure those dimensions were selected because they are contextually relevant to the SSI of wolf reintroduction and how scientist account for wolves' impact on trophic cascades. For instance, the SEEDSII asks students the extent that they think scientific ideas such as trophic cascade can be revised and replaced.

The SEEDSII uses complementary Likert and qualitative measures that enable mixed-methods approaches including triangulation and assessment across data sources and the analysis of nuanced contextual views (Cohen et al. 2011). The reliability of this investigation's coding and analysis is augmented through the SEEDSII's presenting a concluding prompt that asks participants to explain their difficulties with responding to questions. Specific indicators of the SEEDSII reliability relevant to this investigation are presented later in the section titled SEEDSII Validity and Data Efficacy (also, see Herman 2018, for a full description of the SEEDSII construction and reliability).

3.4 Data Collection

The students completed the SEEDSII items immediately before and after the place-based SSI instruction, and the lead researcher and chaperoning teachers were available to address any clarifications requested by the students. Prior to completing the SEEDSII, the students were directed to consider examples that may help contextualize their responses. Throughout the place-based SSI instruction, field notes and student discussions were also recorded and served as auxiliary triangulating data sources of the students' SEEDSII responses.

3.5 Data Coding and Efficacy

An iterative and rigorous process was used to code and, then, analyze students' SEEDSII responses in order to investigate the following: (1) how students' trophic cascade explanations in response to SEEDSII section 1 items changed through the place-based SSI instruction; (2) the extent that students' post-instruction NOS views elicited by SEEDSII section 2 items were accurate and referred to relevant ecology research contexts and considerations (e.g., wolf reintroduction issues and trophic cascades); and (3) how those NOS views correlated with the sophistication of students' trophic cascade explanations. Importantly, when explicitly asked, none of the students indicated being confused with the trophic cascade and NOS prompts used to generate data for this investigation. Throughout the coding process, all student identifiers were removed and the students' names were replaced with pseudonyms. The data coding, efficacy, and analysis are presented in the subsequent texts.

3.5.1 Coding and Efficacy of SEEDSII Responses: Sophistication of Students' Trophic Cascade Explanations

All students' responses to the SEEDSII section 1 items were coded to determine the sophistication of their trophic cascade explanations. As described previously, scientific arguments attempt to defend or persuade and depend on some form of science explanation. During coding, we included responses that may have resembled a scientific argument. However, we did not score students' answers based on their attempt to defend or persuade. Rather, in these cases, our coding focused solely on the scientific explanation the student embedded in their argument. Therefore, our coding of the sophistication of the students' trophic cascade explanations focused on the (1) accuracy and complexity and (2) inclusion of human and natural causal mechanisms.

The students' responses to SEEDSII section 1 items were independently coded through a multi-step process that involved open, axial, and pattern-coding procedures by four of the authors who are science education researchers that specialize in investigating SSI, NOS, and students' science explanations (Strauss and Corbin 1998). First, the lead author developed an a priori rubric to be used for provisionally coding the sophistication of students' trophic cascade explanations. Next, each of the four authors independently reviewed five randomly selected students' trophic cascade explanations, and, then, they all met to propose changes to the rubric that better captured the breadth and depth of those explanations. This process was repeated with different student responses until the rubric was saturated and fully represented the range of the sophistication of students' trophic cascade responses.

The final rubrics presented in Tables 2 and 3 enabled us to determine the sophistication of students' trophic cascade explanations. This was based on two scores that indicate the levels of complexity of students' explanations through their consideration of causal mechanisms and relationships. Invoking the works of Zangori et al. (2017), Bechtel (2011), and Bechtel and Abrahamsen (2005), our coding and scoring determine how the students described their trophic cascade by identifying its causal components or mechanisms, their functions and relationships, and how these causal elements affect the trophic system and its outcomes as a whole.

Complexity was considered to be at the lowest level when students referred only to visible causal components of the trophic cascade system, and did so in a cause and effect single-chain mechanistic fashion, such as describing the following pathway: elk eat aspen and willow and wolves eat elk. Because wolves ate the elk (cause), there will be a lot more aspen and willow (effect). At the next level of complexity, students moved beyond a linear causal chain or path and considered both hidden and visible components of the system. However, they did not explicitly associate causal mechanisms for how and why relationships occurred and were expressed at a systems level. For example, they considered that weather patterns may also cause greater amounts of willow and aspen to exist, but they did not consider how or why weather had an impact on the trophic cascade as a whole. At the highest level of complexity, students were able to explicitly consider the visible and non-visible causal components and mechanisms of the system and to identify the underlying and potentially non-sequential relationships among those elements as they affect system function.

Table 2 Scoring scheme for rating the complexity of students' trophic cascade explanations provided in response to SEEDSII section 1 items

Score/ description	0 = incorrect (provides statement about trophic cascades that is untrue)	1 = correct with little complexity beyond the provided diagram (reasoning presents simple linear causal relationships (i.e., resembles diagram provided or text book model))	2 = correct with tacit indication of complexity beyond the provided diagram (reasoning indicates there are multiple, and possibly non-sequential, causal mechanisms, relationships, and outcomes, but does not explicitly state how or why they affect the system).	3 = correct with explicit indication of complexity beyond the provided diagram (reasoning indicates that there are multiple, and possibly non-sequential, causal mechanisms, relationships, and outcomes and explicitly states how or why they affect the system)
Exemplar quote	With more wolves, there will be less food supply, such as aspen and willow populations, because there are more wolves to eat the food.	Wolf eats elk which eat aspen and willow; so, an increase of wolves would kill elk and aspen and willow will grow more … sun helps grow plants	If wolf populations increase, then more elk will be eaten; therefore, willow and aspen populations will increase. Humans and weather extremes can be responsible for altering populations of plants and animals by hunting, accidents (wrecks, etc.), and drought or too much rain.	I believe that aspen and willow populations will increase because if the wolf population grows, more wolves will eat elk/beavers which will cause decreases in their populations. If there are less elk and beaver eating aspen and willow trees, these plant populations will most likely increase. I drew a picture symbolizing climate change to show that things like droughts can cause a decline in aspen and willow populations which can lead to decrease in beaver, elk, and wolf populations. Another picture I drew shows that if wolves do not hunt elk that inhabit an area with lots of willow and aspen, elk populations may not decrease or increase.

The first score indicates whether the provided trophic cascade explanation was correct and demonstrated complexity (see Table 2, scores ranged from "0" = incorrect to "3" = correct and explicitly demonstrates complexity). The second score was attributed to students' trophic cascade explanations, based on the extent that these added human and natural causal

Table 3 Scoring scheme for rating students' accurate addition of trophic cascade causal mechanisms when responding to SEEDSII section 1 items

Score/ description	0 = no correct addition of human or ecological causal mechanisms	1 = correct addition of one human and/or one ecological causal mechanism	2 = correct addition of two or more human and/or two or more ecological causal mechanisms
Exemplar quote	I do not think anything is missing.	I added sun because that is where plants get their energy	Drought causes less aspen and willow meaning less for elk, bringing down populations of elk and wolves. Floods do the opposite of droughts. Location may be the place where lots of wolves eat elk or where there is lots of food for elk. Humans hunt and change the environment.

mechanisms (see Table 3, scores ranging from "0" = no causal mechanisms added to "2" = two or more correctly added causal mechanisms) beyond the provided trophic cascade diagram. Scoring procedures occurred through the first three authors' use of the final rubrics to independently score all students' pre- and post-instruction trophic cascade explanations. The initial round of independent scoring resulted in a 91% inter-rater match for all items. To further ensure scoring efficacy, the fourth author randomly selected and scored 20% of the explanations. The four authors, then, met to cross-compare their scoring of the students' trophic cascade explanations. The scorers discussed any remaining discrepancies until an agreed upon rating was determined and justified.

3.5.2 Coding and Efficacy of SEEDSII Responses: NOS Responses

We focused only on the students' post-instructional NOS responses. This was because the students' uniformly naïve pre-instructional responses across the SEEDSII NOS dimensions prevented a meaningful analysis of the association between students' pre-instructional NOS views and trophic cascade explanations. Furthermore, we emphasized the analysis and interpretation of students' written NOS responses over their Likert responses, which were used for triangulating purposes, because the students were free to contextualize NOS by using real-world examples and sophisticated explanations in their written responses.

Again, the students' post-instruction NOS Likert responses were used to triangulate and substantiate this investigation's qualitative data sources and analyses. The coding of the students' Likert NOS responses entailed attributing scores ranging from "0" representing inaccurate NOS views to "4" representing accurate NOS views. Each student's Likert NOS response scores were averaged across each dimension.

Herman's (2018) coding of students' written NOS responses focused primarily on their accuracy and secondarily on their reference to any scientific context. For the investigation reported here, the students' post-instructional written NOS responses were coded to determine the extent that they were accurate and, more importantly, provided context through specific reference to relevant ecology research contexts and considerations (e.g., wolf reintroduction and trophic cascades). Coding students' written NOS responses in this manner better enabled us to determine the association between those responses and the sophistication of the students' trophic cascade explanations.

The coding of students' written NOS responses was independently conducted through the use of open, axial, and pattern-coding procedures by the first and last authors (Strauss and Corbin 1998). Provisional taxonomies were generated based on the SEEDSII NOS Likert items and findings from Herman (2018). Then, through multiple reviews of the students' NOS responses, the provisional taxonomies were iteratively modified until the following scoring scheme was developed: "0" = inaccurate; "1" = has merit and lacks reference to relevant ecology research contexts and considerations (e.g., wolf reintroduction issues and trophic cascades in Yellowstone); "2" = accurate and lacks reference to relevant ecology research contexts and considerations; "3" = has merit and refers to relevant ecology research contexts and considerations; and "4" = accurate and refers to relevant ecology research contexts and considerations. The raters, then, independently used this scoring scheme to score students' written NOS responses and determined the percentage of the students' Likert and written responses for each NOS dimension that exhibited congruent degrees of accuracy. For instance, providing inaccurate Likert and written responses for a particular NOS dimension would be considered a congruent degree of accuracy between those responses. Alternatively, providing accurate Likert responses and an inaccurate written response for a particular NOS dimension would be considered an incongruent degree of accuracy between those responses. The initial round of coding resulted in a 95% inter-rater match for all items. The raters discussed the remaining discrepancies until an agreed upon score was determined and justified. Table 4 provides an abbreviated NOS written response scoring scheme that was used in this investigation, including examples of students' responses. The full scoring scheme presenting all five NOS dimensions can be found in Appendix B of the electronic supplementary materials.

Across each SEEDSII NOS dimension, Cronbach's alphas and mean inter-item correlations, respectively, ranged from 0.61 to 0.83 and 0.28 to 0.56, thus indicating satisfactory internal consistency among Likert item responses. Mean inter-item correlations are emphasized here with a minimum threshold of 0.15, because they provide more robust estimates of internal consistency than Cronbach's alpha with scales consisting of fewer than ten items (see, Briggs and Cheek 1986; Clark and Watson 1995). None of the participants indicated experiencing confusion when completing the SEEDSII items used in this study. The students' SEEDSII Likert and written NOS responses were highly congruent with 93–100% of those responses exhibiting agreement (see Appendix C of the electronic supplementary materials for more detailed reporting regarding the SEEDSII validity and data efficacy).

3.6 Data Analysis

A non-parametric Wilcoxon rank sum test was used to determine if students' pre- and post-instructional trophic cascade explanations significantly differed regarding their sophistication and addition of causal mechanisms. Qualitative comparisons were also conducted regarding how the sophistication of and addition of causal mechanisms to students' trophic cascade responses changed through the place-based SSI instruction. Non-parametric correlational analyses were, then, used to determine if an association existed between students' post-instruction trophic cascade explanation sophistication scores and their NOS views as indicated by their Likert and written NOS response scores for each of the five SEEDSII NOS dimensions. These correlational analyses were complemented by frequencies that demonstrate how the accuracy and contextualizing of students' post-instruction written NOS responses varied when organized according to the level of complexity of students' trophic cascade explanations.

Table 4 Abbreviated scoring scheme for students' NOS written responses

NOS dimension	Accuracy level anchor points	0—Inaccurate exemplar	1—Has merit and lacks reference to specific relevant ecology research contexts exemplar	2—Accurate and lacks reference to specific and relevant ecology research contexts exemplar	3—Has merit and refers to specific topics relevant to ecology research contexts and issues exemplar	4—Accurate and refers to specific topics relevant to ecology research contexts and issues exemplar
Methodology of environmental science investigations	Inaccurate: Set scientific method/controlled experiments required Has merit: Significant accurate caveats combined with significant inaccurate caveats or tacitly indicates science does not follow a set method. Accurate: Scientists do not follow set scientific method.	I think that if we want to be accurate you have to have a controlled step-by-step scientific method.	The methods are different with each problem; there is no set method that scientists are required to use, but the method needs to be a controlled experiment for accurate data.	Scientists can use all different kinds of scientific methods. Such as observation method, sometimes they have to make a method up. You do not necessarily need a controlled experiment when they research environmental issues.	There really is not one method that all scientists use. For example, Audrey told us that her wolf project methods were very different. However, controlled experiments are the only way to get accurate information.	Controlled experiments are not the only way to research. Kauffman's research was done through observation in an actual environment. Different scientists use different methods and their conclusions are valid. Kauffman and Ripple are examples.
Nature of scientific theories such as trophic cascade	Inaccurate: Scientific theories will not change, or will change because they are "just theories" and become laws Has merit: Will change due to new	Scientific theories always change until it is a law. Any theories can be disproven. Yes, theories can replace each other to prove them wrong.	Theories can be changed, nothing is set in stone. New evidence could alter certain viewpoints on theories.	A scientific theory can always be further researched. A theory can be supported by more evidence, new theories can be created, or an old theory can be overruled by a new theory. Old theories can resurface if supported by evidence.	People see things and conduct experiments differently, which shows that many things are not 100% correct, like how ideas of how the trophic cascade changes.	There are many investigations that support that the trophic cascade is true, but the trophic cascade is not as simple as it seems and excludes many important variables that could affect how the trophic cascade works (such as drought and floods.). Because of this, the trophic cascade may be

Table 4 (continued)

NOS dimension	Accuracy level anchor points	0—Inaccurate exemplar	1—Has merit and lacks reference to specific relevant ecology research contexts exemplar	2—Accurate and lacks reference to specific and relevant ecology research contexts exemplar	3—Has merit and refers to specific topics relevant to ecology research contexts and issues exemplar	4—Accurate and refers to specific topics relevant to ecology research contexts and issues exemplar
			information/evidence with little explanation. Or, are proven if based on experiments but can typically change.			further investigated and built onto and may very likely change.
Accurate: Will change due to new information and reinterpretation of evidence.						

Qualitative comparisons were interpreted to further demonstrate how students' post-instruction NOS views varied when organized according to the level of complexity of their trophic cascade explanations. Effect sizes were calculated and interpreted because they indicate the strength of relationship or association between analyzed variables that is not indicated through p values (see APA 2001; pp. 25–26). In the case of determining the magnitude that the scores measuring the sophistication of students' trophic cascade explanations changed through the place-based SSI instruction, effect sizes for Wilcoxon tests followed recommendations from Clark-Carter (1997), Conover (1999), and Corder and Foreman (2009). More specifically, these authors have indicated that an observation is the difference between matched pre- and post-instructional scores and effect sizes for Wilcoxon tests are calculated through using the formula r = square root Z / number of observations. In the case of determining the strength of the association between the students' trophic cascade complexity and NOS views scores, we drew from Cohen (1988) and Clark-Carter (1997) to interpret the correlation (r) values between these variables. In both cases, effect size interpretation followed Cohen (1988, 1992) where $r = 0.1$ is a small, $r = 0.3$ is a moderate, and $r = 0.5$ is a large effect, magnitude, or association.

4 Findings

The findings are organized according to this investigation's research questions that sought to determine (1) how the sophistication of students' trophic cascade explanations changed through place-based SSI instruction and (2) the ways the students' post-instruction NOS views demonstrated accuracy and reference to relevant ecology research contexts and considerations and correlated with the sophistication of those students' trophic cascade explanations. First, we present how students' trophic cascade explanations changed through the place-based SSI instruction. Next, we present the extent that students' post-instruction trophic cascade explanations and NOS views were correlated. In addition to quantitative results, we provide context through descriptive qualitative findings and examples of students' responses identified through their assigned pseudonym.

4.1 Students' Trophic Cascade Explanations

Students' trophic cascade explanations became significantly more sophisticated, as they increased in complexity through considering more causal relationships and added more causal mechanisms, from before to after the place-based SSI instruction. The findings that follow include the Wilcoxon rank sum test results and distributions, as well as examples of students' written trophic cascade explanations, based on their level of complexity and addition of causal mechanisms. Students' illustrative additions to the SEEDSII trophic cascade and food web figures were also included if they meaningfully augmented their written trophic cascade explanations.

4.1.1 Complexity

Students' trophic cascade explanation complexity scores demonstrated significant, large, and positive gains after the place-based SSI instruction ($Z = -4.42$, $p < 0.001$, $r = 0.57$). After the place-based SSI instruction, the proportion of students providing inaccurate (trophic cascade

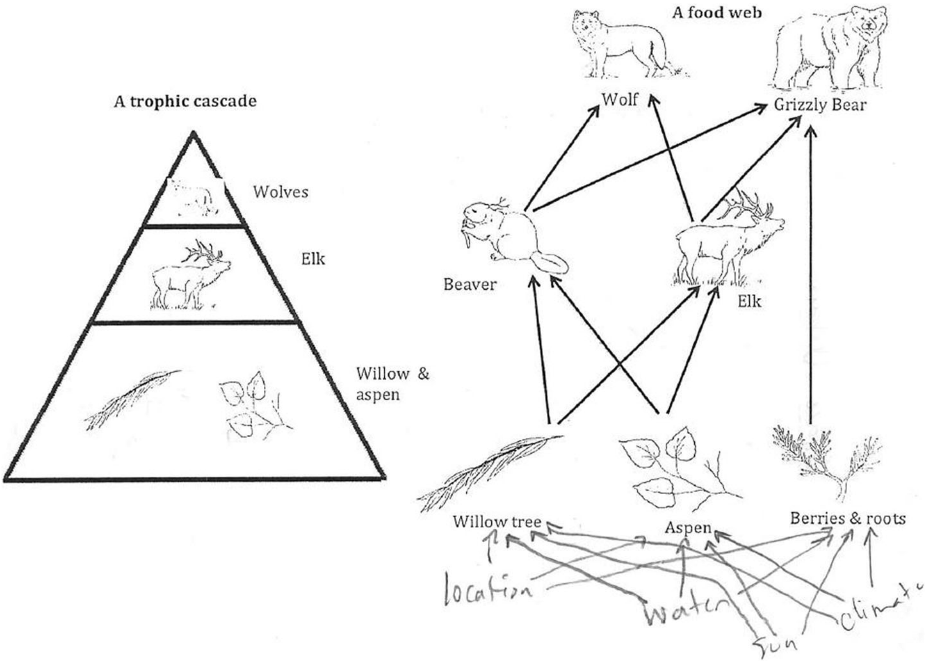

Fig. 1 Gwen's post-instruction additions to the SEEDSII trophic cascade and food web diagrams

complexity (TCC) score = 0) trophic cascade explanations reduced from 22 to 5%. For example, Andrew offered an inaccurate trophic cascade explanation prior to place-based SSI instruction:

> With more wolves, there will be less food supply such as aspen and willow populations, because there are more wolves to eat the food.—*Andrew, pre-instruction (TCC score = 0)*

More specifically, Andrew inaccurately suggested that wolves would consume and reduce populations of aspen and willow. His response failed to recognize that, at the very least, wolves are top predatory carnivores and their impact on aspen and willow is mediated through their prey.

The percentage of students providing trophic cascade explanations that were accurate but demonstrated simplistic linear reasoning with little evident complexity (TCC score = 1) decreased from 68 to 57% after the place-based SSI instruction. These responses appeared to largely be recitations of the top-down trophic cascade and food web model presented on the SEEDSII—a reflection of the simple linear accounts of trophic cascades and food webs that are typically found in life science textbooks. For instance, Sam offered such an explanation (presented subsequently) after engaging in the place-based SSI instruction:

> More wolves would mean more elk would be eaten. This means there are less elk to eat willow/aspen, and thereby increase willow/aspen populations. I added bison because that is what wolves can eat. They would probably decrease plant populations by eating them, but would probably leave (not impact) most animals where they are. Except for wolves because bison sometimes kill wolves.—*Sam, post-instruction (TCC score = 1)*

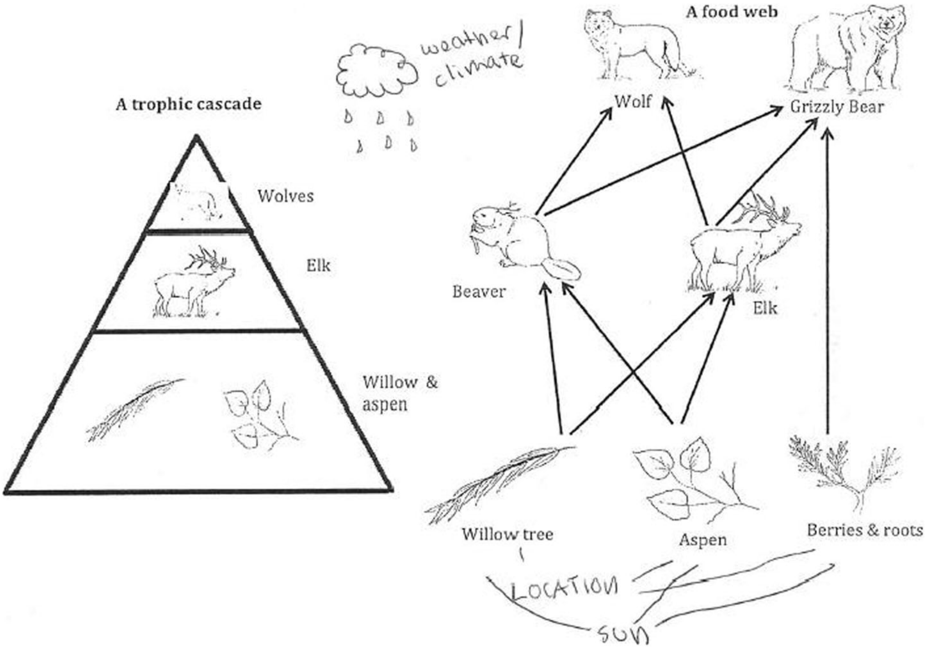

Fig. 2 Mary's post-instruction additions to the SEEDSII trophic cascade and food web diagrams

Here, Sam is considering the relationship between wolves, their prey, and aspen and willow as linear, unidirectional, and isolated from other environmental factors. Sam did indicate that bison sometimes kill wolves, which reflects a passing discussion that occurred during the SSI instruction about how bison engage in defensive behaviors, but this addition did not significantly increase the complexity of his trophic cascade explanation beyond linear reasoning.

The percentage of students providing trophic cascade explanations that were accurate and tacitly demonstrated complexity increased from 8% before the place-based SSI instruction to 26% after that instruction (TCC score = 2). These explanations were characterized by a variety of possibly non-sequential causal mechanisms, relationships, and outcomes that existed beyond those provided in the trophic cascade diagram. However, these explanations did not explicitly state how or why those causal mechanisms and relationships could affect the trophic cascades at a system level. For instance, Maggie's explanation provided consideration of multiple causal mechanisms and relationships in a way that tacitly demonstrated complexity.

> If the wolf population increases, more elk will be eaten, and the aspen and willow that elk eat, won't be eaten. Floods and droughts will influence populations as well, because they contribute to food sources. Sun, well that's obvious. Human interference will always be present and is a variable.—*Maggie, post-instruction (TCC score = 2)*

Maggie's explanation exhibited some complexity by indicating that floods, droughts, and humans affect the trophic cascade, but this description failed to explicate how these causal mechanisms would affect the trophic cascade system.

Gwen (post-instruction) also provided an example of a trophic cascade explanation that tacitly demonstrated complexity beyond the provided diagram (Fig. 1).

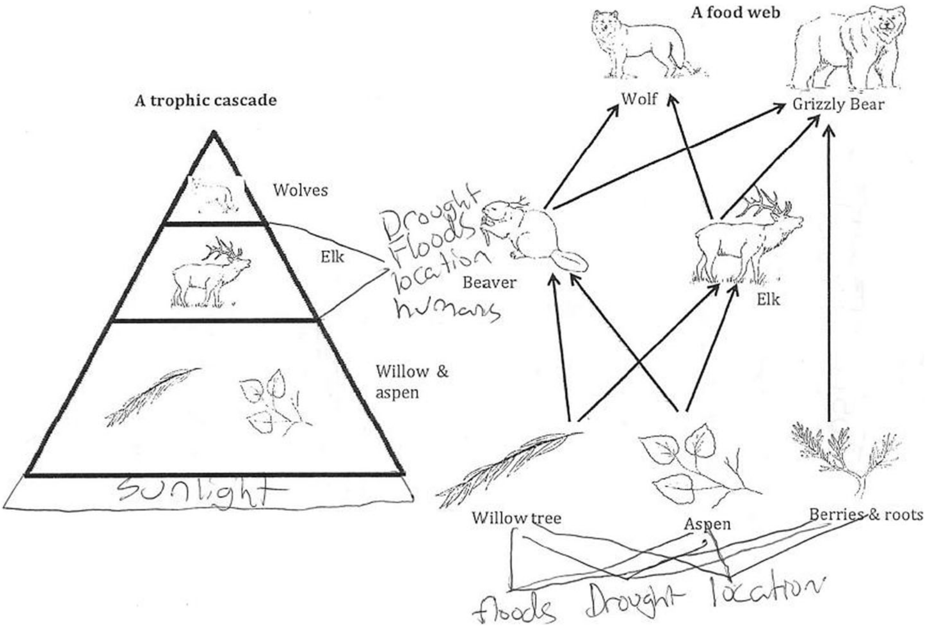

Fig. 3 Mark's post-instruction additions to the SEEDSII trophic cascade and food web diagrams

> The more wolves there are, the less elk and deer there will be. The less elk and deer, the less aspen and willow will be grazed on, resulting in a population increase of the aspen and willow. I added location because in some locations, there is more sun or water (what plants need to grow). I added climate because if the climate changes, it will affect the plants and the whole trophic cascade.—*Gwen, post-instruction (TCC score = 2)*

Here, Gwen began with a simple explanation of trophic cascade and, then, subtly indicated that multiple causal relationships may exist in a way that contributed to its tacit complexity. However, she also neglected to deeply explain how the causal mechanisms she provided would affect the trophic cascade as a whole.

The proportion of students' trophic cascade explanations that explicitly demonstrated complexity (TCC score = 3) increased from 2% before the place-based SSI instruction to 12% after that instruction. Explanations that demonstrated explicit complexity clearly indicated that various causal mechanism, relationships, and outcomes existed beyond those provided in the SEEDSII trophic cascade diagram, and how and why those elements affected the trophic cascade system. For example, Mary was one of those students that explicitly indicated multiple potential causal relationships and outcomes when responding to the SEEDSII trophic cascade and food web models (Fig. 2).

> The increase in the wolf population will have a great effect on the aspen and willow, because elk eat the aspen and willow, and the wolves eat the elk. This will lead to a decrease of elk. The decrease of elk due to the wolves will lead to less willow and aspen being eaten, thus creating an increase in aspen and willow populations. I added weather/climate because the climate can change, causing drought, which can kill off the aspen, which will then kill of the elk, and then kill of the wolves. Another thing I added was location. Location affects the populations because the location can have different climates, and different habitats that will either kill off or increase population depending on the situation. The last thing I added was sun, because the sun gives the plant the energy to grow, which, following the trophic cascade theory, leads to all the other animals/plants benefitting.—*Mary, post-instruction (TCC score = 3)*

Mary began by explaining a simple, linear trophic cascade. Then, Mary explicitly indicated the manner by which multiple causal mechanisms and relationships contributed to trophic cascade complexity by explaining the effects of climate change and drought on aspen populations and how these decreases can cause a bottom-up response. She, then, also suggested non-linear aspects of the trophic cascade by indicating differential effects that location can have on microclimates and population dynamics. Mark also provided an explicitly complex explanation about trophic cascades.

> There are many more factors than just wolves that affect the populations of aspen and willow. Beavers, flooding, and drought all affect the aspen and willow populations. Drought causes less aspen and willow meaning less for elk bringing down population of elk and wolves. Floods do the opposite of droughts. Location may be the place where lots of wolves eat elk or where there is lots of food for elk. Humans [also] hunt and change the environment.—*Mark, post-instruction (TCC score = 3)*

Mark's trophic cascade explanation exemplified explicit complexity through considering multiple causal relationships beyond the SEEDII diagrams, such as how drought and floods have differing impacts on vegetation, herbivores, and predators, which can affect trophic cascade outcomes (Fig. 3).

4.1.2 Causal Mechanisms

A significant and moderately large increase in the number of ecological causal mechanisms provided in students' trophic cascade explanations took place after the place-based SSI instruction ($Z = -3.07$, $p = 0.002$, $r = 0.40$). However, a Wilcoxon rank sum test indicated that the students' consideration of human causal mechanisms remained stable through the SSI instruction ($Z = -0.1$, $p = 0.99$, $r = 0.13$). Table 3 presents the range of human and ecological causal mechanisms provided by the students before and after the place-based SSI instruction.

Prior to completing the place-based SSI instruction, 76 and 50% of the students, respectively, neglected to include human and ecological causal mechanisms, beyond those provided by the SEEDSII diagrams, in their trophic cascade explanations (causal mechanism (CM) score = 0). After that instruction, 72 and 23% of students' explanations, respectively, neglected to include human and ecological causal mechanisms beyond those provided by the SEEDSII diagrams. For example, Jerry's response exemplifies many of the students' perceptions that the diagrams in the SEEDSII were already complete and did not require any additional causal mechanisms: "Nothing needs to be added.—*Jerry, pre-instruction (CM score = 0)"*

The proportion of students including one human or one ecological causal mechanism (*CM score = 1*), beyond those already in the SEEDSII diagrams, in their trophic cascade explanations prior to experiencing the place-based SSI instruction was, respectively, 15 and 31%. After that instruction, 23 and 43% of the students, respectively, included one human or one ecological causal mechanism to their trophic cascade explanations. For instance, Dan's response indicates that water availability also affects the trophic cascade by explaining that drought has a bottom up response on organism populations.

> If there is a drought, then that will kill plants, so that elk and beaver will have less to eat and die out, and wolves and bears will not have as much to eat if elk and beavers die.—*Dan, post-instruction (Ecological CM score = 1)*

Table 5 Frequencies of students' written NOS responses scored according to their accuracy and reference to relevant ecology research contexts and considerations

	NOS score	All students ($N = 60$)	Students separated by trophic cascade explanation complexity level			
			Level 0 ($n = 3$)	Level 1 ($n = 34$)	Level 2 ($n = 16$)	Level 3 ($n = 7$)
Methods of environmental science investigations	0	8.3	33.3	11.8	0	0
	1	36.7	33.3	50.0	18.7	14.3
	2	11.7	0	5.9	25.0	14.3
	3	6.7	33.3	5.9	6.3	0
	4	36.7	0	26.4	50.0	71.4
Nature of scientific theories, such as trophic cascade	0	20.0	66.7	26.5	6.3	0
	1	26.7	33.3	26.5	18.7	42.9
	2	3.3	0	2.9	6.3	0
	3	21.7	0	23.5	31.2	0
	4	28.3	0	20.6	37.5	57.1
Scientific observations and interpretations of nature	0	0	0	0	0	0
	1	38.3	66.7	50.0	18.7	14.3
	2	6.7	0	8.8	0	14.3
	3	25.0	33.3	23.5	31.3	14.3
	4	30.0	0	17.7	50.0	57.1
Role of science and technology for solving environmental issues	0	0	0	0	0	0
	1	51.7	100	55.9	50.0	14.3
	2	6.7	0	5.9	6.3	14.3
	3	15.0	0	17.6	18.7	0
	4	26.7	0	20.6	25.0	71.4
Cultural influences on environmental science and its use	0	21.7	33.3	32.4	6.3	0
	1	38.3	66.7	38.2	31.3	42.8
	2	0	0	0	0	0
	3	28.3	0	23.5	43.7	28.6
	4	11.7	0	5.9	18.7	28.6

Dan accurately added drought to the SEEDSII food web diagram and also justified this addition through explaining how droughts affect plants.

The proportion of students including two or more human or two or more ecological causal mechanisms (*CM score* = *2*) beyond those already in the SEEDSII diagrams through their trophic cascade explanations prior to experiencing the place-based SSI instruction was, respectively, 8 and 18%. After that instruction, 5 and 34% of the students, respectively, included two or more human or two or more ecological causal mechanisms to their trophic explanations. Claire's and Thomas' explanations include two or more human and/or ecological causal mechanisms beyond those provided by the SEEDSII trophic cascade diagram, and, for this, they received a score of 2.

> I added lots of abiotic (rain, fire, soil) things because they can affect how successful animals and plants are at surviving.—*Claire, post-SSI instruction (Ecological CM score = 2)*

Claire identified multiple abiotic causal mechanisms (e.g., rain, fire) through her response mentioned previously and by drawing on the SEEDSII trophic cascade diagram.

Table 6 Spearman's correlations demonstrating the association between the complexity of students' trophic cascade explanations and their NOS Likert and written responses after the place-based SSI instruction

Dimension	Trophic cascade explanation complexity level	*n*	NOS Likert response median	NOS written response median	Correlation test	*r*	*p*	Strength of association based on effect size (*r*)
Methodology of environmental science investigations	0	3	2.5	1.0	Likert	0.48	< 0.001	Moderately large
	1	34	3.0	1.0	Written	0.43	0.001	Moderately large
	2	16	3.6	3.5				
	3	7	3.8	4.0				
Nature of scientific theories such as trophic cascade	0	3	3.0	0	Likert	0.29	0.02	Moderate
	1	34	3.0	1.0	Written	0.37	0.004	Moderate
	2	16	3.3	3.0				
	3	7	3.8	4.0				
Scientific observation/interpretation of nature	0	3	3.0	1.0	Likert	0.30	0.02	Moderate
	1	34	3.4	1.5	Written	0.42	0.001	Moderately large
	2	16	3.5	3.5				
	3	7	4.0	4.0				
Role of science and technology for solving environmental issues	0	3	2.8	1.0	Likert	0.21	0.12	Insignificant/weak
	1	34	2.7	1.0	Written	0.31	0.02	Moderate
	2	16	2.7	1.5				
	3	7	3.3	4.0				
Cultural influences on environmental science and its use	0	3	3.0	1.0	Likert	− 0.10	0.47	Insignificant/weak
	1	34	2.6	1.0	Written	0.41	0.001	Moderately large
	2	16	3.0	3.0				
	3	7	2.0	3.0				

> Humans and weather extremes can be responsible for altering populations of plants and animals by hunting, accidents (wrecks, etc.) and drought over too much rain.—*Thomas, post-SSI instruction (Human CM score = 2)*

Thomas stated two ways in which humans can impact animal populations; hunting and vehicle accidents.

4.2 Students' Post-Instruction NOS Views and Their Correlation with the Complexity of Students' Trophic Cascade Explanations

The students' post-instruction written NOS responses demonstrated a wide range of accuracy and reference to relevant ecology research contexts and considerations (Tables 4 and 5). Across the five NOS dimensions, significant and moderate to moderately large correlations (r = 0.31 to 0.43, p = 0.02 to 0.001) existed between the accuracy and contextualization of students' written NOS responses and the complexity of their trophic cascade explanations (Table 6). Substantiating these findings, triangulating analyses demonstrated that significant and moderate to moderately large correlations (r = 0.29 to 0.48, p = 0.02 to < 0.001) existed between the accuracy of students' Likert responses across three of the NOS dimensions and the complexity of their trophic cascade explanations. In the subsequent texts, we, first, present a profile of students' post-instruction written NOS responses and the extent that they were accurate and provided references to relevant ecology research contexts and considerations. We, then, present quantitative findings demonstrating the association between the students' NOS views and the complexity of their trophic cascade explanations.

4.2.1 Students' Post-Place-Based SSI Instruction NOS Views

Table 5 presents the frequencies of students' written responses across the five NOS dimensions that were accurate and referred to relevant ecology research contexts and considerations (again, see Table 4 and the electronic supplementary materials for the coding scheme and additional examples). None of the students provided inaccurate responses regarding the nature of scientists' observations and interpretations and the role of science and technology for solving environmental issues. Between 8 and 22% of the students' responses regarding the methods used in environmental science investigations, the nature of scientific theories (e.g., trophic cascade) and the ways culture influences environmental science researches were inaccurate (*NOS score = 0*). For instance, Dave's and Sam's comments exemplify the naïve responses from this group of students:

> Theories are just theories, and not proven science. So, it can be changed and altered—*Dave, post-SSI instruction (NOS score = 0)*
> Culture should not limit how science is used in an area.—*Sam, post-SSI instruction (NOS score = 0)*

When responding about the nature of scientific theories, Dave inaccurately equated these bodies of knowledge to fleeting and unsubstantiated ideas and indicates the only valuable ideas in science are those that are "proven." Sam, however, wrongly responded that cultural factors should not influence the utilization of scientific knowledge.

Across the five NOS dimensions, between 27 and 52% of students' post-instruction written NOS responses demonstrated some merit but provided no references to relevant ecology research contexts and considerations (*NOS score = 1*). Broadly, these responses provided a clear combination of accurate and inaccurate NOS ideas or presented accurate yet conjectural NOS claims devoid of substantiating caveats and reasoning. For instance, Tony's somewhat merited response vacillated between accurate and inaccurate NOS notions and provided no contextual reference to the Yellowstone wolf reintroduction issue and trophic cascade research.

> I think that there is a method but scientists do not need to follow it every single time because they have come up with different results.—*Tony, post-SSI instruction (NOS score = 1)*

Despite recognizing that scientists are not required to consistently adhere to a set method, Tony conceded that it exists as an option for scientists to follow. Lisa's response was rated similarly to Tony's, but for providing an accurate, yet decontextualized, conjectural and unsubstantiated claim regarding the role that science and technology plays for environmental issues resolution:

> Science and technology cannot solve all of the environmental problems, because if people disagree with science and technology, then if they end up going with the science to fix it, then people would not be happy.—*Lisa, post-SSI instruction (NOS score = 1)*

Lisa rightly indicated that science and technology demonstrate limited capacity to resolve environmental issues. However, she, then, trivially substantiated this claim by simply stating that people may not be happy with purely scientific solutions.

None of the students' provided post-instruction responses about the cultural influences on environmental science that were accurate without reference to relevant ecology research contexts and considerations (*NOS score* = *2*). Between 3 and 12% of the students' responses to the other four NOS dimensions demonstrated accuracy without tangible contextualizing. For instance, Gwen provided such a response about the methods used to research environmental issues:

> Scientists can use all different kinds of methods. Such as observation methods, and sometimes they have to make a method up. They do not necessarily need a controlled experiment when they research environmental issues.—*Gwen, post-SSI instruction (NOS score = 2)*

Despite accurately clarifying that scientists develop and use diverse methods, Gwen's response lacked contextual reference to the relevant ecology research examples provided in the place-based SSI instruction, such as how wolf ecologists discussed their inventing creative ways to monitor wolf populations and behaviors.

Across the five NOS dimensions, 7 to 28% of students' post-instruction responses demonstrated some merit and provided references to relevant ecology research contexts and considerations (*NOS score* = *3*). Again, responses rated as "has merit" provided a clear combination of accurate and inaccurate NOS ideas or presented accurate yet conjectural NOS claims devoid of substantiating caveats and reasoning. Providing such a response, Aaron's sentiment drew on the place-based SSI instruction about how two competing research groups (Beschta and Ripple 2013; Kauffman et al. 2013) developed different interpretations of wolf driven trophic cascades and ecosystem impacts in Yellowstone.

> If an event occurs differently when seen by different scientists, they will likely interpret it differently. For instance, Beschta and Kauffman both have different beliefs, because they have seen different evidence.—*Aaron, post-SSI instruction (NOS score = 3)*

Aaron accurately noted that Beschta's research group and Kauffman's research group interpreted the extent that wolf-driven trophic cascades occurred differently in

Yellowstone—a topic addressed multiple times during the place-based SSI instruction. However, Aaron's response provided the caveat that scientists' observations and evidence had to be different in order for them to arrive at these different interpretations. In a response also having merit, Tim tacitly claimed how there are many scientific methods by referring to one of the wolf biologist's, Audrey's, varied methodological approaches she described to the students.

> So Audrey's methods had to make sure her results were right for the wolves and what happened to them, and which ones had a collar on them.—*Tim, post-SSI instruction (NOS score = 3)*

This comment reflects Audrey's presentation during the place-based SSI instruction where she discussed the need to be creative with combining several methods (e.g., radio telemetry, aerial surveys) when tracking and monitoring wolf populations.

From 12 to 37% of the students' post-instruction responses across the five NOS dimensions demonstrated accuracy and references to relevant ecology research contexts and considerations (*NOS score = 4*). When asked about the nature of scientific theories, Mary and Tasha provided accurate responses contextualized through reference to ecologists' interpretations and research about trophic cascades.

> Theories such as the trophic cascade are constantly being debated over. They are based on evidence, but that doesn't mean that it is a [proven] fact. It is a theory for a reason, and could still be changed. They are not likely to be completely replaced, though new ideas could arise. I also believe that evidence can be interpreted in many ways. This is shown specifically in the trophic cascade debate because the two sides of researchers have the same evidence, but have come up with different conclusions.—*Mary, post-SSI instruction (NOS score = 4)*

Here, Mary claimed that while trophic cascade theory is durable and evidence-based, it is subject to revision and reinterpretation by ecologists using the same evidence. Tasha's quote was also exemplary with accurately describing the nature of scientific interpretations and theories:

> Scientific theories are never truly proven because they are altered by new evidence and different interpretations of currently used evidence. There are several ways to interpret all events in nature and experiments. It mostly has to do with the fact that each person can have a different personal view of these things. For example, the trophic cascade has been altered and interpreted differently by a multitude of scientists. The trophic cascade was thought to only be top-bottom or bottom-top, but it actually can be from the middle out.—*Tasha post-SSI instruction (NOS score = 4)*

In Tasha's quote, she accurately indicated that the trophic cascade theory has been revised and may undergo further revision, because of scientists' interpretations of new and existing evidence. Notably, Tasha's sentiments reflect the place-based SSI instruction about how assumptions established through early trophic cascade research (e.g., Paine 1966) are being challenged by current research regarding wolves' impact on the Yellowstone ecosystem (e.g., Kauffman et al. 2013).

4.2.2 Correlation Between the Students' Post-Instruction NOS Views and the Complexity of Their Trophic Cascade Explanations

Again, students' post-instruction trophic cascade complexity scores significantly correlated, from a moderate to moderately large degree, with their written response scores for all five of the SEEDSII NOS dimensions (r = 0.31 to 0.43, p = 0.02 to 0.001). Substantiating these findings, students' trophic cascade complexity scores significantly correlated, from a moderate to moderately large degree, with their Likert response scores for the SEEDSII NOS dimensions of environmental science methods, tentativeness of theories, such as trophic cascade, and scientists' observations and interpretations ($r = 0.29$ to 0.48, $p = 0.02$ to < 0.001). Across these NOS dimensions, the students' median Likert and written NOS response scores increased when organized according to trophic cascade explanation complexity level (Table 6). The complexity of students' trophic cascade explanations was not significantly associated with their Likert responses about the role of science and technology for resolving environmental issues and the cultural influences on environmental science ($p > 0.05$).

4.3 Students' NOS Responses at Each Trophic Cascade Explanation Complexity Level

4.3.1 NOS Responses of Students Providing Naïve TC Explanations (TCC Score = 0)

Again, only three students provided naïve trophic cascade explanations (*TCC score* = *0*) after the place-based SSI instruction. Table 5 demonstrates that at best two of the students each provided one written NOS response that had merit with references to relevant ecology research contexts and considerations (*NOS score* = 3). One of these responses described the methods used to investigate environmental science issues; the other detailed how scientists' observations and interpretations may differ. Three, two, and one of students' responses about the role that science and technology play for resolving environmental issues, the methods used for environmental science investigations, and cultural influences on environmental science and its use, respectively, had merit but contained no references to relevant ecology research contexts and considerations (*NOS score* = *1*). The remaining NOS written responses were provided by students who also provided naïve trophic cascade explanations were inaccurate (*NOS score* = *0*).

4.3.2 NOS Responses of Students Providing Simplistic TC Explanations (TCC Score = 1)

The proportion of students demonstrating linear and simplistic trophic cascade explanations (*TCC score* = *1*) and inaccurate (*NOS score* = *0*) written NOS responses after the SSI instruction ranged from 0 to 32% across the five SEEDSII NOS dimensions (Table 5). The proportion of students providing simplistic trophic cascade explanations and somewhat merited (*NOS score* = *1*) and accurate (*NOS score* = *2*) written NOS responses with no references to relevant ecology research contexts and considerations, respectively, ranged from 27 to 56% and from 0 to 9%. Between 6 and 24% of the students providing simplistic trophic cascade explanations also provided written responses across the SEEDSII NOS dimensions that had merit and references to relevant ecology research contexts and considerations (*NOS score* = *3*). Finally, between 6 and 26% of students providing simplistic trophic cascade explanations also provided written responses across the SEEDS II NOS dimensions that were accurate and referred to relevant ecology research contexts and considerations (*NOS score* = *4*).

4.3.3 NOS Responses of Students Providing Tacitly Complex TC Explanations (TCC Score = 2)

Only two of the sixteen students demonstrating tacitly complex trophic cascade explanations (*TCC score* = *2*) each provided one naïve (*NOS score* = *0*) written NOS response after the SSI instruction about different SEEDSII NOS dimensions (Table 5). Of the students providing tacitly complex trophic cascade explanations, between 19 and 50% and between 0 and 25%, respectively, provided NOS written responses that were somewhat merited (*NOS score* = *1*) or accurate (*NOS score* = *2*) with no references to relevant ecology research contexts and considerations. The proportion of students demonstrating tacitly complex trophic cascade explanations and written NOS responses that had merit and references to relevant ecology research contexts and considerations (*NOS score* = *3*) ranged from 6 to 44% across the five SEEDSII NOS dimensions (Table 5). Finally, from 19 to 50% of the students provided tacitly complex trophic cascade explanations and also provided written responses across the SEEDS II NOS dimensions that were accurate and referenced relevant ecology research contexts and considerations (*NOS score* = *4*).

4.3.4 NOS Responses of Students Providing Explicitly Complex TC Explanations (TCC Score = 3)

None of the students demonstrating explicitly complex trophic explanations (*TCC score* = *3*) provided naïve (*NOS score* = *0*) written NOS responses after the place-based SSI instruction (Table 5). Of the students providing explicitly complex trophic cascade explanations, between 14 and 43% provided NOS written responses that were somewhat merited (*NOS score* = *1*), whereas between 0 and 14% provided NOS written responses that were accurate (*NOS score* = *2*) with no references to relevant ecology research contexts and considerations. Of the students providing explicitly complex trophic cascade explanations, between 0 and 29% provided written responses across the SEEDSII NOS dimensions that had merit (*NOS score* = *3*), whereas between 29 and 71% of students provided written responses across the SEEDSII NOS dimensions that were accurate (*NOS score* = *4*) and referred to relevant ecology research contexts and considerations.

4.4 Summary of Findings

Students' trophic cascade explanations became significantly more sophisticated through the place-based SSI instruction that focused on Yellowstone wolf reintroduction. Furthermore, our findings demonstrate that an association existed between the sophistication of students' post-instruction trophic cascade explanations and NOS views. In summary, our findings demonstrate the following:

1. Students' trophic cascade explanations became less linear and demonstrated more complex relationships and outcomes after the place-based SSI instruction. Upon entering the place-based SSI instruction, 90% of the 60 participating students' trophic cascade explanations were either inaccurate (22%) or simplistic and demonstrated linear reasoning (68%). The remaining students' pre-instruction trophic cascade explanations were either tacitly or explicitly complex. The proportion of students demonstrating naïve and simplistic (i.e., linear reasoning) trophic cascade explanations, respectively, decreased 17 and 11% from before to after the place-based SSI instruction. Also, the proportion of students providing tacitly and explicitly complex trophic cascade explanations increased 18 and 10%, respectively, through that instruction.
2. The students afforded significantly more consideration to ecological trophic cascade causal mechanisms after completing the place-based SSI instruction. Upon entering the

place-based SSI instruction, 50 and 76% of the students failed to consider ecological and human causal mechanisms, respectively, which may impact trophic cascades beyond the provided SEEDSII diagrams. After that instruction, 27% more students considered ecological causal mechanisms in their trophic cascade explanations beyond those provided by the SEEDSII diagrams. However, only 4% more of students' post place-based SSI instruction trophic cascade explanations considered additional human causal mechanisms.

3. Most (> 90%) of the students' written NOS responses after completing the place-based SSI instruction demonstrated at least partial accuracy. Furthermore, between 40 and 55% of the students' responses across the five NOS dimensions after that instruction presented contexts reflective of the Yellowstone wolf reintroduction issue and associated trophic cascade research.
4. Significant and moderate to moderately large correlations existed between the accuracy and contextualization of the students' written NOS responses and the complexity of their trophic cascade explanations. Correlations between the sophistication of students' trophic cascade explanations and NOS written response scores ranged from 0.31 to 0.43. These findings were largely substantiated through similar correlational values occurring between scores measuring the students' trophic cascade explanations and NOS Likert responses.

5 Discussion

Among the important goals of science education is to facilitate students' development of accurate science explanations as a way of understanding natural phenomena, including how and why those phenomena occur (Osborne and Patterson 2011; NGSS Lead States 2013). Congruent with this goal, the place-based SSI instruction used in this investigation appeared to help secondary students' trophic cascade explanations become more sophisticated and representative of the complex interactions that occur within ecosystems. That is, from before to after the SSI instruction students' explanations as a whole looked less like what Bechtel (2011) referred to as the "basic account of mechanistic explanation," where causal mechanisms are treated as a sequentially operating chain of causal factors with a clear start and finish. Rather, they could be better considered as depicting multiple and often non-sequential and non-evident causal relationships.

The goal of helping students develop more sophisticated trophic cascade explanations was accomplished through the novel approach of immersing students in Yellowstone, where the SSI instruction focused on the contention among the ecological research community regarding the extent that the top-down trophic cascade model sufficiently accounts for changes in the Yellowstone ecosystem that have occurred since wolf reintroduction in the mid-1990s. During these instructional experiences, the students observed aspects (e.g., growth of aspen and willow stands within wolves' home ranges) of the Yellowstone ecosystem with ecologists involved with the wolf reintroduction effort and subsequent research. As part of those experiences, the wolf ecologists and author delivers summarizings explained that many interacting apparent and unapparent (e.g., rainfall, climate change) factors, beyond what is represented in simple top-down trophic cascade models, must be accounted for when determining wolves' impact on the Yellowstone ecosystem. Furthermore, the place-based SSI instruction drew on actual peer-reviewed ecological research about the presence of a wolf mediated top-down trophic cascade in Yellowstone to address and contextualize several NOS themes. Such themes included the limits of scientific models and how scientists' disparate interpretations of data regarding the same natural phenomena can cause contention among the scientific community and rethinking of science ideas.

We also demonstrated that significant and moderate to moderately large correlations existed between the accuracy and contextualization of students' written NOS responses and the complexity of their trophic cascade explanations. Several scholars have postulated that helping students better understand NOS may facilitate their interest in and learning of science (McComas et al. 1998; Rudolph and Stewart 1998). This is particularly the case when NOS is contextually aligned with the science ideas that students are required to understand (Clough 2006; Herman 2015, 2018). We found a general trend in our investigation that students who were more adept after the SSI instruction at providing accurate NOS responses, contextualized through relevant ecological research references, also provided the most sophisticated trophic cascade explanations. Therefore, we feel that this investigation provides a much-needed step toward establishing the link between science content and NOS understanding (Lederman 2007).

6 Limitations and Future Research Directions

Despite the positive impacts of the place-based SSI instruction, we noted several limitations with this investigation and the ways that students' thinking about trophic cascades, ecosystem dynamics, and NOS remained deficient. First and most obvious, this investigation lacks replicability and generalizability of its findings. These shortcomings are due primarily to two characteristics of this investigation. First, the participants in this study were a somewhat small and relatively homogenous non-random sample and there was no comparison group of students. Second, as is the case with many informal and place-based learning environments, the educational context used as an intervention for this investigation is quite unique and relatively inaccessible to many researchers, educators, and students. While these issues limit the generalizability of this investigation, they do provide opportunities to pose future questions for the field. For instance: How would students who learned similar ecological concepts in formal classroom settings compare to the group investigated here? To what extent would the formal classroom learners' science content explanations associate with their NOS views? How would a larger and more diverse group of students' science explanations and NOS expressions vary? Would they vary when learning similar ecology and NOS concepts, but under different place-based SSI contexts (e.g., learning about climate impacts on trophic levels in the Great Barrier Reef)? Given that the majority of peoples' learning occurs outside of formal school settings, researchers should explore questions such as these to determine how place-based and informal learning that occurs beyond the walls of compulsory settings impacts life-long science engagement and decision-making (Falk et al. 2007; Herman et al. 2013).

Another concern regarding this investigation could be that the SEEDSII provides trophic cascade and food web models that are typical of those presented in science textbooks and classrooms. On one hand, these models provide a means by which students can develop and express more sophisticated and situated science explanations and NOS understandings. On the other hand, prompting with those models probably shaped the students' responses. This issue deserves more attention given that scientific models powerfully encourage people to develop and hold long-withstanding ontological and epistemological views (Cheng and Lin 2015; Gericke et al. 2013; Grosslight et al. 1991). In the case of the biological sciences, the way students understand knowledge usually reflects a naïve realist position—even more so than the ways they understand other scientific fields (Krell et al. 2015). Furthermore, students often think about biological ideas and physics ideas similarly—that science ideas must provide high degrees of predictability and seemingly unambiguous linear causal explanations for natural phenomena (Mayr 1982, 1997; Rudolph and Stewart 1998). Perhaps, these reasons help explain why students' initial explanations were largely simplistic and representative of the linear trophic cascade models typically found in classrooms and textbooks, and their post-instruction explanations retained some of these linear causal characteristics. In hindsight, we feel that this investigation missed an opportunity to assess students' views about the nature of models across the science disciplines and how previous experiences impact those views and students' science explanations. Future scholarship could compare students' science explanations and epistemological views about models in the presence and absence of the scientific models they so often experience in their science classrooms.

Lastly, while this investigation demonstrated an association between students' NOS views and science explanations, we strongly discourage readers from interpreting that there is a causal or directional relationship between the two (e.g., that more accurate NOS views lead to better science content understanding). This interpretation would be spurious and too simplistic. Several factors could play a role in the relationship between NOS and science content understanding as part of a broader scientific literacy (Herman 2015, 2018; Hodson 2009). For instance: Is the relationship more dynamic and reciprocal, where developing deeper NOS understanding helps students develop more complex science explanations, and constructing more complex science explanations helps students recognize more accurate epistemological views (e.g., reflecting that developing science ideas is an iterative and dynamic process)? Furthermore, is it the accuracy of or the ability to contextualize NOS views (or both) that is more associated with developing sophisticated science explanations? We think that the ability to contextualize NOS takes a leading role in this relationship, but we cannot be certain from the findings of this investigation. Further complicating matters, the possibility exists that the sophistication of NOS views and science explanations is impacted by broader cultural, developmental, and epistemological characteristics among the students. These are certainly issues worth investigating.

7 Pedagogical Implications

Several pedagogical implications and recommendations can be proposed in light of this investigation's findings. Broadly, this investigation demonstrates that place-based SSI instructional approaches can help students develop more sophisticated explanations of natural phenomena. We attribute this to the deliberate scaffolding approach, through which they experienced the Yellowstone ecosystem firsthand with more knowledgeable others (e.g., wolf ecologists) who possessed deep understandings and had even conducted research on ecology topics such as the wolves' reintroduction and impact on trophic systems. Scaffolding experiences deliberately implemented for the students by more knowledgeable others included guided observations in the areas where wolves, elk, willow, and aspen coexist and are investigated, and, then, discussions and readings about how scientists develop competing accounts regarding the extent that wolves exert a top-down trophic cascade in the Yellowstone. In a sense, this SSI learning environment reflects those described as rich and authentic where students are connected with a community of practice—where they obtain the insights about the conceptual and physical tools involved in scientists' accounting for natural phenomena (Herman 2018; Sadler 2009).

Despite the rich SSI educational context and overt instructional emphasis on human impacts on wolf populations (i.e., extirpation and reintroduction), most students neglected to include humans in their post-instruction trophic cascade explanations. We are not entirely surprised by this finding given the significant literature that discusses humans' tendency to perceive themselves as detached from nature or that natural places are those devoid of human interference (Lamb 1996; Vining et al. 2008). The pervasiveness of these perspectives has been linked to humans' increasingly frequent experiences in built and artificial environments instead of natural ones, which stresses the need for students to be provided with more immersive educative experiences in nature (Goralnik et al. 2012).

In our literature review, we struggled to find examples where students developed science explanations and contextualized NOS views while immersed in real-world place-based SSI experiences. One could argue that this is because these kinds of experiences are only accessible through unique and special venues (e.g., field trips) outside of schools—such as the one profiled in this investigation. Therefore, formal classroom teachers may feel constrained from implementing place-based SSI instruction that promotes students' developing sophisticated science explanations and NOS views.

However, issues that are endemic to a students' community can often be used to deliver place-based SSI instruction that meets these important pedagogical goals. As described earlier in our literature review, Wong et al. (2008) drew on the SARS outbreak that students were experiencing in their local community to help them learn about the NOS and the authentic work of epidemiologists. Zangori et al. (2017) co-designed with a secondary teacher an SSI-based curriculum focused on climate change through student investigations of climate impacts on a local prairie. Dolan et al. (2009) (also, see Zeidler and Kahn 2014) described SSI activities focused on local contexts (e.g., community speed laws, erosion and weathering on a local Florida beach) where 5th-grade students can learn science concepts. Lastly, several of the teachers profiled in Herman et al. (2013a) effectively taught science concepts and NOS through diverse contexts, including those that integrated their students' everyday experiences. The point to be taken here is that SSI are ubiquitous as are the opportunities to use them by well-prepared teachers to help students learn science explanations and NOS through readily-accessible local place-based contexts. Many, including Herman (2018), Herman et al. (2013a,b), Olson et al. (2001), and Zeidler and Kahn (2014), provide practical insights that should be considered when preparing teachers to be able to create and capitalize on these kinds of opportunities.

A primary outcome of this investigation was substantiating the claim that science content knowledge (as expressed through explanations) was at least moderately correlated with students' NOS views. While more work needs to be done to explicate this relationship, our findings lend support to the concerns expressed by others regarding the extent that NOS receives scant attention in comparison to science content in terms of curricular standards and teacher practice. Herman et al. (2013b) determined that a substantial association exists between the quality of science teachers' general reform-based practices and their NOS implementation. Considering this, science teacher educators must extensively model how to connect and scaffold science concepts and NOS across a bevy of contexts, including those focused on inquiry, historical scenarios, and

SSI (Allchin et al. 2014; Clough 2006; Kampourakis 2016). This type of scaffolding occurred extensively throughout the place-based SSI instruction in our study and appeared to have a substantial impact on the students' science explanations and NOS views (see, also, Herman 2018).

Teaching NOS and content are equally important and complementary instructional goals (Clough 2006; Kampourakis 2016; Lederman and Lederman 2014; McComas and Nouri 2016). Furthermore, compelling arguments strongly assert that deeply understanding important and foundational science ideas (e.g., pendulum motion, evolution) requires comprehending relevant NOS aspects (Clough 2011; Matthews 1994; Rudolph and Stewart 1998). If this is the case, the unwavering expectation among science educators should be that NOS and content are consistently, firmly, and obviously linked in reforms documents and standards as those guide teacher practices. However, Olson (2018) has demonstrated that across the standards analyzed from nine diverse international communities, only one country consistently presents NOS as a focused student learning expectation. Therefore, Olson pointed out that teachers in the majority of the international communities are unlikely to receive conceptual and pedagogical support for effective classroom NOS implementation. Focusing solely on the Next Generation Science Standards (NGSS Lead States 2013), McComas and Nouri (2016) demonstrated that NOS is afforded an inconsistent and marginal focus across the K–12 grade levels in comparison to science content, cross cutting themes, and science and engineering practices. Furthermore, McComas and Nouri (2016) made evident that NOS is not linked with NGSS science content recommendations, which can result in teachers' eschewal of NOS implementation. They (pp. 560 and 572) summarized these bothersome issues by stating:

> It is unfortunate that the Framework failed to provide a single robust treatment of NOS such that it could have served as a more useful reference to educators who might look to that document for guidance … We concur [with Lederman and Lederman 2014] that the NOS recommendations in NGSS fail to have the prominence of the other three main NGSS elements and are therefore highly concerned that NOS may continue to be ignored or minimized by science teachers.

As our investigation and others' previously described work has demonstrated, NOS views and explanations about science ideas are linked and appear complementary. Moreover, students' understanding of science explanations and NOS has been connected to more profound goals for science education such as socioscientific engagement and decision-making (Herman 2015, 2018; Hodson 2009; Khishfe 2012; Sadler and Fowler 2006). Therefore, constructing science explanations alongside and in connection with NOS should not only be a practically important teaching goal and forefront current standards as it helps students understand and appreciate science. This instructional activity should also be viewed as a moral educational imperative in the interest of helping students to become better citizens and democratic decision-makers. Achieving such lofty goals would require a unified and concerted effort among science educators, particularly NOS scholars.

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

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