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Transformative learning in graduate global change education drives conceptual shift in invasive species co-management and collaboration

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ABSTRACT

Many graduate training programs in global change recognize the importance of policy and appreciate the complex, multi-stakeholder nature of policymaking in practice. However, few engage directly with diverse stakeholders, an important goal in transformational education, through traditional curricula. We present the results following analysis of a course designed to provide graduate students with an immersion-based experience focused on the flow of information between science, advocacy, policymaking, and management as they relate to invasive species, an important driver of global change threatening many facets of the human condition. In this course students constructed a conceptual model of these interactions. Then, in an immersive experience, they directly engaged with a diverse group of stakeholders, including government agency officials, policymakers, and land managers. Finally, to drive transformational learning, students were challenged to refine the conceptual model and develop a revised framework that more accurately reflected the true co-production (transdisciplinary) nature of these interactions. Thematic analysis of student perceptions revealed a shift from a science-centric view to one where science was but one of many inputs responsible for shaping invasive species policy. This immersive approach, founded in face-to-face interactions among diverse stakeholders, represented a transformative shift in student thinking toward the importance of co-management and collaboration in addressing invasive species.

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Introduction

Graduate training drives human capital development through knowledge creation and innovation, which ultimately contributes to social, economic, and cultural prosperity (Stewart 2010, Mitra, Abubakar, and Sagagi 2011). As such, graduate education in sustainability science has

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the potential to facilitate the broad institutional change needed to meet the challenges posed by complex intractable problems associated with environmental change. This requires a shift away from traditional linear models of knowledge transfer and towards transformational and transdisciplinary approaches designed to engage diverse stakeholders in the co-production of knowledge for the public good (O'Brien et al. 2013; Scholz 2020). This shift toward transformational learning provides the open framework for systemic change in self, institution, society, and ultimately, sustainable practices (Papenfuss et al. 2019; Sharpe et al. 2016). Many such training programs are already forming out of broad inter- and transdisciplinary research collaboratives (Borrego and Newswander 2010; Keck et al. 2017; Killion et al. 2018).

These collaboratives are generally organized around a central sustainability issue, such as global change. These groups depend on the free exchange and co-production of knowledge among stakeholders, yet the extent to which information flows is often a reflection of the disciplinary breadth of the collaborative (MacLeod 2018; Urbanska, Huet, and Guimond 2019). Differences in information flow (e.g. asymmetry or interruption) can create disconnects among stakeholders within these transdisciplinary groups, impeding progress, or worse, suppressing important outcomes (Fazey et al. 2014). This is particularly important for global change related issues such as invasive species that may be characterized as 'wicked' in nature (McNeely 2013). Managing biological invasions has been defined as a wicked problem (McNeely 2013, Seastedt 2015) as the tension in social priorities (e.g. individual right to own exotic pets vs. environmental damage from released pets) results in a complex problem with no obvious solutions (Woodford et al. 2016). The net result is a challenging landscape of diverse perspectives among stakeholders that must collaborate to work toward sustainable actions.

In such situations, information exchange among stakeholders can lead to policy outcomes that are discordant with isolated disciplinary goals and understanding. For example, in a recent analysis of regulated noxious weeds, Lakoba et al. (2020) found that species listings among US states were not always congruent with biological distribution. This suggests that the regulatory landscape for noxious weeds is most often defined by disjointed communications and divergent interests across diverse stakeholder groups, highlighting the importance of information exchange and collaboration. In fact, Borrego and Newswander (2010) found that the majority of successful National Science Foundation (NSF 2016) Integrative Graduate Research and Traineeship (IGERT) proposals focused on integration and critical awareness of information flows. Yet, despite this central role of more interactive information transfer and engagement, like other sustainability programs heavily influenced by the natural sciences, invasive species education often defaults to transactional modalities, wherein the exchange of information is largely linear (Fischer et al. 2014; Barney et al. 2019). This leaves students with a narrow understanding of how, when, and where their work can deliver measurable impacts on these challenging sustainability issues. In order to expand students' grasp of the opportunities, we must move beyond modifying or adapting existing approaches and instead develop educational opportunities that provide first-hand exposure to the uncertain and inherently complex nature of intractable problems and provide roadmaps for building agency, which will ultimately lead to the systemic change needed to confront global challenges (Sharpe et al. 2016).

The past decade has seen the development of many complementary democratic approaches to environmental education. These have tended to center on shifting educational paradigms to reflect the complex and uncertain topography of environmental challenges (O'Brien et al. 2013). Transformative learning as a pedagogical tool and a mechanism for affecting change across diverse systems has been well described, and work toward achieving these educational goals well established (Taylor 2007; Fazey et al. 2014; O'Brien et al. 2013; Walsh et al. 2015; Sharpe et al. 2016). For instance, O'Brien et al. (2013) suggest that traditional content delivery approaches are being replaced with learning systems that are self-focused, student-driven investigations that integrate the diverse systems needed to confront environmental challenges, therein creating an open co-production of knowledge. By exposing learners to the full range of decision-making

processes, and potential intractability associated with environmental challenges, the learning environment becomes conducive to reflection, affording the self-transformation needed to see the challenges in a new way and perhaps address them differently—emancipatory learning (Wals et al. 2008; Leggett, Wen, and Chatman 2018). Of course, an inherent risk is that a lack of balance along the multi-dimensional axes of decision-making can lead to the challenge being viewed as recalcitrant in any single axis, leading to reinforcement of collective assumptions (Sharpe et al. 2016). An important way to address this issue is through the use of experiential learning (O'Brien et al. 2013; Fazey et al. 2014), where engaging alternative viewpoints forces reflection and challenges assumptions. Shifting the institutional view is a critical piece of graduate training as the new insights that arise from questioning established precepts will be needed to confront expanding global challenges.

Experiential learning forms the bulwark of training for many graduate programs in global change. For example, models that incorporate service learning (Levkoe, Brail, and Daniere 2014), and community-based learning models (Walsh et al. 2015) have led to important transformational shifts for students. Yet, the number of models for driving systemic change in educational paradigms is limited at the graduate level. In particular, there is an emerging need for course design models that push beyond traditional disciplinary boundaries and aim to provoke Bloom's higher order thinking (Keser and Karahoca 2010; Wagner, Baum, and Newbill 2014; McGregor 2017) that can be implemented across educational levels. Such models must introduce students to the complexities of decision-making processes as inherent because they are not merely technical in nature, but also social and thus contested (Innes and Booher 2010, Lundholm and Stöhr 2014, Stöhr et al. 2014). The goal of our work was to design a graduate-level transdisciplinary experiential learning module around the global change topic of invasive species. We developed and tested an experiential learning module, centered around the question of, "How is scientific information used in invasive species policy and management?" This course was intended to stimulate transformative learning among an interdisciplinary group of graduate students. Elevating the importance of global thinking among students was our primary outcome, evaluated by theme analysis of student writing before and after the immersion experience.

Methods

Course motivation and design

The course presented here (Table 1) employs a problem-based learning approach that also integrates techniques supporting knowledge exchange, modeling the transdisciplinary approach (Reed et al. 2014; Sharpe et al. 2016). Specifically, this course incorporates Reed et al. (2014) five principles of knowledge exchange practices: design, represent, engage, generate impact, and reflect and sustain. Our design focused on the problem of information flow among stakeholders

Table 1. Course structure and assignments. Each course meeting was 2h except for the immersion trip which was 8–9h for each of 3 days, and the final session which took place during the 3h exam period.

Meeting	Agenda	Homework
1	Discussion of the trip, begin drafting questions	Independently draft a series of questions
2	Submit questions for peer evaluation	Organize questions by agency
3	Discuss questions, develop concept map	Revise questions based on concept map
4	Trip planning, discussion of expectations, establish timeline	Develop summary of expectations, identify rooming partners
5	Meet with agency and advocacy groups	Summarize notes and prepare for
6	Meet with policymakers	Submit reflective paragraphs
7	Open discussion, refine concept map based on immersion experience	

who work with invasive species. However, in the spirit of transformational learning, students defined the boundaries of the problem space by identifying the important questions ([Supplementary Material](#)). For representation, we spent time collectively identifying the critical players in the problem space at large, and specifically for our planned immersion trip. Engagement was accomplished through establishing and building connections with stakeholders across disparate groups. Generate impact was attained through direct engagement with stakeholders and viewing decision-making processes. Reflection was generated with the creation of reflective essays that provoked students to summarize how their views of information-exchange shifted. Lastly, sustaining this new view of information flow was achieved through having students develop a revised network model of stakeholder interactions in the invasive species arena.

Student enrollment

Due to anticipated cost and budget constraints, we limited course enrollment to ten. Students interested in participating in the course were asked to write a brief paragraph indicating their interest in the course and how they thought the course would help them achieve their educational goals. This brief paragraph served two purposes, first, it provided a primary step in the commitment to the course and secondly, it afforded the instructors an opportunity to identify a group of students that reflected the disciplinary diversity of students interested in the global change issue of invasive species. Of the students enrolled in the course the primary disciplinary areas were basic invasion biology (5), applied invasion management science (3), and public policy (1). Nine out of the initial ten students (1 basic invasion biology student dropped due to time constraints) enrolled completed the course.

Course coordination

The co-instructional model is important for courses aimed at transdisciplinary engagement. Four faculty members were involved in the planning, development, and coordination of this course. Instructor disciplinary expertise reflected that of the students, with two faculty in basic invasion biology and one in each of management and policy. The co-instructional model was particularly important for this course to both model transdisciplinary interactions and ensure the breadth of the immersive experience. Additionally, all instructors, as faculty affiliates with the Global Change Center at [institution removed for peer review], had some degree of experience with transdisciplinarity in practice. This experience ranged from interdisciplinary research in invasive species, to full expertise in developing and coordinating transdisciplinary efforts (policy faculty member). Developing and implementing this course required substantial faculty time, with the four instructors and one of the students meeting weekly for one hour to plan and coordinate course activities and trip plans. Four of these meetings included teleconferences with the contracted organizing group (Woods Institute: woodsinstitute.com) to identify contacts and define a schedule of activities ([Supplemental Material](#)). Coordination of timing and locations for these activities was handled by this organizing group, affording the instructors an opportunity to focus on supporting student-led engagement.

Building the transformative experience via conceptual models

The use of models to drive conceptual understanding, and thereby learning, have a well-documented foundation at all educational levels (Konicek-Moran and Keeley 2015). Indeed, diagrammatic conceptual learning is a hallmark of many post-graduate professional training programs in the medical and human health sciences, as well as a few graduate training programs (Fink 2003; Coil et al. 2010). For instance, in the global change related fields of ecology

and climate science, statistical models form a nucleus for building an understanding of factors that interact to affect changes in ecological or climatological outcomes. This diagrammatic or conceptual model approach formed the centerpiece for our learning objectives which sought to:

1. Identify the key areas in which science, advocacy, and policy overlap and influence the management of invasive species;
2. Describe the basic principles governing the formation of new regulation regarding invasive species;
3. Learn how to engage points of contact with appropriate government agencies and/or advocacy groups for the dissemination of scientific information.

To meet these objectives, students were initially led through the development of a verbal conceptual model that was centered on addressing essential questions (e.g. “Who?”, “What?”, “How?”, and “Why?”). In practice, the group met for seven two-hour sessions over the course of the semester and then participated in a three-day field trip immersion experience engaging key players in the policy-management-advocacy arena, resulting in about 40 student contact hours, comparable to other US institution one credit courses. The course revolved around active discussions of the science, policy, and management of invasive species. Concept mapping was developed through students devising a set of questions (“What?”, “Why?”) for policymakers, managers, and advocacy groups (“Who?”). To facilitate cross-fostering of conceptual understanding, students were asked to peer-evaluate question sets and refine the questions to a single set that could be addressed in formal meetings. In the week leading up to the immersion experience, students were challenged to develop a conceptual model (“How?”) of the interactions between science, management, and policy regarding invasive species including the interactions among the chief actors/stakeholders.

The importance of designing a meaningful and representative immersion experience reflective of the full breadth of stakeholders and perspectives, especially in an off-campus setting, cannot be overstated. We were fortunate to leverage personal and professional connections in addition to having the resources to contract with a third party (Woods Institute) that specializes in supporting courses in U.S. government operations, who made all logistical arrangements based

Table 2. Structured student meetings representing different focus areas and key stakeholders during our three-day visit to Washington DC. Each focus area represents a separate meeting.

Focus	Stakeholders met (at least one representative from each group)
Federal and State Policy Management	<ol style="list-style-type: none"> 1. USDA Forest Service 2. USDA Animal Plant Health Inspection Service 3. Bureau of Land Management 4. US Geological Survey 5. National Park Service 6. US Customs and Border Protection 7. Department of Defense 8. Pest Management Board 9. Maryland Department of Natural Resources
Environmental Advocacy Groups	<ol style="list-style-type: none"> 10. American Bird Conservancy 11. Reduce Risks from Invasive Species Coalition 12. Weed Science Society of America 13. National Wildlife Federation
Industry Organizations	<ol style="list-style-type: none"> 14. AmericanHort 15. National Wood Pallet and Container Assoc. 16. Pet Industry Joint Advisory Council
Legislators and Staffers*	<ol style="list-style-type: none"> 17. Rob Whitman, Representative for Virginia’s 1st District 18. Congressional Staffers serving members Sheldon Whitehouse (RI) and Tom Carper (DE). 19. A Legislative Fellow for the Invasive Species Caucus with Congressman Mike Thompson (CA).

*Stakeholders did not meet with students as a panel but came in separately to meet with the group. RI=Rhode Island, DE=Delaware, and CA=California.

on our collective suggestions and interests. Structured meetings were established with stakeholders who fell into three broad groups: federal agency personnel, advocacy groups, and policymakers (Table 2), all of whom were provided with an overview of our goals and schedule, but not the student questions.

The initial session with government agency representatives was larger than the rest of our sessions and, due to its size, multi-directional discourse was limited. The rest of the meetings were limited to 3–5 stakeholder participants, allowing for a more interactive and, consequently, more informative discussion among all parties present. In general, the participants in each focus area were eager to engage with students. In each session, every participant began by presenting some background to the issue of invasive species from the perspective of the group they represent, what their perceptions of the surrounding issues were, and how they were involved in the political process. The questions prepared by the students were used as a starting point, but discussions also allowed for unscripted or unanticipated questions to become part of the conversation. Students and instructors took notes in each meeting and debriefed at the end of each day.

Following the immersion experience, students and faculty developed individual reflective paragraphs (Supplemental Material) on the experience overall, and in the final class meeting collectively rebuilt the concept map using their newly gained insights. Reflective writing or journaling has been a staple of experiential learning across a wide array of disciplines (Bean 2011; Bruno and Dell'Aversana 2018). Reflective thinking allows students to reinforce the principles of the active engagement process and drives home conceptual understanding (Schön 1987; Mann 2016). This can be particularly useful in global change education wherein students are often engaging information from diverse sources and disciplines. For example, students in this course interacted with professionals with training in a range of fields, from agency officials with PhDs in physical and biological sciences to legislative staffers with backgrounds in political science and law.

Assessment of learning outcomes

Course enrollment and structure limited analyses to qualitative assessments of learning outcomes. These included comparing the conceptual model before and after the trip, word clustering from the pool of developed questions and finally a theme analysis of the student essays. The theme analysis was constructed as a grounded analysis. Essays were read by two independent raters (one naive to the course goals) and overlapping themes were identified without regard to the intended learning outcomes.

Results

Our primary learning objectives represented the course goal of a deeper understanding of how information flows among multi-stakeholder groups dealing with complex problems and where exchange gaps lead to discordance between science and policy. It is important to recognize that these objectives are broad and somewhat vague compared to a typical course with concrete outcome measures. This was intentional, as it allowed students to bring their own diverse skill sets and prior knowledge to the course and therein structure deeper understanding through their own lens. Nonetheless, student takeaways largely reflected learning vis-a-vis each of these objectives.

Identifying key areas of overlap

Our first learning objective was for students to identify how the primary areas of overlap in science, advocacy, and policy influence the management of invasive species. Students were

asked to develop a series of questions targeted at each of these primary areas. Going into the discussions with stakeholder groups, student questions largely reflected the concept of science as the central connecting point across stakeholders. For instance, the terms ‘science’ or ‘scientist’ is consistent across the questions directed at the three stakeholder groups (Table 3). Importantly however, the context shifts by stakeholder group. Questions directed to the members of the agency/management stakeholder group generally focused on the generation and use of scientific information, while questions for the policy group focused on gathering scientific information. In contrast, questions prepared for the advocacy group tended to focus on agenda setting and information gathering (e.g. identifying stakeholders and building networks). Thus, the initial pre-immersion framework, developed from student concept mapping, placed science at the center of the information flow between policy, management, and advocacy (Figure 1A). This was, in part, unsurprising as most graduate preparation in global change places science at the center of discussion. The final conceptual framework following the immersion experience (Figure 1B) included a much more developed and representative view, wherein science was but one of the inputs shaping invasive species policy.

Table 3. Representative student questions for each stakeholder group as they pertained to the learning objectives (the complete set of questions are available in the supplemental material).

Learning objective	Stakeholder	Example student questions	
Science, advocacy, and policy overlap	Management	How do you balance scientific knowledge and socioeconomic aspects for the best practices of invasive species management? As a scientist, do you most prioritize scientific facts and knowledge among others when making management decisions? Is there any ongoing place for scientists to deliver and discuss scientific discoveries (new scientific information) with decision makers?	
	Policy	Do you ever work with scientists outside the government/your organization? If so, what role do they play? How do you integrate scientific knowledge that scientists communicate to you into policy-making processes?	
	Advocacy	How do you define who the stakeholders are and how do you involve the community for planning management actions? What are your priorities for new legislation or regulations (in terms of lobbying or organizational priorities)?	
	Basic principles governing the formation of new regulation	Management	Do [sic] your organization have any experiences of collaboratively working with NGOs to delegate monitoring activities? How much do you interact with people outside of your organization, agency, etc. to achieve objectives?
		Policy	What is the timeline for a new policy, like how does it start and do you start it from scratch or amend the current policies? How to balance scientific knowledge and socioeconomic aspects for the best practices of invasive species management? Do you most prioritize scientific facts and knowledge among others when making management decisions?
		Advocacy	What are your priorities for new legislation or regulations (in terms of lobbying or organizational priorities)? What can scientists do better to help our research influence policy decisions?
Dissemination of scientific information	Management	How do you and other members of your agency/organization approach communication with the news media? What are some protocols and/or experiences that have shaped this approach? Do[sic] your organization have any experiences of collaboratively working with NGOs to delegate monitoring activities? (mostly for agencies)	
	Policy	How to [sic] define boundaries of stakeholders/community involvement for proceeding management actions? How much do you work with people across agencies?	
	Advocacy	What role does your organization play in linking stakeholders and general public to policies? How do NGOs communicate new information they obtain and to what degree does that information affect policy and management?	

Describing the basic principles governing the formation of new regulation

Pre-immersion student perspectives tended to support a somewhat linear process with various inputs, regarding the formation of new regulations are revealed in the prepared questions (Table 3). This is evidenced by a narrow focus on policy formation to the policy stakeholder group, while questions for the other stakeholder groups centered around inputs to this process. For example, questions for the agency/management group focused on external collaborations to meet objectives and, subsequently, feedback on policy. In contrast, the revised framework following the immersion experience (Figure 1B) more accurately reflects the interactions among groups and processes through which policy is formed, at least according to the officials and other stakeholders the group met with. One student commented,

“The second theme is conflict resolution and being able to find middle ground on issues. This was more explicitly stated with policymakers, but this was also hinted at when we met with the agencies and advocacy groups. The final theme that was touched on was that invasive species management tends to be a bipartisan issue.”

This comment reflects the dynamic nature of information exchange that ultimately leads to political support for policy and or regulations. For example, there is a clear expectation that policymakers work to seek middle ground, but the thought that agency or advocacy groups do as well, seems to be a new insight. In addition, a few essays reflect a larger tension between issues, funding, and resolutions.

“I thought the real value of the trip for me came from learning about the process, the more specific roadblocks (beyond just funding), and the ideas each individual stakeholder had for solving the issues (the [advocacy groups] CDC-esque model, the places the federal folks though the process could be streamlined, etc.)”

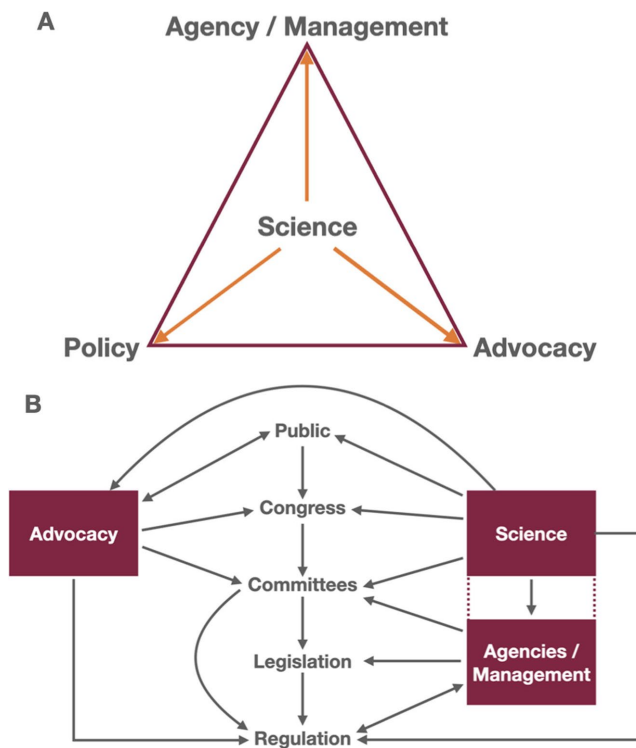


Figure 1. Conceptual framework generated by students (A) at course initiation and (B) after an immersive experience engaging managers and policymakers.

Or,

"I found a number of common themes that came up in many of the groups: (1) The most obvious theme that came up is that everyone agreed that the issue of invasive species needs to take more of a priority than it currently is; (2) there is general a lack of funding for invasive species; (3) there seems to be a general lack of consensus among the groups on how to deal with invasive species. Should they prioritize prevention and early detection, or management?"

The first quote acknowledges the challenge associated with resolving independent ideas to address the invasive species challenge. The second quote modifies this idea to include asymmetries in funding. Intriguingly, while the terms 'compromise' and 'communication' are frequent in the reflective essays, they are not seen in the pre-immersion question set (Table 3). Similarly, the network diagram of information flow (Figure 1B) represents a matured understanding of transdisciplinary exchange wherein inputs are more equitably shared among stakeholders. Our thematic analysis extended these insights to include an expanded appreciation for the flow of information.

Student essays highlighted how existing relationships among members of these transdisciplinary groups often dictate how and what information is transferred. For example, the recognition that advocacy groups and policymakers do find common ground from having worked together on other environmental issues.

"I was impressed how connected the scientists at the NGOs were to everyone in the government. It seemed like most of the people we talked to knew each other, and that there was a lot of productive discussion happening on the issue. On a personal note, I think my interactions with these groups, especially the meetings with the NGOs, taught me that there's lots of space for advocacy in science while still doing research."

And,

"It was helpful to hear from advocacy groups and policymaking groups about how sometimes information is picked up based on existing relationships rather than scientific information itself."

Or,

"I now have a clearer understanding on how much bureaucracy, politics, and knowing the "right" person has on pushing invasive species funding, awareness, and decision making."

These comments reflect both a deeper understanding of the flow of information among groups and the lens through which participants viewed the information exchange. This aspect was very important for class discussions as it generated a microcosm of the broad multi-stakeholder interests. Thus, discussions were engaging and supported the formation of a common lexicon for information exchange.

This insight also facilitated more global solution-level thinking. Some essays recognized the operational impact of this flow of information:

"Additionally, invasive species appear to receive very little (if any) attention by the major environmental advocacy groups which are instead focusing on climate change and endangered/threatened species. Due to this, policymakers mentioned only [advocacy groups], specific scientists, or research papers as their resources of scientific information. Because of this bottleneck in the information flow, it is unlikely that thorough, updated, and broad information regarding invasive species is being compiled and provided to policy makers."

Or,

"Once momentum builds locally and across districts, the likelihood of it reaching into the higher echelons of the political realm seems only effective if it's lobbied by NGO's."

This broader recognition provided an important point of engagement for class discussions, wherein identifying and framing the disconnects among stakeholders, also provided solution-centered insights on where to target information delivery.

Engaging and disseminating scientific information

Information flow is represented by both entry points and barriers. Yet, as with how new regulations are generated, student prepared questions tended to focus on linear processes for the dissemination of information. Here, student developed questions rarely mentioned 'scientists,' but often mentioned stakeholder group communication through engagement of other stakeholder groups, interaction with media outlets, and the general public (Table 3). In stark contrast, a consistent theme from the reflective essays was, the indirect routes through which scientific information enters these discussions. An example of this was the role of advocacy groups in both developing and supplying relevant scientific information to the agency and policymakers, which was entirely missing from discussions early in the course (Table 3).

"Before visiting Washington and looking into advocacy groups I had little knowledge on the extent that advocacy groups helped to keep the agency groups informed as well as informing policymakers."

Or,

"The non-profit organizations seem to rely more on the scientific literature than scientists hired by the non-profit; though, I know the larger non-profits have funds to do their own research."

The role of advocacy groups was also noted in the indirect transmission of information to policymakers.

"I was surprised by the power and use of the lawsuits in policy making. The collaboration of scientists with the advocacy groups, who have experience about the lawsuits can really bring the change in the policy."

And the need for informational documents that present a targeted message (e.g. interpretation of impact) along with the scientific information.

"Though the path our research takes to get to policymakers is not direct (or even guaranteed at all), we did receive a few recommendations: focus on economic costs (stressing human health and safety) and mitigation to help inform policy focus and strategies."

Or,

"As scientists, we are uncomfortable with quantifying risk assessment and future predictions; however, that seems to be what is wanted/needed to gain public awareness/concern"

Finally, a great deal of discussion after the trip was on building capacity among scientists, recognizing how to find common ground and succinctly deliver scientific information.

"After attending the trip I realize[sic] that the research we are doing can have impacts on policy. However, we are disconnected from policymakers and we need to work on making a connection with them. I think that our disconnect with policymakers and other organizations is due to a lack of scientists having soft skills."

Students often remarked that advocacy groups and policymakers finding compromise is at odds with training in the sciences, where research results are viewed as non-negotiable.

"However, I now see with greater clarity that basic invasion science is a product of a particular confluence of interests which led to federal funding which is dwarfed by the interests leading to the funding of other priorities. This suggests that the way forward is not entrenchment in the bio-centric positions of the current science, but rather persistent positive engagement with economic and social disciplines which can help us understand what invasion is, what it means, and what should be done about it."

These comments reflect both a deeper understanding of the flow of information among groups and the lens through which participants viewed the information exchange. This aspect was very important for class discussions as it generated a microcosm of the broad multi-stakeholder

interests. Thus, discussions were engaging and supported the formation of a common lexicon for information exchange.

Support without action

A surprising outcome that emerged from our theme analysis was the realization that information was not the sole (or sometimes even the important) driver of action. For instance,

“And though we heard consistently from all individuals that there was a growing bipartisan awareness and interest in managing invasive species, it appeared that no significant policy change was likely to occur in the near future.”

or,

“One of the major themes of the discussions that struck me the most was that bipartisan desire doesn't necessarily lead to action.”

The role of funding was a common focal point among all stakeholders with the net result being inaction on policy, regulation, or management strategies.

“There were a few common threads between the various governmental entities, NGO's, and politicians we met with in that invasive species are in the backyards of all stakeholders on both sides of the isle (local and non-partisan issues) nationwide, there is no consolidated direct source for funding directed towards our fight against invasive species (funding compartmentalization), and the use of species specific strategies rather than an overarching strategic framework to implement fast acting management strategies to prevent the establishment and impact of a novel pest.”

And,

“...this and to the persistent lack of funds, agency heads and legislators...emphasized the needs for creative solutions and improved efficiency, such as more citizen science, coalition building, public outreach, and interdisciplinary staffing.”

As well as funding for mandated management.

“My views on government involvement with invasive species have changed after interacting with each of these groups. Starting with the agency, this seemed to be the most relatable group because I felt like I knew most of what they were talking about and how they functioned. However, I found that is [*sic*] was astonishing how little money actually goes to invasive species compared to other programs in the USDA.”

This emergent awareness reflected both an increased appreciation for the interconnectedness of so-called wicked problems as well as a transformation from the internal or self-focus to external or global thinking. For example, in combining funding issues with information flow, students were moving away from science based thinking toward collaborative, coalition based approaches.

Discussion

It is apparent that the process of using science to inform policy is a lot “messier” than the students (and faculty) anticipated. The lack of linear relationships makes the planning and participation on informing policy much more complicated. Understanding how the process works, in this case at the federal level, is the first step in considering how to effectively inform non-scientist policymakers into taking appropriate actions that lead to addressing the issues surrounding, in our case, invasive species. The interconnections among people from different backgrounds and with different roles required to engage and inform critical participants in the policymaking process is essential, yet not well known to the average observer. A better

understanding of how this process operates was an important learning outcome for all involved in this class. This recognition of messiness in science policy is rooted in the philosophical basis for identifying wicked problems (Schickore 2020). Another important outcome of this course was advancing transformational learning—or moving from an internal focus to broader ‘global thinking’. The extent to which these objectives were met was assessed by comparing student perceptions of engagement before and after an immersion experience and evaluating student reflections after the immersion experience.

Developing co-management perspectives for future practitioners

Student perceptions of information flow in invasive species issues shifted from a direct input, science-centric view to one that reflected scientific input as, more often, an indirect input that was balanced by other concerns such as funding of management strategies, impacts on industry, and political will. For instance, in the conceptual map of information flow students moved science from the primary connection to a secondary input with fewer direct connections to policymakers. Intriguingly, our thematic analysis revealed a heightened awareness among students that advocacy groups are often the indirect source of “agenda driven” scientific information. This shift in awareness was also evidenced by the fact that student questions for advocacy groups were devoid of any mention of scientific information transfer. This awareness reflects an increase in shared understanding among the students (O’Brien et al. 2013; Fazey et al. 2014; Reed et al. 2014; Sharpe et al. 2016). This is a critical step in dialogue towards co-management. For example, Lundholm and Stöhr (2014) demonstrated that, even though complete shared understanding may be unattainable due to complexity, it is an important step toward identifying common ground for sustainable co-management of environmental problems.

Students learned that *advocacy* and *engagement* are at the core of policymaking, rather than peripheral and to be avoided by scientists. While engagement with decision-makers and other stakeholders had its own impacts, more immediate and tangible impacts came from asking assembled stakeholders specific pre-planned questions that students designed to address a particular issue in the problem space. Here the importance of relationships among stakeholders became apparent. This was reinforced in the analysis of student written reflective essays, where there was some angst about these connections, but also an awareness of paths toward resolution. For example, students expressed some frustration with couching invasive species issues in the framework of litigation around other environmental issues, but also recognized this approach is sometimes a path forward, when consensus-building is not possible. This is an example of how important it is to understand these relationships to help identify the behavior of a collaborative system (Gray 2008). Such recognition emphasizes the multi-stakeholder nature of the problems we face and emphasizes collaborative governance and approaches like joint fact-finding to promote shared learning and collective decision-making (Innes and Booher 2010; STEP Program n.d.). In interdisciplinary global change and sustainable agricultural education programs the importance of relationships is noted both in addressing the problem and among the student cohort (Walsh et al., 2015, Murakami, Hendrickson, and Siegel 2017).

Developing transformational learning in environmental education

A substantial transformation in our graduate education to develop the next generation of transdisciplinary scientists is critical, yet the number of examples of this instructional modality, while growing, remains limited. Many of the nascent suite of approaches are holistic and focus on promoting higher-order thinking, expanding beyond self towards more global views (De La Sierra Servin et al., 2017). The described course was designed to promote transformative learning through an immersive transdisciplinary experience. Immersion is an effective approach for

shaping transformative learning while incorporating other pedagogical concepts (White and Nitkin 2014). This was evidenced by the changes in student perceptions of information flow and broader understanding of multi-stakeholder interactions as described above. However, another important benchmark in our assessment came from shifts in student thinking toward broad collaborative discussions of the problems, in class and in their reflective essays. For instance, many students developed questions for stakeholders focused on how the stakeholders used information, yet the reflective essays demonstrated an understanding of the co-production of knowledge through existing relationships. In another example, students noted the problem of multi-stakeholder support for addressing invasive species issues, only to have no funding for moving forward, but rather than a dead-end, multiple students focused on broad coalition-based solutions to address this impasse. These types of shifts toward global thinking are a critical component of transdisciplinary approaches to solving complex problems (O'Brien et al. 2013, Fazey et al. 2014, Sharpe et al. 2016). Shifting educational paradigms often starts with grass-roots efforts with institutional support (O'Brien et al. 2013). Importantly, for this course, support came in the form of ongoing curricular revision for the Interfaces of Global Change graduate education program and financial support for the implementation of experiential learning. The faculty and students involved in this course were mostly members of the Global Change Center (GCC), which is housed under the Fralin Life Sciences Institute at Virginia Tech. Further, the course described herein arose from the efforts of a broader transdisciplinary group focused on invasive species (Invasive Species Working Group; IWSG) as a complex socio-ecological problem [Author(s) b]. This course expanded on an existing model from a capstone experience offered through the GCC to provide an alternative transformational instructional model. This existing structure provided several important resources, including the framework for visiting the National Capital Region with a group of students, essential contacts with the Woods Institute for coordinating the trip, and essential administrative support for financial management (budgeting, payment, reimbursement, etc.). Yet, the established capstone experience in the GCC was limited to only providing students with the immersion experience and not the extended dialogue covering multiple class sessions. Virginia Tech's presence in Northern Virginia also supported this effort, not least with available affordable lodging accommodations.

Another important barrier that can be overcome with institutional support is the burden that developing transformational courses and curricula places on faculty. Part of this obstacle is due to challenges for faculty to depart from familiar disciplinary boundaries and formats. This is an important barrier as it requires a significant time investment from faculty outside their baseline teaching, research, extension, and service duties. For example, developing and implementing this one credit hour (one student contact hour per week in a 16week semester) course required a conservatively estimated six faculty hours per week. Thus, the distributed teaching model was not only necessary for transdisciplinary interactions, but was also essential for reducing the burden on any individual faculty member. The support for this model came from both the GCC and instructors' individual academic units.

Similarly, it can also be difficult to envision successful outcomes for students when the course material strays from disciplinary expertise. Here, again, the strength of the existing collaborative of the Invasive Species Working Group was leveraged to cross the wide disciplinary gaps covered by this course. In practice, this relied on the co-production of course content via open faculty-faculty and faculty-student discussion. For example, course learning objectives were initially defined through faculty-assessed gaps in knowledge (discussion based) and then consistently refined to meet goals identified by students as the course progressed. For example, a 'how to engage' theme emerged from student devised questions and the third learning objective was modified to incorporate this theme. This intentional step provided open student-led course discussion and also served to model the exploration of information exchange toward a common goal (Sharpe et al. 2016). On a positive note, faculty and students become more comfortable over time as they learn how to operate in a transdisciplinary manner and accept the messiness this can entail; one faculty

member involved in this course is now, for example, director of a new transdisciplinary educational initiative at Virginia Tech on *Science, Technology, and Engineering in Policy* (STEP).

While many programs and universities are willing and able to help support faculty in educational transformation, the rather high costs of an immersive experience described in this case study can be a limitation. Financial support for this program came from funds that supported the ISWG. While beneficial for initial implementation, this financial model for course support is not sustainable as the execution of this course was very expensive (ca. \$15,000 USD), on top of faculty time. In addition, in the described format, this course is not broadly accessible, limiting participation. Yet, there are paths forward despite these limitations. With changing financial models across many universities, the implementation of course fees could be one solution forward. Unfortunately, with course fees the burden of cost gets shifted to students; however, students in our course indicated a comfort level if this fee was in line with other fees they pay. Other solutions could include external sponsorship, either in full, or in part to balance fees, or virtual/hybrid modalities that are cost-effective ways to improve access. For example, the two largest costs associated with the described implementation were the contracting organization (ca. 80%) and lodging (ca. 15%). These costs could be offset by hosting the experience on campus and inviting panelists to join the discussion virtually or in person as able. Further, this event could be paired with a larger campus-level event where invited panelists could serve a larger audience. These solutions could help scale across a larger student group as well. At our institution, large interdisciplinary graduate classes have an enrollment of around 25 students, which these solutions would fit well. Scaling to larger groups of graduate and undergraduate students, it may be more feasible to defray costs by bringing representatives of the groups to campus. How these changes would impact student learning and the transformational shifts we describe from this implementation would need to be investigated.

Limitations and future directions

As with most courses, there were some unanticipated limitations and benefits that emerged over the course of the semester. The biggest adjustment was in our schedule of events as we had to adjust the timing of our immersive experience. To minimize impact on academic schedules the trip was planned for spring break and students were notified before registering for the course. However, an unforeseen government shutdown (2018–19) extended well into the semester, hampering our ability to coordinate with critical stakeholders, making the planning for our original timeline impossible. Initially, this seemed to be a significant limitation to planned activities following the trip, however it turned out to be a net gain as the preparation ahead of time amplified the power of the immersive experience. Ultimately, the benefits from this unplanned change were sufficient to change the plan for future iterations of the course.

As mentioned, funding was another limitation and will certainly be a limitation in the future. The cost of contracting with a group that specializes in implementing courses in governmental operations was a significant point of discussion during course planning. However, there were benefits from leveraging the experience and connections of this organization that only became apparent as we progressed through the immersive trip. Perhaps most importantly, having the Woods Institute handling scheduling and coordination of stakeholder groups, the instructors were able to focus on course content and supporting student engagement. In addition, trip logistics were eased tremendously by having everything (security, guest passes, etc.) prearranged. In future offerings of this course, we look forward to evaluating alternative models of implementation to evaluate the impacts of different modalities of instruction (e.g. virtual, hybrid), with the hope of a successful implementation that uses fewer resources.

Another unanticipated benefit from the course was the ability to directly connect students with potential sources of employment. While we fully expected students to make professional contacts that would result in lasting connections we did not anticipate direct recruiting. For

example, during several of our panel discussions, panelists openly discussed current and planned positions and encouraged students to contact them if interested. We hope to formally incorporate this type of networking into the learning goals of the course as it is an important part of relationship building in these multi-stakeholder interactions.

The off-campus trip created informal opportunities for relationship-building and conversation among the group, including both students and faculty. The value of these relationships should not be underestimated, especially given the interdisciplinary composition of the group and subsequent opportunities to turn those new relationships into productive research partnerships. The faculty team continues to collaborate extensively, and several student-led collaborations have resulted in various types of products, such as an state-level invasive species listing, a podcast, a publication, and continued interaction through the working group. It will be important to drive these sorts of connections in future iterations of the course including, and especially, in versions that might include virtual interactions.

Conclusions

Tackling the complex socio-environmental issues caused by global change will require the development of professionals with the skills to engage in transdisciplinary teams. For sustainability graduate education this means a shift from traditional transmissive interdisciplinary approaches to experiential opportunities that expose both the complexity and uncertainty of the problem, thus elevating the importance of information exchange over knowledge transfer (Sharpe et al. 2016). This transformational shift is already underway (Walsh et al. 2015), with the development of academic structures focused on addressing sustainability like the GCC that support transdisciplinary teams such as our ISWG. Formal courses are naturally evolving from these programs (Levkoe, Brail, and Danieri 2014; Walsh et al. 2015). Yet, with the rapid acceleration of global sustainability issues, there is a tremendous need for the development of courses and programs that can rapidly revise traditional curricula. In the case study presented here, we were able to support a transformational shift in student (and instructor) understanding of the complex interplay that leads to action on invasive species.

It is important to recognize that even though this course built on an existing framework, the development and implementation took considerable faculty time. Further, without the multidisciplinary expertise of the faculty involved, this course would have taken a different tone as well as substantially more time to develop. While this level of faculty time may be difficult to justify for any given graduate program, the shared model allowed for a distributed burden, one in which faculty were able to juggle additional teaching responsibilities. Another important consideration for developing a course such as the one presented here is engaging a third party for help in connecting with relevant stakeholders and coordinating a schedule of events. We were fortunate to have institutional support for team teaching and financing the immersive trip. Though the source of much deliberation, in the end we felt that the time gained on course content and the experience of the Woods Institute added significant value to the course. Informal student perceptions after the trip indicated that they found the experience valuable enough to pay for out of pocket, up to roughly 1/5th of the actual cost. Thus, while instructors and students found great value in third-party coordination, all firmly agreed that future course offerings could work toward creative replacements.

Evaluating different approaches to develop transdisciplinary skills will be essential in solving sustainability issues. Developing frameworks for courses that can lower the activation energy for implementation will be important. In the present case study, we have presented a framework for implementing an experiential learning course for graduate students in various global change related programs. This case study provides important insights on the limitations and benefits of an immersive experience in the 'wicked problem' of invasive species. Importantly, the concepts used in this course can be scaled across other global change topics and the course design can

hopefully serve as a framework to lower the time and financial costs required for the development of additional courses across sustainability education curricula.

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Disclosure statement

The authors have no conflicts of interest to disclose.

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References

- Barney, J. N., T. Schenk, D. C. Haak, S. Salom, B. Brown, and E. R. Hotchkiss. 2019. "Building Partnerships and Bridging Science and Policy to Address the Biological Invasions Crisis." *Invasive Plant Science and Management* 12 (1): 74–78. doi:10.1017/inp.2018.33.
- Bean, J. C. 2011. *Engaging Ideas: The Professor's Guide to Integrating Writing, Critical Thinking, and Active Learning in the Classroom*. Hoboken: John Wiley & Sons.
- Borrego, M., and L. K. Newswander. 2010. "Definitions of Interdisciplinary Research: Toward Graduate-Level Interdisciplinary Learning Outcomes." *The Review of Higher Education* 34 (1): 61–84.
- Bruno, A., and G. Dell'Aversana. 2018. "Reflective Practicum in Higher Education: The Influence of the Learning Environment on the Quality of Learning." *Assessment & Evaluation in Higher Education* 43 (3): 345–358. doi:10.1080/02602938.2017.1344823.
- Coil, David., Mary Pat. Wenderoth, Matthew. Cunningham, and Clarissa. Dirks. 2010. "Teaching the Process of Science: Faculty Perceptions and an Effective Methodology." *CBE—Life Sciences Education* 9 (4): 524–535. doi:10.1187/cbe.10-01-0005.[Mismatch][Mismatch]

- De La Sienna Servin, E. E., T. Smith, and C. Mitchell. 2017. "Worldviews, a Mental Construct Hiding the Potential of Human Behaviour: A New Learning Framework to Guide Education for Sustainable Development." *The Journal of Sustainability Education* 13: 1–21.
- Fazey, I., L. Bunse, J. Msika, M. Pinke, K. Preedy, A. C. Evely, E. Lambert, E. Hastings, S. Morris, and M. S. Reed. 2014. "Evaluating Knowledge Exchange in Interdisciplinary and Multi-Stakeholder Research." *Global Environmental Change* 25: 204–220. doi:10.1016/j.gloenvcha.2013.12.012.
- Fink, L. Dee. 2003. *Creating Significant Learning Experiences: An Integrated Approach to Developing College Courses*. San Francisco, CA: Jossey-Bass.
- Fischer, A., S. Selge, R. Van Der Wal, and B. M. Larson. 2014. "The Public and Professionals Reason Similarly about the Management of Non-Native Invasive Species: A Quantitative Investigation of the Relationship between Beliefs and Attitudes." *PLoS One* 9 (8): e105495. doi:10.1371/journal.pone.0105495.
- Gray, B. 2008. "Enhancing Transdisciplinary Research through Collaborative Leadership." *American Journal of Preventive Medicine* 35 (2 Suppl): S124–S132. doi:10.1016/j.amepre.2008.03.037.
- Innes, J. E., and D. E. Booher. 2010. *Planning with Complexity: An Introduction to Collaborative Rationality for Public Policy*. Routledge, London: Routledge.
- Keck, A. S., S. Sloane, J. M. Liechty, M. S. Paceley, S. M. Donovan, K. K. Bost, B. A. McBride, and B. H. Fiese. 2017. "Longitudinal Perspectives of Faculty and Students on Benefits and Barriers to Transdisciplinary Graduate Education: Program Assessment and Institutional Recommendations." *Palgrave Communications* 3 (1): 1–10. doi:10.1057/s41599-017-0027-y.[Mismatch][Mismatch]
- Keser, H., and D. Karahoca. 2010. "Designing a Project Management e-Course by Using Project Based Learning." *Procedia - Social and Behavioral Sciences* 2 (2): 5744–5754. doi:10.1016/j.sbspro.2010.03.938.
- Killion, Alexander K., Kelley Sterle, Emily N. Bondank, Jillian R. Drabik, Abhinandan. Bera, Sara. Alian, Kristen A. Goodrich, et al. 2018. "Preparing the Next Generation of Sustainability Scientists." *Ecology and Society* 23 (4): 39. doi:10.5751/ES-10395-230439.
- Konicek-Moran, Richard, and Page. Keeley. 2015. *Teaching for Conceptual Understanding in Science*, 248. Arlington, VA: NSTA Press.
- Lakoba, V. T., R. K. Brooks, D. C. Haak, and J. N. Barney. 2020. "An Analysis of US State Regulated Weed Lists: A Discordance between Biology and Policy." *BioScience* 70 (9): 804–813. doi:10.1093/biosci/biaa081.
- Leggett, J. M., J. Wen, and A. Chatman. 2018. "Emancipatory Learning, Open Educational Resources, Open Education, and Digital Critical Participatory Action Research." *Scholarship of Teaching and Learning, Innovative Pedagogy* 1 (1): 4.
- Levkoe, C. Z., S. Brail, and A. Daniere. 2014. "Engaged Pedagogy and Transformative Learning in Graduate Education: A Service-Learning Case Study." *Canadian Journal of Higher Education* 44 (3): 68–85. doi:10.47678/cjhe.v44i3.186039.
- Lundholm, C., and C. Stöhr. 2014. "Stakeholder Dialogues and Shared Understanding: The Case of Co-Managing Fisheries in Sweden." *Sustainability* 6 (7): 4525–4536. doi:10.3390/su6074525.
- MacLeod, M. 2018. "What Makes Interdisciplinarity Difficult? Some Consequences of Domain Specificity in Interdisciplinary Practice." *Synthese* 195 (2): 697–720. doi:10.1007/s11229-016-1236-4.
- Mann, K. V. 2016. "Reflection's role in learning: increasing engagement and deepening participation." *Perspectives on Medical Education* 5 (5): 259–261. doi:10.1007/s40037-016-0296-y.
- McGregor, S. L. 2017. "Transdisciplinary Pedagogy in Higher Education: Transdisciplinary Learning, Learning Cycles and Habits of Minds." In *Transdisciplinary Higher Education*, 3–16. Cham: Springer.
- McNeely, J. A. 2013. "Global Efforts to Address the Wicked Problem of Invasive Alien Species." In *Plant Invasions in Protected Areas*, 61–71. Dordrecht: Springer.
- Mitra, J., Y. A. Abubakar, and M. Sagagi. 2011. "Knowledge Creation and Human Capital for Development: The Role of Graduate Entrepreneurship." *Education + Training* 53 (5): 462–479. doi:10.1108/00400911111147758.
- Murakami, C. D., M. K. Hendrickson, and M. A. Siegel. 2017. "Sociocultural Tensions and Wicked Problems in Sustainable Agriculture Education." *Agriculture and Human Values* 34 (3): 591–606. doi:10.1007/s10460-016-9752-x.
- NSF. 2016. <https://www.nsf.gov/od/oia/convergence/index.jsp>
- O'Brien, Karen., Jonathan. Reams, Anne. Caspari, Andrew. Dugmore, Maryam. Faghihmani, Ioan. Fazey, Heide. Hackmann, et al. 2013. "You Say You Want a Revolution? Transforming Education and Capacity Building in Response to Global Change." *Environmental Science & Policy* 28: 48–59. doi:10.1016/j.envsci.2012.11.011.
- Papenfuss, J., E. Merritt, D. Manuel-Navarrete, S. Cloutier, and B. Eckard. 2019. "Interacting Pedagogies: A Review and Framework for Sustainability Education." *Journal of Sustainability Education* 20: 19.
- Reed, M. S., L. C. Stringer, I. Fazey, A. C. Evely, and J. H. Kruijssen. 2014. "Five Principles for the Practice of Knowledge Exchange in Environmental Management." *Journal of Environmental Management* 146: 337–345. doi:10.1016/j.jenvman.2014.07.021.
- Schickore, J. 2020. "Mess in Science and Wicked Problems." *Perspectives on Science* 28 (4): 482–504. doi:10.1162/posc_a_00348.
- Scholz, R. W. 2020. "Transdisciplinarity: Science for and with Society in Light of the University's Roles and Functions." *Sustainability Science* 15 (4): 1033–1049. doi:10.1007/s11625-020-00794-x.
- Schön, D. A. 1987. *Educating the Reflective Practitioner: Toward a New Design for Teaching and Learning in the Professions*. Hoboken: Jossey-Bass.

- Seastedt, T. R. 2015. "Biological Control of Invasive Plant Species: A Reassessment for the Anthropocene." *The New Phytologist* 205 (2): 490–502. doi:10.1111/nph.13065.
- Sharpe, B., A. Hodgson, G. Leicester, A. Lyon, and I. Fazey. 2016. "Three Horizons: A Pathways Practice for Transformation." *Ecology and Society* 21 (2): 47. doi:10.5751/ES-08388-210247.
- STEP Program. n.d. <https://step.vt.edu>
- Stewart, D. W. 2010. "Important, If True": Graduate Education Will Drive America's Future Prosperity." *Change: The Magazine of Higher Learning* 42 (1): 36–44. doi:10.1080/00091380903449110.
- Stöhr, C., C. Lundholm, B. Crona, and I. Chabay. 2014. "Stakeholder Participation and Sustainable Fisheries: An Integrative Framework for Assessing Adaptive Comanagement Processes." *Ecology and Society* 19 (3): 14. doi:10.5751/ES-06638-190314.
- Taylor, E. W. 2007. "An Update of Transformative Learning Theory: A Critical Review of the Empirical Research (1999–2005)." *International Journal of Lifelong Education* 26 (2): 173–191. doi:10.1080/02601370701219475.
- Urbanska, K., S. Huet, and S. Guimond. 2019. "Does Increased Interdisciplinary Contact among Hard and Social Scientists Help or Hinder Interdisciplinary Research?" *PloS One* 14 (9): e0221907. doi:10.1371/journal.pone.0221907.
- Wagner, T., L. Baum, and P. Newbill. 2014. "From Rhetoric to Real World: Fostering Higher Order Thinking through Transdisciplinary Collaboration." *Innovations in Education and Teaching International* 51 (6): 664–673. doi:10.1080/14703297.2013.796726.
- Wals, A. E., F. Geerling-Eijff, F. Hubeek, S. van der Kroon, and J. Vader. 2008. "All Mixed up? Instrumental and Emancipatory Learning toward a More Sustainable World: Considerations for EE Policymakers." *Applied Environmental Education & Communication* 7 (3): 55–65. doi:10.1080/15330150802473027.
- Walsh, T. C., O. L. Miller, B. Bowen, Z. A. Levine, and J. R. Ehleringer. 2015. "Sphere of Sustainability: Lessons from the University of Utah's Global Changes and Society Course." *Journal of Water Resources Planning and Management* 141 (12): A5015001. doi:10.1061/(ASCE)WR.1943-5452.0000514.[Mismatch[Mismatch
- White, S. K., and M. R. Nitkin. 2014. "Creating a Transformational Learning Experience: Immersing Students in an Intensive Interdisciplinary Learning Environment." *International Journal for the Scholarship of Teaching and Learning* 8 (2): n2. doi:10.20429/ijstol.2014.080203.[Mismatch[Mismatch
- Woodford, Darragh J., David M. Richardson, Hugh J. MacIsaac, Nicholas E. Mandrak, Brian W. van Wilgen, John R. U. Wilson, and Olaf L. F. Weyl. 2016. "Confronting the Wicked Problem of Managing Biological Invasions." *NeoBiota* 31: 63–86. doi:10.3897/neobiota.31.10038.