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CASE REPORT

Transforming sustainability science for practice: a social–ecological systems framework for training sustainability professionals

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Abstract

New applied approaches are needed to address urgent, global environmental issues. Practitioners, scholars, and policy makers alike call for increased integration of natural and social sciences to develop new frameworks for better addressing the range of contemporary environmental issues. From a theoretical perspective, social–ecological systems (SES) offers a novel approach for enhancing sustainability science and for improving the practice of environmental management. To translate SES theory into action, education and training programs are needed that focus on the application of SES approaches across the education and professional spectrum, from K-12 to graduate training to agency management. We developed a training framework that serves sustainability practitioners by building their capacity to apply SES approaches to real world problems and decision-making. The framework uses a SES-based environmental management approach based on a systemic worldview, transdisciplinary thinking, co-development of knowledge, stakeholder engagement, and adaptive governance. The social–ecological systems training and education program (SESTEP or "see-step") framework was designed to provide SES training opportunities as a response to the need expressed by senior directors of US federal land management agencies. The core of the framework is a 12-step SES heuristic that provides a diagnostic tool for practitioners as they work through a SES case-study issue or problem. The curriculum provides adaptable and tailored professional development training for sustainability professionals to enhance sustainability science in practice. The evaluation of the inaugural course indicates achievement of positive course learning outcomes consistent with advancing sustainability science in practice.

Keywords Educational programs · Environmental management · Natural resources · Sustainability · Professional development · Social–ecological systems

Introduction

Practitioners in sustainability science must balance the protection of natural resources and ecosystems (ecological systems) with the needs for and uses of them by people (social systems) and this requires making decisions under uncertainty, flexible management, collaborative interactions, and understanding interdisciplinary concepts (Rogers et al. 2013; Virapongse et al. 2016; Pereira et al. 2018; Davis et al. 2019; Alessa and Kliskey 2020). The skills, habits of mind, and perspectives necessary for monitoring social–ecological systems, integrating disciplines, and developing collaborative relationships for sustainability science are essential in graduate education or through job-training (Blickley et al. 2012; Wei et al. 2015; Magliocca et al. 2018). Social–ecological systems (SES) offers an approach for understanding the complex social and ecological interactions that affect and shape environmental use and management (Van Assche et al. 2019). A major shift is needed to integrate SES thinking into current sustainability and natural resource planning and practice, requiring new frameworks and approaches (Ban et al. 2013; Pahl-Wostl 2009; Hunt et al. 2018). The complex and uncertain nature of issues in SES necessitates

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sustainability professionals with "new skills and capabilities, informal and flexible management structures, and access to expert knowledge as well as local lay knowledge" (Pahl-Wostl et al. 2007, p. 2). Sustainability professionals, therefore, need support if they are to develop skills to manage sustainability problems and issues as a SES (Virapongse et al. 2016; Baird et al. 2019). Much has been written about SES management in the past decade (e.g., Resilience Alliance 2010; Rogers et al. 2013; Trimble and Plummer 2019), but there are few examples of comprehensive SES training for sustainability managers and pre-professionals that have been implemented and assessed (Plummer 2013; Puettmann et al. 2016).

Life-long-learning by sustainability professionals is essential; not only learning new skills and ways of understanding the systems they manage, but also updating their understanding of social and ecological changes in the places they manage (Dietz et al. 2003; Virapongse et al. 2016; Davis et al. 2019; Trimble and Plummer 2019). Training for sustainability professionals should include consideration of the educational needs of professionals. Research on SES learning by professionals is diverse and has encompassed many different scales, contexts and interpretations of learning. Additionally, some learning outcomes are explicit or expressed, while in other research they are not (Suškevičs et al. 2018; Diduck et al. 2019; Ernst 2019).

The goal of this paper is to provide guidance on transforming the application of SES for sustainability science in practice through the implementation of an education and training framework for SES by sustainability professionals. First, we describe different educational and training approaches for using SES in practice that research suggests have achieved desired learning outcomes; we identify several mechanisms of learning SES management and discuss critical perspectives on learning in SES. Next, we propose the social ecological systems training and education program (SESTEP, pronounced "see-step") as a novel framework for SES training. A SES training program is timely for meeting the changing capacity and needs of today's sustainability practitioners. Finally, we describe the formal evaluation of the SESTEP curriculum in practice.

Education approaches for training sustainability professionals in SES science

Learning is an essential component of sustainability science applied in practice because changing social and ecological conditions require knowledge to be updated, and without learning there can be no adaptation or transformation in the face of change (Gunderson and Holling 2002; Berkes et al. 2003; Lof 2010; Roux et al. 2017; Macintyre et al. 2018). Learning has been a prominent theme in SES literature (Carpenter and Gunderson 2001; Pahl-Wostl and Hare 2004; Armitage et al. 2008; Pahl-Wostl 2009; Cundill and Rodela 2012; Brown and Williams 2015; Phillip et al. 2018). Learning is discussed in a variety of contexts: at individual, institutional, and societal scales (Lof 2010; Golden and Earp 2012; Diduck et al. 2019); with different catalysts such as field-based learning or deliberate learning through trainings and/or institutions (Wei et al. 2015; Virapongse et al. 2016); and through different lenses such as social, transformative, and experiential learning theories (Armitage et al. 2008; Romina 2014; Rodela and Swartling 2019). SES learning describes how, when, and with whom this learning occurs (Baird et al. 2016; Phillip et al. 2018) in order to avoid the "paradox of learning" in which discussion of learning is often too vague to be practically applied or observed (Armitage et al. 2008; Van Epp and Garside 2019).

Formal training has been cited as a way to develop human capital, which can be considered the acquired knowledge and skills that an individual brings to an activity. Brondizio et al. (2009) assert that human capital is critical to addressing complex governance problems. Additionally, sustainability professionals often work within, or in collaboration with, bridging institutions, which can strengthen social capital and create new opportunities for cooperation and social learning (Pahl-Wostl et al. 2007). Thus, it is important for sustainability professionals to enhance and practice collaboration skills (Clement et al. 2019; Ernst 2019; Rodela and Swartling 2019). Recent reviews of graduate training programs for sustainability highlight the increasing adoption of collaborative approaches in formal learning (Chang et al. 2020; Salovaara et al. 2020). The wide array of scales, contexts, and interpretations of learning for sustainability practitioners requires consideration of the how, when, what, and why of learning relevant to sustainability issues, or as posed by Cundill and Rodela (2012, p. 8): "who learns, what are the outcomes of learning, and what are the processes that support these outcomes?" Identifying and describing these dimensions of learning is important for ensuring that learning SES concepts applicable to sustainability is transparent, measurable, and focused in purpose and method, especially in the context of SES training geared toward specific outcomes (Roux et al. 2017; Suškevičs et al. 2018), including management and policy changes. Based on these assumptions, training programs should consider such questions as:

1. What are the immediate needs of sustainability professionals?
2. How can the training help sustainability professionals meet their needs?
3. How can the past experience of trainees be incorporated into course design?

In addition, formal training needs to build capacity beyond the scope of the training or educational program

(Van Epp and Garside 2019) to support outcomes of sustainability science in conservation governance (Clement et al. 2019), water governance (Pahl-Wostl 2019), and urban biodiversity (Diduck et al. 2019).

The social and institutional contexts of SES impose important considerations on learning for sustainability professionals. and foster adaptive co-management (Suškevičs et al. 2018; Clement et al. 2019; Rodela and Swartling 2019). The nature of social networks and governance impacts the extent to which learning takes place among stakeholders and the response to environmental change (Krupa et al. 2018). For example, the maintenance of strong links within a group improves knowledge transfer, while access to many actors can enhance the accumulation and distribution of knowledge (Bodin et al. 2006). Sustainability professionals can leverage social networks to facilitate social learning, both among other sustainability professionals as a community of practice (Lave and Wenger 1991), and among local stakeholders, and should therefore be included as an approach to learning in SES. Other learning outcomes include greater understanding of the interconnections between social learning, social–ecological change, and adaptive responses by communities (Phillip et al. 2018; Ernest 2019; Rodela and Swartling 2019; Clement et al. 2019; Van Epp and Garside 2019).

Targeting multiple levels of change is critical to training for sustainability professionals (Baird et al. 2019). Both individual and group (social or institutional) learning is important for good adaptive management (Fazey et al. 2005; Van Assche et al. 2019). Individual learning is influenced by the learning culture, and so the social context in which individual learning takes place must also be attended to. Consideration of multiple scales of learning, though ideal, is not often achievable (Golden and Earp 2012). However, layering learning vertically and horizontally in institutions can facilitate multiple loop learning embedded in collective action (Lof 2010).

Key learning concepts and theories of relevance to SES include: experiential learning—learning viewed as a process of creating knowledge through experience; transformative learning—learning as a process of change in one's worldview; social learning—learning with other individuals as a group or cohort; communities of practice—a type of social learning where group interactions are grounded in a specific purpose; loop learning—the point in the iterative process of learning and action at which learning results in change, and; societal learning—the learning processes that occur through multiple institution interactions in the context of natural resource governance for sustainability issues (Table 1).

Connecting learning concepts and theories to learning processes and outcomes provides a way for theory to influence assumptions, priorities, and perspectives of learning (Table 1). Learning theory also creates the framework for interpreting observations of learning and serves to link research with practice (Suppes 1974). We incorporated these learning approaches and the associated outcomes using the SES-based environmental management approach (Virapongse et al. 2016):

1. A systemic worldview;
2. Transdisciplinary approaches;
3. Co-development of knowledge;
4. Stakeholder engagement;
5. Adaptive governance;
6. Social and ecological monitoring; and
7. Responsive education and training.

This approach was used because it supports the translation of SES theory into sustainability science and practice (Virapongse et al. 2016).

The SESTEP approach

A strong consensus has been expressed by managers from the United States Bureau of Land Management, the United States Forest Service, and the United States National Park Service, on the importance of developing training for federal, tribal, state, and local government management professionals, as well as academic and NGO personnel, in the theory and practice of SES as applied to land, resource, and sustainability management issues (Alessa et al. 2018). SESTEP answered this call by creating a certificate-granting program that builds capacity among the groups of interest and responded to the current challenges facing those groups (Dietz et al. 2003; Cumming et al. 2006; Virapongse et al. 2016; Bourgeron et al. 2018; Hunt et al. 2018), including managing systems with:

1. Multiple scales from local to global;
2. Conflicting stakeholder worldviews;
3. Spatial and temporal scale mismatches;
4. Limitations with existing legal and institutional frameworks; and
5. Lack of empirical data to support integrated management approaches.

SESTEP uses an adaptive process to provide SES training to professionals, while integrating participants' knowledge and experiences into the course design and curriculum (e.g., feedback loops), so that they are better prepared to tackle the complex human and environmental challenges present in natural and built landscapes (Rogers et al. 2013; Virapongse et al. 2016). The SESTEP Framework was designed to meet the needs of sustainability professionals and natural resource managers to provide: (1) a flexible but rigorous course structure; (2) learning outcomes to develop cognitive change and

Table 1 Learning approaches, concepts, and outcomes in SES

Learning approach	Associated learning concepts	Learning outcomes	Category of learning outcome
Case studies	Problem-based learning, student-centered learning, Transformative, Experiential (Kolb and Fry 1975; Kolb 2014; Mezirow 1995, 1997; Clement et al. 2019)	1. An understanding of socio-environmental systems 2. An understanding of how patterns and processes are scale and context dependent 3. The ability to find, analyze, and synthesize existing data, knowledge, methods, and ideas 4. The ability to co-develop research questions in interdisciplinary or transdisciplinary teams (Wei et al. 2015; Kliskey et al. 2017; Preise et al. 2018; Reyers et al. 2018)	Cognitive change, skill development
Heuristic tools	Transformative, experiential (Kolb and Fry 1975; Mezirow 1995, 1997; Phillip et al. 2018; Preise et al. 2018)	1. Understanding the dynamics of systems within and across scales (Walker et al. 2006; Greier et al. 2017; Preise et al. 2018) 2. Analyze mental models to allow convergence of view and purpose for dealing with competing desires (Walker et al. 2006; Cinner and Barnes 2019) 3. Identify 'what is' and 'what can be' (Mitchell et al. 2014; Phillip et al. 2018; Davis et al. 2019)	Cognitive change, skill-development, action-orientation
Social networks	Social learning, 'communities of practice' (Cundill and Rodela 2012; Lave and Wenger 1991; Kliskey et al. 2017; Rodela 2013; Schluser et al. 2003; Diduck et al. 2019)	1. Group management and generation of knowledge (Pahl-wostl et al. 2007) 2. Enhanced processes between collaborating stakeholders in collaboration processes (Pahl-wostl et al. 2007; Baird et al. 2019) 3. Ability to use new information in social learning processes and derive collective action from new insights rooted in shared experiences (Davis et al. 2019)	Relational change, action-orientation, wider capacities
Targeting multiple levels of change	Triple-loop learning (Lof 2010; Pahl-Wostl 2009; Macintyre et al. 2018; Ernest 2019; Pahl-Wostl 2019)	1. Reconsideration of underlying values, beliefs, and worldviews (triple loop learning) 2. Multi-party cooperation and participatory processes (Pahl-Wostl 2009, 2019) 3. Changes in cultural values, norms, and paradigms of formal and informal institutions (Pahl-wostl et al. 2007; Alessa and Kliskey 2020)	Relational change, wider capacities

Based on Suškevičs et al. (2018), Ernst (2019), Rodela and Swartling (2019) and Van Epp and Garside 2019

skill-development and support wider capacities and action orientation; (3) curriculum developed based on the identified needs and learning outcomes, and; (4) learning processes chosen for their relevance to SES learning and adapted for sustainability professionals.

The SESTEP framework uses a model that is experiential, adaptive, and participatory (Virapongse et al. 2016; Baird et al. 2019; Davis et al. 2019). This is an appropriate model for SES, which is a field that is continuously evolving. SESTEP uses a participatory training approach, so that knowledge within the participant group is used to enhance learning capabilities within the program (e.g., feedback loops) leading to improved SES tools for resource and land management, and natural and built landscapes (Krasny et al. 2010; Trimble and Plummer 2019). Participants progress through the program as a cohort in order to facilitate network building, collaboration, information sharing, and support across governance, community, and educational spectra. The cross-domain collaborations among cohort participants also facilitate individual learning and problem solving by transferring ideas and solutions from other participant's SES case-studies and applying them to their own (Lave and Wenger 1991; Masterson et al. 2019). The cohort then serves as a long-term support and information network for participants after course completion. The participatory training approach also ensures that knowledge within the participant group is used to enhance learning capabilities within the program (e.g., double and triple loop learning). Participants used one of their work projects as a case study to help apply learning in real-world scenarios, as well as to further develop SES as a discipline through learning from the experiences brought to the course by the students. This helped participants apply SES concepts in an experiential way to incorporate their prior knowledge and experience into the course, and to apply course learning to a real-life scenario. Participants developed this case study as an independent project during the course.

SESTEP curriculum

The SESTEP course is structured as a blended learning model with three parts: an in-person introductory week; an 8-week section of virtual learning modules; and an in-person final capstone week. This structure allows for cohort development and social learning through in-person components with minimal interruption to work and personal life. In the introductory in-person training week, course participants learn foundations of SES concepts and how these concepts are applied to management challenges. Five virtual modules are then offered remotely as live teleconferenced sessions or as pre-recorded web courses with online exercises that participants can take at any time. Participants select two or three facilitated course modules to deepen their knowledge of specific areas of SES in application. The capstone, week-long residential workshop is used to examine, diagnose, and critique solutions for participants' SES case-studies. During this workshop week, participants present proposed SES solutions and integrated management plans for their management scenarios.

The SESTEP curriculum teaches a framework to identify the components of a SES for the purposes of developing better sustainability strategies and understanding the connections and feedback dynamics between the different components of a SES. The challenges listed above are addressed in the SESTEP curriculum by adopting the SES approach for environmental management (Alessa et al. 2015; Virapongse et al. 2016; Davis et al. 2019; Egli et al. 2019) described earlier.

By engaging participants from different agencies and governance levels and consideration of multiple SES scales—from local to global, the program targets multiple levels of engagement. By delivering breadth in course content, through theory, site assessment, project development, and data management/analysis, the curriculum targets the needs of adult learners for practical application of curriculum. The curriculum also allows for the development of linkages between education, research, and SES.

The SES heuristic

The core process for the curriculum is a 12-step SES heuristic (Table 2). Heuristics are tools to aid decision-making under complex and uncertain conditions (Gigerenzer and Gaissmaier 2011). Mitchell et al. (2014) used heuristics along with a four-step collective learning process: beginning with sharing ideals of 'what should be,' resilience thinking tools and heuristics helped participants move towards understanding 'what is' and 'what can be' to set an agenda for action. Heuristic tools can be used in such circumstances to encourage transformative learning by scaffolding concepts of complexity (Rogers et al. 2013). Here we define a heuristic as a diagnostic protocol for examining the key elements, actors, dynamics, and procedures in a SES issue (Alessa et al. 2015; Kliskey et al. 2017; Trimble and Plummer 2019). The SES heuristic builds on the four-step framework for analyzing resilience (Walker et al. 2002; Ostrom 2009; Resilience Alliance 2010; Cinner and Barnes 2019; Egli et al. 2019) and the SESTEP pedagogical framework to provide a diagnostic protocol. Step 5 of the heuristic, the "Anatomy of a SES," identifies the stakeholders involved in the problem or issue and their value sets, since stakeholder values underpin decisions and behaviors (Resilience Alliance 2010; Kliskey et al. 2017; Roux et al. 2017). A key element of the heuristic is that following the identification of stakeholders in Step 5 and producing a map of the SES in step 6, the key questions raised in steps 1–5 are revisited in collaboration

Table 2 The SESTEP social–ecological system 12-step heuristic

1. Identify an issue, problem, or set of concerns that are to be examined from a SES perspective
2. Identify a geographical area that is relevant to the issues identified in Step 1
3. Identify the major social, economic, and biophysical drivers that affect the issues identified in Step 1 in the geographical area identified in Step 2
4. Identify gaps in knowledge of the issues, geographic domain, and drivers that are barriers to understanding the dynamics of the system being examined
5. Anatomy of a SES—identify collaborators/stakeholders (specifically or by discipline) that could help to better understand the system dynamics by filling in knowledge gaps identified in Step 4, and revisit steps 1–5 with stakeholders once they have been identified. This includes:
   a. Who are your stakeholders?
   b. What are their values?
   c. What is the strength of their values?
   d. What are the trust levels for these values?
   e. What data are available that map these values?
6. Create a physical representation of the system described in steps 1–5, including the issue of concern, the physical boundaries of the system, major drivers of system dynamics, knowledge gaps, and collaborators/stakeholders
7. Collaboratively, refine the issues or concerns of interest to be examined from a SES perspective
8. Re-evaluate the physical, geographical area described in step 2, in light of knowledge gaps and knowledge of collaborators
9. Identify new or expand on earlier social, economic, and biophysical drivers that affect issues identified in step 7 in light of expertise from collaborators
10. Identify data sets and sources for the drivers identified in step 9.
11. Identify those drivers for which data (or sufficient data) do not exist, and which will need to be collected in order to better understand or intervene in the SES of interest
12. Re-map the SES with the new information collaboratively produced in steps 7–11, including issues, geographical domain, drivers, gaps in knowledge and data, and key stakeholders

with stakeholders. Steps 7–12 are designed to re-describe the SES of interest from a group perspective and are key for not only building trust with stakeholders necessary to effect change but also producing a better understanding of a SES than a single practitioner is capable of. The adaptive cycle and the panarchy concept, common in resilience approaches (e.g., Resilience Alliance 2010; Reyers et al. 2018), were not used in the SESTEP approach due to the difficulties of operationalizing the concepts in management contexts (Virapongse et al. 2016; Alessa et al. 2018; Baird et al. 2019). Instead the heuristic focuses on the complexity of SES as messy systems (Preise et al. 2018; Alessa and Kliskey 2020). The 12-step SES heuristic is introduced during the opening week, using case-studies on which instructors have previously worked and applied, to illustrate the mapping of a SES issue (Cenek and Franklin 2017; Kliskey et al. 2017; Krupa et al. 2018). Participants are then led through the use of the heuristic for their own SES issue or case-study—a process that is continued through the virtual SES modules and then the sessions during the concluding capstone week of the program.

SESTEP modules: choice learning

Elective modules allow participants to choose to learn what they believe they need to know and what will be most useful for them. Five modules for SESTEP were developed as 2-week online sessions, and each participant chooses two modules according to their own training background and their current professional development needs:

1. A deeper dive into ecology—basic foundation in ecological and biophysical science in a human context (e.g., Holling 1973);
2. A deeper dive into social sciences—social science methods, stakeholders, and the collection and analysis of social data (e.g., Kristjanson et al. 2013; Krupa et al. 2018; Magliocca et al. 2018);
3. Social and political contexts for decision-making—policies and legal context for the complex issues surrounding decision-making in land management jurisdictions with an emphasis on federal relations with sovereign Native American tribes (Smith 2012; Kovach 2014);
4. Social–ecological data integration and modeling—practical issues of working with social data and ecological data and examples of integration models (e.g., Cenek and Franklin 2017);
5. Team-based SES approaches—skill development in team-based SES science, the co-development of knowledge with stakeholders, and conflict resolution techniques for situations that become contentious (e.g., Kliskey et al. 2017; Rodela and Swartling 2019).

Each module builds on and expands parts of the 12-step SES Heuristic and each involves an exercise that intersects the themes of the module, the SES Heuristic, and the participant's SES issue or case-study—typically contributing to the assembly of a set of SES best practices (Bammer 2013; Alessa et al. 2015; Kliskey et al. 2017). The case-study exercises completed during each module will provide material to be used during the capstone week of the course to complete the SES heuristic for each participants SES case-study.

SES case-study

The SESTEP course is underpinned by a requirement that each participant choose and develop a case study on a SES issue or project with which they are familiar. Case-studies are used to help apply learning in real-world scenarios (Meyfroidt et al. 2018), as well as to further develop SES as a discipline through learning from participants' experiences (Kliskey et al. 2017). Case-studies are compelling narratives which present a problem or scenario, providing context for more abstract ideas and making a complex SES issue more relevant and accessible to learners (Wei et al. 2015). For a sustainability professional, the case-study is typically derived from a complex issue or problem that they are engaged in as part of their job. For, example, case studies in the SESTEP program have examined wolf reintroduction in the Pacific Northwest, particularly in rural and ranching country and the importance of understanding differences in perceptions of wolf reintroductions between urban and rural communities. Other case-studies have considered: floodplain resilience of the Upper Mississippi River Basin with consideration for the multiple and sometimes competing stakeholder viewpoints; the economic and ecological sustainability of Central Idaho communities; water vulnerability in the Columbia River Basin among diverse communities of interest, and; coastal protection and restoration in the Chenier Plain among impoverished rural communities. These examples are consistent with the Wei et al. (2015) suggestion that cases should be chosen based on the focus on a SES problem or issue, that they be aligned with specific learning objectives, used to demonstrate the coupled nature of SES, and demanding enough to challenge learners to synthesize natural and social science data and/or knowledge. The case-study approach provides a valuable opportunity in SES practice for participants to work diagnostically, systematically, and progressively through the 12-step SES heuristic (Table 2) over the 10–12 weeks of the two residential courses and the intervening virtual modules. As a long-term approach to maintaining and sharing the lessons learned from the case-studies, participants with mature case studies (i.e., those that have moved from a proposal to implementation) are encouraged to submit case-study details to the social–ecological systems current practices archive (SES-CPA). The SES-CPA is a collection of case-studies and best practices in SES, and gives SESTEP participants an opportunity to participate in ongoing learning and connect to broader SES endeavors beyond the SESTEP curriculum (CRC 2018). Assessments of case-studies as teaching tools provide some evidence of improved student learning and positive engagement (Mezirow 1995, 1997; Clark et al. 2017).

SESTEP in practice

The inaugural SESTEP curriculum that was developed and taught in 2016–2017 was evaluated. We structured the evaluation to assess whether learning outcomes were achieved and to identify other unanticipated impacts and improvement opportunities for future courses.

Evaluation methods

Both quantitative and qualitative evaluation methods were used to examine program impacts. Due to the small number of participants in the course ($n = 7$), sampling and randomization were not possible, and the quantitative findings were used primarily to enrich qualitative data.

A pre-post survey design was applied to assess participants' self-perceptions of their knowledge and skills related to the course learning outcomes. The survey instrument measured participants' perceived efficacy (one's perceived ability to do something), a concept that links human beliefs to behaviors (Bandura 1982). The survey asked participants to rate their agreement with statements on a Likert-type scale from 1–5 (strongly disagree–strongly agree). The survey also included two open-ended questions about what they liked and did not like about the SESTEP course. The survey instrument was pilot-tested and reviewed by program leaders for content validity. Participants took the survey at the start of the program, at the end of the capstone week in April 2017, and finally 6-months after the end of the capstone week.

The interviews were intended to understand participant perspectives on the impact of the program, including unanticipated impacts, as well as opportunities for program improvement. The interview guide was developed and revised with input from program leaders, and through pilot-testing of questions. The interviews were coded using general inductive methods and categorized by themes (Thomas 2006).

Evaluation findings

Survey findings showed that participants reported improved understanding of learning outcomes from before the course to the end of the course and 6 months after the end of the

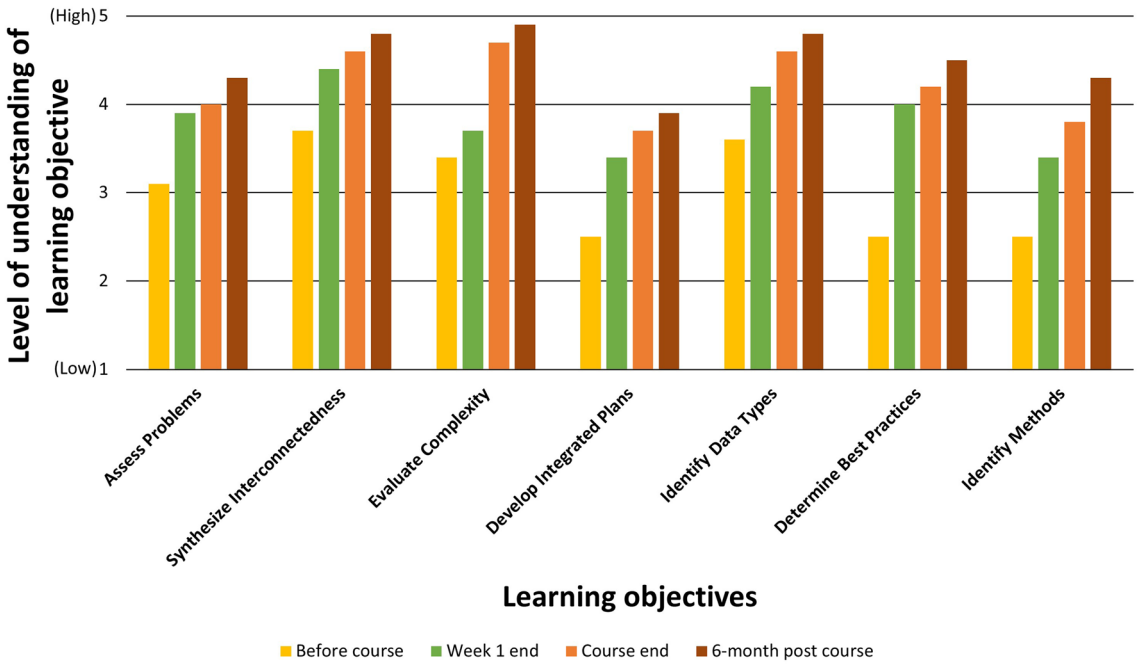

Fig. 1 Average understanding of learning objectives by SESTEP participants: (i) before start of course; (ii) after end of week 1; (iii) at end of course, and; (iv) 6 months following end of the course

course, with continued improvement throughout the reporting period (Fig. 1). On average, participants' understanding of learning outcomes increased 31% from the first week to the final week, and 34% from the first week to 6 months after (Fig. 1). The qualitative findings, based on the open-ended survey questions and interviews, suggest substantial advances in participants' abilities to respond to complex issues, particularly for critical thinking skills such as problem solving as a result of taking the SESTEP course (Table 3).

Interview data revealed the aspects of programming participants found most useful or beneficial. Participants expressed appreciation for the practical and applicable aspects of the program, including the case studies, the 12-step SES Heuristic model, development of a data management plan, and project design. They felt that the opportunity to talk with experienced SES researchers and practitioners about how SES is applied on the ground in real world scenarios was especially beneficial. When asked specifically how their experience in the program had

Table 3 Qualitative results from open-ended SESTEP evaluation questions on learning outcomes reported 6 months following the end of the course

In what ways has SESTEP impacted your approach to respond to complex issues in your work?
1. I am more familiar with theory. I have thought critically about the various concepts that should be considered in order to carry out an SES assessment
2. I've continued to break problems down into social and ecological components in order to better understand how they interact. I've also been better able to engage with stakeholders/community members in meaningful ways
3. SESTEP has helped me broaden my perspective of ecological problems and the array of options for looking at problems more holistically. In many ways I tend to think in an SES way, but didn't know what tools were out there for assessing social aspects of the system in relation to the ecological aspects
What aspects or concepts from SESTEP have you used in your work?
1. Long-term sustainability planning, adaptive planning, critical assessment of socio-physical synthesis and feedback loops, social learning processes, stakeholder engagement
2. The main concept/practice I've used is scenario building
3. While I am not currently implementing an SES approach to my current work (funding-limited), I regularly emphasize the importance of an SES perspective to my colleagues and funding partners. I have started to regularly engage colleagues outside of my institution to better understand the opportunities where an SES approach would be feasible and effective in moving the resource management problem forward

impacted their work, participants felt they were better able to identify key stakeholders, access relevant research, and utilize the process skills necessary for SES project work.

When asked about course structure, participants felt the cohort approach and group size/dynamic created a comfortable environment perfect for discussion and learning. They appreciated that the diverse group brought different perspectives and networking opportunities, while sharing a common language around SES. Participants indicated that the course provided a supportive atmosphere that encouraged a sense of community—they felt the relationships developed through the course were one of the biggest strengths, and this was aided by unstructured time to collaborate.

Unanticipated impacts were related to new perspectives. Participants expressed that the way they thought about complex environmental problems had changed, and they had developed new ideas and perspectives to apply to SES issues—"I was exposed to new ideas, reconsidered my understanding of SES… overall I feel more confident in understanding it as a framework." Participants also expressed the importance of understanding new and shared perspectives, including stakeholder perspectives. Participants felt that perspective-taking allowed them to understand larger systems from multiple worldviews and disciplines and was particularly useful to them in their work.

When asked how the program could be improved, participants felt they would benefit from additional examples and case-studies of SES in practice, more time on limitations and troubleshooting SES issues, and additional sessions on technological tools and their application for SES.

Evaluation discussion

In the course evaluation, participants reported cognitive, relational and skills-development changes. Based on feedback through interviews, participants found new perspectives and ways of thinking, practical tools, and the experience of experts to be the most useful and impactful aspects of the SESTEP course. Many described a new ability to see larger systems from multiple perspectives as especially practical in their professional work (cognitive change). They also felt that they now have tools and skills to develop SES project work such as the SES Heuristic, data management planning skills, and project design skills (skills-development).

As participants reported improvement across all learning outcomes during the course and six months following the course, it is reasonable to conclude that the course successfully met each of the learning outcomes. Improvement was not uniform throughout the course for all learning outcomes. Some learning outcomes showed more improvement than others, and some showed more improvement during a particular part of the course. For example, the learning outcome with the greatest improvement during the first in-person week, learning outcome 6—determining an approach for implementing a SES strategy, saw only minor improvement during the remainder of the course. Learning outcome 2 (critically evaluating the complexity of a SES system) was the opposite with more improvement after the first week. These differences point to the importance of the mixed-format course design for adequately addressing all learning outcomes, as well as suitability of some learning outcomes for certain course segments.

Conclusions

Training and education is critical for enhancing the way that sustainability science is practiced (Plummer 2013; Puettmann et al. 2016; Weinberg et al. 2020). The SESTEP framework and curriculum uses the SES-based approach to environmental management (Virapongse et al. 2016) and applies it to the practice of sustainability science by professionals in real world management contexts. The principles applied in the SESTEP curriculum included: (1) the engagement of participants from different agencies and governance levels; (2) a cohort approach through all elements of the course; (3) breadth of course content—theory, site assessment, project development, and data management/analysis; (4) the use of a case-study approach throughout the course; (5) development of linkages between education, research, and SES; (6) a variable course delivery approach with in-person introductory and capstone elements, including a series of online tailored modules bridging the residential sessions, and; (7) consideration of multiple SES scales—from local to global. Learning outcomes that support the practice of sustainability science through the SESTEP framework include an enhanced understanding of both theory and practical aspects of SES thinking and science (cognitive change). Other outcomes of the program are perspective-taking and a capacity to evaluate the complexity of a sustainability issue through the use of the SES Heuristic (skills-development), along with an improved sense of how to link social, ecological, and biophysical processes in specific landscapes using real-world case-studies (Table 2). The framework has been applied to sustainability science that spans urban to rural issues, impoverished to affluent communities, and watershed, wildlife, and resource extraction challenges for sustainability. Improving sustainability science in practice via the SESTEP approach occurs through: (1) change in management style (system interactions and consequences recognized); (2) better alignment of different management frameworks and goals (top-down vs. bottom-up), and; (3) building networks between stakeholders and managers as a foundation for future management decisions. Increasingly, sustainability professionals must contend with complex problems that intermingle biological, physical, and social realms (Alessa

et al. 2018; Schluter et al. 2019; Van Assche et al. 2019). SES-based learning frameworks such as those presented here can provide the building blocks for tackling these problems.

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