How to promote the integrative ability of transdisciplinary graduate students

Abstract

By integrating the insights of academic researchers and stakeholders from outside the academy, transdisciplinary research promises to help address complex challenges that threaten the safety and well-being of people the world over. This promise has led to the development of systematic efforts to train graduate students to conduct transdisciplinary research, and there is increasing interest in transdisciplinary education in the graduate training literature. This article discusses the promotion of integrative ability in transdisciplinary graduate students, focusing specifically on an educational approach that fostered transdisciplinary skills in a complex, transdisciplinary, international and multi-year project dealing with invasive alien woody plant species in eastern Africa, the "Woody Weeds" Project. Graduate students in the project were expected to collaborate with each other, with senior scientists, and with stakeholders in several work packages to conduct research addressing the project's goals. Research success required integrating perspectives across many differences, including different disciplines, institutions, languages, nations, and cultures. The Woody Weeds graduate student training program was designed to help students meet integration challenges across these categories of difference. Using the Woody Weeds training program as a framework, we offer a set of ideas for others interested in designing programs that can produce graduate students capable of conducting international, transdisciplinary research by fostering the *integrative consciousness* of individual students and the *integrative capacity* of student teams. We critically assess the extent to which the training program enhanced integrative ability using interviews with participants, outputs of the project, and the author team's experiences.

Keywords: transdisciplinary, training, integration, integrative capacity, difference, invasive species, graduate education, Woody Weeds Project

Introduction

Addressing complex problems through transdisciplinarity requires the involvement of people with different epistemic perspectives from inside and outside academia (Klein 2017). Complex problems affecting social-environmental systems (SES) are especially challenging, often crossing disciplinary, geographic, cultural, and temporal boundaries. Transdisciplinary training in academia should impart knowledge, skills, and experiences that support communication among disciplines and with stakeholders from outside the academy, to enable problem-oriented collaboration across disciplines and sectors that have differing perceptions, epistemologies, and sources of information (Haider et al. 2018; Pohl et al. 2017; Ramachandran et al. 2022). To integrate research about social and environmental elements of an SES, the similarities and differences among research perspectives must be understood and coordinated throughout a given project from the research planning phase through data acquisition and analysis to the writing of manuscripts (Hall and O'Rourke 2014).

Many contributions to the literature on transdisciplinary graduate student training emphasize the need for learning, among other things, about other perspectives, including other academic disciplines (e.g., Daneshpour and Kwegyir-Afful 2022; Horn et al. 2023). However, there are fewer contributions that describe training activities designed to promote integration of student work (e.g., Graybill et al. 2006; Lyall and Meagher 2012; Wilson et al. 2021), establish that training has enhanced the transdisciplinary capacities of graduate students and produced integrated interdisciplinary and transdisciplinary outputs (e.g., Bosque-Pérez et al. 2016), or identify what elements of training contributed to particular interdisciplinary outputs. This paper outlines an approach to integration in transdisciplinary research projects that provide cohort-based training to graduate students, using as example the graduate training provided in the Woody Weeds Project (hereafter, WW; Box 1), a complex, transdisciplinary and international research-for-development project that trained 18 PhD and MSc students in five countries over seven years. The project investigated environmental and livelihood impacts of woody invasive alien species (IAS) in eastern Africa and evaluated management practices to mitigate their impacts. It aimed both to integrate co-produced knowledge into societal practice in the form of sustainable management plans (Lang et al. 2012), and to contribute to the academic literature on the complex, social-environmental consequence of biological invasions. Graduate training and student collaboration within WW is distinctive in at least four ways:

1. Its training program was focused on enhancing the ability of project participants to integrate across the many categories of difference built into the structure of WW.
2. The training program was structured in two successive and linked student cohorts (a first, more research-focused cohort and a second, more implementation-focused cohort), each of which collaborated as an interdisciplinary team.
3. The students' integrative research findings and outputs, based on interdisciplinary and transdisciplinary collaboration, were key to achieving the aims of the project.
4. The transdisciplinary efforts of the students enabled outputs effective for informing IAS management decisions by local stakeholders and influencing policy at the national level.

We begin by canvassing the literature on integration in transdisciplinarity and transdisciplinary graduate education, highlighting the categories of difference that figure into transdisciplinary research and two capabilities that support integration across these differences, viz., the *integrative consciousness* of the students (cf. Kjellberg et al. 2018) and the *integrative capacity* of teams comprising students and senior scientists (Salazar et al. 2012; Piso et al. 2016). We then describe the WW training program, emphasizing the elements designed to enhance integrative ability. After assessing the successes and limitations of the integration-focused training elements in WW, we close by offering recommendations to those seeking to create a transdisciplinary training program.

The Need for Transdisciplinary Education

Transdisciplinary research: Context and motivation

Woody IAS, such as *Prosopis juliflora (Prosopis* hereafter) in eastern Africa, present complex challenges, both environmental and social. Environmentally, a plant like *Prosopis* promises to stabilize the landscape and increase nitrogen and carbon in degraded soil (Schaffner et al. 2025), but over time it leads to the reduction of plant species richness, herbaceous biomass and water availability, and it may replenish soil organic carbon pools less quickly than active land restoration (Linders et al. 2019; Mbaabu et al. 2020; Shiferaw et al. 2021). Socially, *Prosopis* can offer economic benefit in the form of wood for charcoal and aesthetic benefit in the form of wooded landcover, but again, over time, it adversely affects important ecosystem services such as fodder for livestock and water availability (Bekele et al. 2022; Mbaabu et al. 2020; Shiferaw et al. 2021). All things considered, the invasion of *Prosopis* in eastern Africa qualifies as a *problem* because it has done more harm than good (van Wilgen and Richardson 2014); further, its acknowledged benefits alongside its adverse effects qualify it as a *complex* problem that cannot easily be remediated.

Given that the invasion of *Prosopis* in eastern Africa is a problem, it makes sense to seek a solution, and there are many parties with an interest in such a solution. Academic researchers, such as biologists, geographers, economists and sociologists, are interested in understanding various social-environmental aspects of the problem. Members of communities that are adversely affected by the invasion, as well as those that profit from it, have their livelihoods at stake. Others with an interest in responses to the problem are governmental organizations responsible for policy in the affected regions (e.g., forest research organisations or ministries), and non-governmental organizations that are dedicated to aiding the affected communities. This is just the type of context in which transdisciplinary research responses are pursued (Hirsch Hadorn et al. 2008). We follow Klein in understanding transdisciplinary research to be "trans-sector, problem-oriented research involving a range of stakeholders in society" (2008, S117) that centers the "[c]o-production of knowledge with stakeholders in society" and is "realized through mutual learning and a recursive approach to integration" (2017, 30).

Transdisciplinary research responses to complex social-environmental problems like the invasion of woody IAS are *integrative* responses because they combine contributions from academic experts with contributions from experts outside academia. Characterized as "the core methodology underpinning the transdisciplinary research process" (Pohl et al. 2008, 421), integration within a transdisciplinary research context applies to knowledge, social/political elements, and communication (Jahn and Keil 2015; Hoffmann et al. 2017; cf. Burger and Kamber 2003, p. 56). Pohl et al. (2021) treat integration "as an interactive process of co-constructing knowledge that might happen during all stages of a [transdisciplinary research] process" (22). The interactive co-construction of knowledge in transdisciplinary contexts by participants who differ in many ways requires the creation of common ground, i.e., shared values and beliefs that improve collaborative capacity and support joint consideration of their different perspectives on the problem (Klein 2012; Boix Mansilla et al. 2015; Piso et al. 2016).

We follow Pohl et al. (2021) in emphasizing knowledge integration in this article, but as we just noted, integration in transdisciplinary contexts applies to more than just knowledge – it also applies to relational aspects of collaborative projects. Achieving transdisciplinary integration in collaborative projects requires communicating with people who have different core values and beliefs, negotiating project boundaries and addressing power differentials that influence the commitment of collaborators (Bammer 2016, Turnhout et al. 2020). Collaborators need to come together around project objectives and plans that they can jointly execute, and that will be complicated by the inevitable differences in power, priorities, and engagement across a transdisciplinary team. Without relational integration that enables the team to function as a team, the likelihood of significant knowledge integration will be greatly reduced. While we foreground the epistemic (i.e., *knowledge*-related) aspects of transdisciplinary collaboration that figure centrally into project success and into the curricula of transdisciplinary graduate training programs, we recognize their dependence on socio-political considerations. For example, as will be noted below, many training elements focused on enhancing the ability to communicate across differences, and that required relational connection in addition to informational exchange (Hall and O'Rourke 2014). Others aimed to build interpersonal and intercultural relationships that strengthened camaraderie and shared identity. We also call attention to socio-political considerations that obstructed integration, such as power differentials.

Categories of difference in transdisciplinary projects

Leveraging common ground to integrate across differences is a hallmark of transdisciplinary projects. In general, collaborative, transdisciplinary projects embed numerous differences among the participants, such as differences in expertise across academic disciplines and between academic disciplines and perspectives from outside the academy. Difference is the point of these projects – by integrating different perspectives, a transdisciplinary project positions itself to meet complex problems with complex responses (Newell 2001; cf. O'Rourke et al. 2019). Typically, though, transdisciplinary projects that focus on complex problems will involve more than just differences in expertise, and that is certainly true of WW.

Like many SES problems, invasion by woody IAS has effects at different spatial and temporal scales that affect ecological and human communities in interconnected and non-linear ways and require integration of interdisciplinary data through joint analysis for their understanding. SES problems are multidimensional and complex, rarely end at national borders, and typically engage experts from across the disciplinary map, as well as communities, organizations, and institutions with a range of interests and priorities. Thus, the categories of difference in WW included the *international*, *interdisciplinary*, and *interorganizational* differences highlighted in the I^3 framework of Perz et al. (2010) and Schmidt et al. (2012).

In addition, very complex projects may include differences not represented in the I^3 framework (Table 1). For example, WW was *intercultural*, including participants from different regions with their own histories, traditions, and religions. The project required sensitivity to *international* differences among cultures, of course, but there were also critical *intranational* differences among cultures, including different languages spoken by those affected by the invasions and different relationships with the locations where the invasions took place. Moreover, as a team-based research project, it was essentially collaborative, entailing all the usual *interpersonal* differences. WW involved more than 40 collaborators over the life of the project who ranged from graduate students to senior scholars, with the graduate students doing most of the focal research. Finally, it involved *interstage* differences, in the sense that it was segmented into interlocking but distinct stages and work packages. Specifically, WW was structured into three work packages that fed into one another across two phases, research and implementation, with researchers having to hand off data and findings to others they didn't know, including non-academic stakeholders.

Transdisciplinary education and training

Growing attention to transdisciplinary research on complex problems has led to increased interest in transdisciplinary education (e.g., Hansson and Polk 2018; Daneshpour and Kwegyir-Afful 2022; Horn et al. 2024), since this mode of research practice confronts characteristic challenges that people can be trained to identify and surmount, e.g., collaborating with multiple disciplines, communities, and sectors (Neuhauser and Pohl 2015). Graduate transdisciplinary education and training programs aim to supply students with skills that enable them to thrive as active participants in research-based responses to complex, real-world problems, addressing the many categories of difference that mark these transdisciplinary efforts (Di Giulio and Defila 2017; Kemp and Nurius 2015; Pearce et al. 2018; Nash 2008; Stokols 2014).

Although interest in transdisciplinary education and training is increasing, there is sparse literature on graduate-level transdisciplinary training programs that provide instruction in conducting integrative research with partners from sectors outside academia (cf. Keck et al. 2017), and so we expand our consideration to discussions of any graduate training program that emphasizes integration across disciplines. For the purposes of this paper, we take 'training program' to refer to a formal, cohort-based program that provides systematic training in research approaches, methods, and tools to groups of students.

Transdisciplinary education and training programs described in the literature include a variety of formats designed to facilitate development of relevant skills, such as classroom-based courses, field courses, internships, team-based research projects, training workshops, international trips, seminars and symposia, and joint mentoring (e.g., Atienza-Casas et al. 2023; Chang et al. 2020; Fortuin and van Koppen 2016; Neuhauser and Pohl 2015; Supplementary Material A). The content of instruction delivered in these formats focuses on topics like systems knowledge, communication across academic disciplines (i.e., interdisciplinary communication), development of a common language, joint study design and analysis, team building, student-stakeholder interactions, and data integration and interpretation (e.g., Cianelli et al. 2014, Muhar et al. 2013, O'Neill et al. 2019, Pohl and Hirsch Hadorn 2007, Wilson et al. 2021; Supplementary Material A). A key feature of these programs – and our primary interest in this paper – is a commitment to help trainees develop their integrative capabilities by making meaningful connections across categories of difference that include discipline and culture.

To effectively integrate across the categories of difference characteristic of transdisciplinary research, students need to develop three capabilities: (a) they must be able to *identify* a diversity of elements to be integrated, including their own perspectives (Fortuin and van Koppen 2015; Kemp and Nurius 2015; McGregor 2017); (b) they must remain balanced and capable of functioning as researchers in the context of that diversity, despite disorientation and discomfort (Akkerman and Bakker 2011; Boix Mansilla et al. 2015; Freeth et al. 2019); and (c) they need to find ways to *integrate* the different elements understood as inputs to the integrative process, e.g., by creating mutual dependencies among them (Mishra et al. 2011; O'Rourke et al. 2016). While integration across differences is recognized as a key training element by numerous contributions to the inter- and transdisciplinary education and training literature (e.g. Nash 2008; Cosens et al. 2011; Bammer et al. 2020; Schmidt et al. 2012; Esler et al. 2016; Wagner 2012), to our knowledge, no one paper pulls together the range of differences that characterizes the complex transdisciplinary problems addressed by WW.

Integrative capabilities in individuals and teams

As we see in Perz et al. (2010) and Schmidt et al. (2012), *boundary crossing* (or *border crossing*) is a metaphor used to represent activity that takes advantage of what is found across nations, organizations, and disciplines. Akkerman and Bakker (2011) recommend that we understand a *boundary* as "a sociocultural difference leading to discontinuity in action or interaction," so on this view participants in transdisciplinary projects inherently *cross boundaries* and encounter *difference*. This point was developed earlier by Suchman (1994), who argued that boundary crossing can mean "entering into a process of profound and uncomfortable social change" where we encounter "difference, entering onto territory in which we are unfamiliar and, to some significant extent therefore, unqualified" (25).

Of course, for "uncomfortable social change" to take place, more must be involved than merely *crossing* boundaries – crossing boundaries ensures exposure to difference, but as Akkerman and Bakker (2011) argue, we must *do something* with that difference once we are exposed to it. In particular, they argue that we must *learn* when we cross boundaries, where that involves *identifying* relevant differences, *coordinating* across them, *reflecting* on them, and *transforming* under their influence (2011, 151). These learning processes are related to what Kjellberg et al. (2018) called "interdisciplinary consciousness," i.e., a "specific type of interdisciplinary competence" comprising "cultivated sensitivities" that make students "aware of conditions under which inputs drawn from multiple disciplines can be integrated into interdisciplinary outcomes" (36-7). Kjellberg et al. (2018) argue that those with high interdisciplinary consciousness can reflect on their own perspectives (i.e., *reflexivity*), adopt the perspectives of their collaborators (i.e., *perspective taking*), and exercise those abilities in collaboratively conducting integrative research.

For our purposes, *interdisciplinary* consciousness is too narrow, since WW is a transdisciplinary project that transcends academic disciplines. Generalizing to accommodate both inter- and transdisciplinary consciousness, we'll refer to it henceforth as *integrative consciousness*. The training described in this paper aimed to cultivate integrative consciousness within WW graduate students, and it was also focused on enabling the cohort of graduate students in each phase to function as an integrated research team (Box 2). Success required the students to integrate perspectives with each other, with their supervisors, and with manifold stakeholders (Eigenbrode et al. 2025). Given this, it was important for the training to enhance their *integrative capacity* as a cohort, that is, to enable them to "build effective communication practices, a shared identity, and a shared conceptualization of a problem space that helps them recognize how their unique knowledge resources can be potentially combined to create an integrated knowledge product" (Salazar et al. 2012, 528). Integrative capacity comprises social integration processes, such as communication practices and shared goal formation, and cognitive integration processes, which begin with identification of available expertise (i.e., *positioning*) and then iteratively proceed with negotiated combination of different perspectives and evaluation of those combinations (Piso et al. 2016, 87; cf. Akkerman and Bakker 2011). Thus, the WW training aimed to develop the ability of trainees to integrate across differences by enhancing *integrative consciousness* in individuals and *integrative capacity* across cohorts. The presumption behind this pair of objectives was that heightened integrative consciousness would make individuals better inter- and transdisciplinary communicators, thereby making it easier to create a shared identity and share project goals and problem conceptualization. We acknowledge, though, that the fallacy of composition lurks here, and simply gathering individuals with high integrative consciousness does not ensure that together they would exhibit high integrative capacity.

The Woody Weeds Training Program

Our primary interest in this paper is training that increases integrative ability in graduate students. To that end, we focus on the WW training program as a case study. In this section, we describe the WW training program, emphasizing program elements that are designed to enhance the integrative ability of the graduate students, before turning in subsequent sections to the successes and limitations of the WW approach.

The WW pedagogical approach

The project leaders realised early on that to perform their central role in achieving project outputs and outcomes, graduate students required training that respected their diverse backgrounds. Beyond committing to cohort-based learning (O'Neill et al. 2019), WW did not impose a predetermined instructional plan, allowing it instead to develop organically in a way that was responsive to the requirements of the project and the needs of the students. The WW training program embedded traditional instructional methods, such as lectures, presentations, and other forms of transmissive learning (UNESCO 2012), but the dominant approach was *constructivism*, according to which learning is an active "search for meaning" that emphasizes reflection and collaboration (Khalil and Elkhider 2016, 148; cf. Hilger and Keil 2022, p. 431, and Stauffacher et al. 2006). The WW training program emphasized research into an existing problem defined by experts from different disciplines that involved transdisciplinary experiences in the field, collaboration with each other as teammates, and collaboration with stakeholders, highlighting the centrality of constructivist approaches that support transdisciplinary integration, such as inquiry-based learning (McGregor 2017), problem-based learning (da Rocha et al. 2020), and experiential learning (Kemp and Nurius 2015). The graduate student learners were *active* participants in their own education, collaborating with each other and with stakeholders in ways that leveraged reflection and encouraged perspective taking (Di Giulio and Defila 2017; Esler et al. 2016; Fortuin and van Koppen 2016; Pearce et al. 2018). Constructivist learning that emphasizes reflexivity and perspective taking is especially important in a training program that focuses on integrative consciousness and integrative capacity, both of which require awareness of the knowledge-related resources that can be shared in collaborative pursuit of research objectives.

The WW students

The main aims of the training provided by the project were to ensure that all students had (1) the skills to engage in interdisciplinary collaboration, and (2) enough knowledge of all disciplines to be able to understand the methods employed and data collected by other students. Training in most of their respective disciplines was not provided by the project, as it was assumed that the students would receive this from their home institutions. Some training in remote sensing was provided to all PhD students in the first cohort, because remote sensed data would be used to combine disciplinary data in joint analyses. In total, eight PhD and ten MSc students were trained over the course of the project in two cohorts. All PhD students but one were enrolled in universities in the Global South. PhD students in the initial cohort were based in five countries, their primary disciplines included ecology, economics, genetics and remote sensing, and they were required to collaborate to meet the expectations of the project. The PhD students in the second cohort, a geographer and an ecologist from different countries but both based in Kenya, relied for their projects on data and knowledge from the first cohort. The PhD positions were advertised internationally, and applicants were interviewed by supervisor teams composed of project scientists from hosting universities and project leadership. MSc student projects, all conducted at universities in the Global South, were related to PhD projects in various degrees; results generated by some MSc students directly supported PhD projects, while other MSc students did projects that supported project outputs more broadly. As such, student projects in WW were highly collaborative and there were links between most student projects that required mutual understanding, coordination and knowledge transfer, irrespective of whether students pursued MSc or PhD degrees.

Training elements

A number of training elements were implemented to support students and their PhD or MSc projects at different stages of WW (Table 2, Supplementary Material B). The elements aimed to foster integration across the many categories of difference represented in WW, and they took advantage of regular project activities that enabled all the students to meet at least twice per year, in addition to physical and virtual meetings of smaller groups. In addition to the focus of the training elements described here that specifically aimed at supporting the inter- and transdisciplinary skills of the students, some elements simultaneously increased the students' understanding of their study systems.

Disciplinary lectures by experts. Senior scientists and invited experts gave lectures about disciplinary topics related to the project, such as invasive species management, collection and analysis of socio-economic data, and governance. These lectures provided a similar, basic disciplinary background to all participants, contributing to each student's integrative consciousness by making them sensitive to differences across the disciplines.

Stakeholder days. Each project meeting involved one day assigned to local and national stakeholders. These days served as conduits for stakeholder knowledge into the project, influencing research in the region represented by the stakeholders. Students from the host country presented project activities and results to the stakeholders and led groups of stakeholders through IAS and land management mapping exercises. This enabled students to practice transdisciplinary communication and build integrative capacity with stakeholders who could become collaborators.

Pre-meeting student training days. Held prior to project meetings, student training days addressed gaps in understanding and skills among students. Activities that fostered integrative consciousness included facilitated communication, joint exploration and analysis of data to develop and address research questions, presentation of results to diverse audiences, and preparation of abstracts, posters, and manuscripts. Training days also contributed to the integrative capacity of cohort teams through joint development of required skills for team-based research, facilitation of specific collaborative deliverables, and provision of various collaborative infrastructures.

Joint student supervision. Each student was supervised by a multidisciplinary team that included university supervisors and senior scientists from countries in the Global South and the Global

North, ensuring exposure to different nations, cultures, and institutions, and preparing students to integrate across these categories of difference.

Joint data analysis. Since many project objectives required the interdisciplinary combination of different disciplinary perspectives, training in joint data analysis was provided during student training days to prepare students to jointly analyze data from different disciplines. This enhanced student perspective taking ability and the joint activity strengthened integrative capacity by enabling them to develop collaborative methodological skills (cf. Piso et al. 2016).

Joint manuscripts. To ensure that the students generated findings that derived from integrated data, each PhD student was required to include one first-author publication in their thesis that was jointly authored with other students and senior scientists as part of their participation in the project. Leading development of a manuscript strengthened integrative consciousness by exercising both reflexivity and perspective taking, and co-authorship strengthened integrative capacity by encouraging shared goal formation and shared conceptualization of the problem space addressed by the article.

Write shop for PhD students. When all six PhD students of the first cohort were writing manuscripts and preparing theses, the students met in Switzerland for a weeklong write shop. The students presented the state of their joint manuscripts at the start of the week and received frequent feedback on their drafts. This provided an additional opportunity to meet face-to-face and advance interdisciplinary manuscripts with technical support from senior scientists. It contributed to the integrative development of the students by supporting their interdisciplinary communication skills and by enabling them to jointly pursue a set of shared goals.

Student-led paper. The six PhD students in the first cohort were encouraged to jointly write a paper, which they decided would focus on ways to do interdisciplinary research in solving complex social-environmental issues, drawing on their experiences in the Woody Weeds project. This was an opportunity to learn how to write interdisciplinary manuscripts, how to work collaboratively on a co-writing project, and how to lead the preparation of a manuscript, and as such contributed to integrative development in the same way as the previous two elements.

Meeting of student cohorts. All eight PhD and several MSc students were present at one project meeting in the project's third year. The first cohort of PhD students presented their key scientific findings and the policy relevance of their research to the second cohort. The aim of this exercise was to help students think about their most important findings, the real-world implications of their work, what knowledge should be transferred to the new cohort of students, and how best to transfer it. In addition to increasing the number of disciplinary differences to integrate across, this element supported the development of a shared identity between cohorts, a key part of integrative capacity.

Toolbox workshops. Throughout the project, students and supervisors took part in Toolbox workshops designed by the Toolbox Dialogue Initiative (Hubbs et al. 2020). Toolbox workshops consist of dialogues structured by prompts that get at key, research-relevant differences that remain unacknowledged among collaborators. The primary goals of these workshops were to facilitate communication by enhancing both self- and mutual understanding through reflexivity and perspective taking, strengthening both integrative consciousness and integrative capacity.

Other activities. In addition to these activities, students enjoyed joint dinners (without non-student participants) during workshops to build camaraderie, spent time together collecting data in the field to strengthen relationships and understanding of other disciplines and possible challenges of combining, analysing and interpreting inter-disciplinary data sets, and some students participated in a SESYNC summer institute where they practiced synthesizing multidisciplinary datasets. These additional activities enhanced relational communication and strengthened shared identity.

Integration in the WW Training Program: Indications of Success

WW was a challenging project, in part because of the many interacting categories of difference that had the potential to hinder integration and because of the heavy reliance on students to deliver project outputs. For example, the geographic spread and different institutional arrangements of the PhD students made it difficult to coordinate research activities, which was aggravated by infrequent opportunities for in-person meetings and differences in preparedness because of different disciplinary and educational backgrounds. Coordinating research activities was a particular challenge for this project, as the activities were designed to be tightly integrated, with many interdependencies among parallel student projects and sequential activities across the seven-year duration of the project.

It was therefore important to support student collaboration across these differences, develop integrative consciousness and capacity early in the project, and continue providing support throughout the project to ensure all students, individually and collectively, had the capacity to fulfil the requirements of their research projects as well as meet project demands. The variety of training elements WW offered, described above, aimed to address integrative consciousness of individuals, integrative capacity of the team, or both, which are described below (see also Table 2 and Supplementary Material B).

In this section, we consider reasons to believe that the WW training program enhanced the ability of WW graduate students to integrate across the categories of difference manifest in the project. We begin by considering project outcomes, including interdisciplinary papers and policy impact. We then turn to the training elements and evaluate their success in enhancing integrative ability through perception of program participants. Participant perception was assessed after the project ended through semi-structured interviews or an online survey of participating students and senior scientists. Eight students and ten supervisors were interviewed, while two students and two supervisors responded via the survey. The interview and survey focused on the value of different training elements, differences with other graduate training programs, strengths and weaknesses of training in the project, interviewees' involvement in the development of research in the project and whether and how the project helped overcome challenges with respect to teamwork. The interviews were designed by the authors of this paper and conducted by an independent researcher who had not been involved in the project before. Interviewees came from all participating countries. Interviews were conducted with prior IRB approval of Michigan State University (exempt STUDY00007689).

Project Outcomes

One common measure of success for training programs is the degree to which the program achieves its training objectives. This measure involves data about retention, graduation, and placement, but for projects like WW they must be augmented by data about the success of project research, including integrative publication and policy impact, since WW was primarily a research project that depended for its success on graduate student research. In terms of metrics related to progress to degree, WW was a success. Overall, 8 PhD students and 10 MSc matriculated into WW, and seven PhD students and ten MSc students earned degrees.

WW was even more impressive as a student-driven research-for-development project. Of 24 peer-reviewed papers published up to two years after the project end that acknowledged WW funding, only one was co-authored by people from a single discipline (Paper #15, Box Figure 2). Seven PhD students and two MSc students were first author of at least one interdisciplinary paper. These papers have been cited over 1000 times at the end of 2024. Only three papers were led by senior scientists.

More importantly, given the transdisciplinary nature of WW, the research results led to meaningful change on the ground in eastern Africa. The results of the stakeholder-informed, student-led research in WW, especially from the first cohort of students, have been presented to and used by Kenyan and Tanzanian authorities in the development of invasive species management strategies. This was acknowledged by two supervisors in the interviews, with one saying that *"the best thing about this project is that it wasn't just research that we did for six years, but actually we're now trying to address the issues. We have the science and we're now trying to address the issues together with the government, local government, local population"* (Supervisor 2). Several students expressed disappointment during the interviews that they didn't see their results being put into practice. However, the duration of the project and the path to impact were longer than the participation of the students, and the results of their work have been very influential. Indeed, some of the management practices that students tested during their research have been adopted and are being implemented by communities (Eschen et al. 2024). The expressed disappointment highlights the need to make explicit the roles of students in transdisciplinary projects and training programs and the expected outcomes of their contributions. It also highlights the fact that while WW is a transdisciplinary project, not all modes of transdisciplinarity are the same. The length of time between the research and its impact on stakeholders indicates that WW is not a participatory action research project in its early work packages, for example, since the systems-focused research in the first two work packages is not conducted in iterative action-observation-reflection loops (Cornish et al. 2023).

The research and policy outcomes underscore the success of the WW training program in helping students develop integrative consciousness as individuals and integrative capacity as collectives. The students' active contributions to different article projects suggests that they learned how to function effectively in different inter- and transdisciplinary contexts. Contributing to high-quality research, measured in terms of both citations and policy impact, requires reflexivity and perspective taking so that one can make a contribution that is well coordinated with the contributions of one's collaborators. These aspects of integrative consciousness also positioned students to contribute coherently to different article projects that involved different combinations of collaborators, thereby forging the integrative capacity necessary to successfully co-author influential papers. Thus, the students developed through the training the three capabilities for dealing with differences in transdisciplinary contexts: they were able to *identify* and *integrate* a diversity of elements, while remaining able to *function as a researcher* in the context of that diversity.

The contribution of training elements to integration across differences

The second column of Table 2 distinguishes between the *focal* and *peripheral* categories of difference for each element. To say that a specific category of difference is "focal" for a training element is to say that the element was designed with that particular category of difference in mind; to say that a particular category of difference was "peripheral" for a training element is to say that the element enhanced the ability of trainees to integrate across that category even though it wasn't designed with that particular goal in mind. The last column of Table 2 distinguishes between *individual* and *collective* impacts the training element is intended to have, i.e., the impacts it is intended to have on integrative consciousness and integrative capacity.

Interviews and reflections of the students and senior scientists revealed that some of the elements were more successful than others at achieving these aims. When asked to choose the three elements that were most useful for integration from a list of 10 alternatives which corresponded broadly to the elements described above, six elements stood out in the responses (Fig. 1). Responses by students and supervisors were generally in agreement, but students mentioned interdisciplinary student papers and student-stakeholder interactions more frequently than supervisors, while joint supervision and joint data analysis were more frequently mentioned by supervisors than by students. We consider these six in what follows, focusing on their relation with integration and their effectiveness as communicated through interview and survey responses.

<u>Interdisciplinary student papers</u>. One important piece of evidence that WW students improved their integrative consciousness and the research team built its integrative capacity is the number of inter- and transdisciplinary papers generated by the project, many of which were led by students as part of their theses (Box Fig. 2). The students in WW benefitted from the interdisciplinary papers, as indicated by this statement during the interviews: *"we were able to produce* […] *quality work. Looking at the national recognition, some of the papers we've been able to publish are just – even as international recognition"* (Student 3). In addition to requiring integration across disciplinary, personal, and cultural differences, these papers also supported integration across national boundaries. This is highlighted by the involvement of authors from both the Global North and Global South on almost all the papers. Although there isn't much literature describing publication output of research for development projects, the fraction of papers with authors from the Global North and South in WW (96%) appears very high compared to some other programs. For example, an analysis of north-south partnerships by Luetkemeier et al. (2024) revealed that only about 10% of publications produced in the analysed research programme had at least one author from the North and one from the South.

<u>Student-stakeholder interactions</u>. Meeting stakeholders is an essential component of transdisciplinary, problem-based learning (Kemp and Nurius 2015; da Rocha et al. 2020), and it helped WW students leverage cultural, organizational, and national differences and create interpersonal connections that facilitated both research and implementation. One student noted, *"it created some type of bond […] between me and local people … we still communicate with the*

locals, we still communicate with the peers we worked [with] *and we have plans for more collaboration"* (Student 5). A supervisor echoed this, highlighting the importance of connection for knowledge co-production: *"I think it's taught* [the students] *how to connect and talk to the local population, like to people and show them respect and appreciate their local knowledge"* (Supervisor 2). Most students mentioned the importance of collaborative in-person activities, including field visits and engagement with local communities, which enhanced their ability to communicate their science. During these activities, *"the students had a chance to also ask questions or get into engagement with other stakeholders which we were working within the project. That was also quite good. And this is something that should be promoted"* (Student 1). A supervisor emphasized another positive impact, observing that students learned *"to adapt their language, adapt their discourse to be palatable to a broader audience. That was certainly a success"* (Supervisor 3).

<u>Joint study design and data analysis</u>. Both integrative consciousness and integrative capacity were enhanced by training on joint study design and data analysis in WW. WW's heavy reliance on students for collection and analysis of multidisciplinary data from each region was largely well perceived, even though it required the first cohort to function as a team, with their projects being closely coordinated from the design phase to the analysis phase. One supervisor remarked that the *"really careful preparation of data collection resulted in good quality data"* (Supervisor 1), and a student said, *"The project allowed people from different disciplines to come together, work together, trying to solve a common problem. That was quite innovative and it was quite successful"* (Student 1). The joint development of their studies *"helped* [the students] *to understand the connectedness between the different disciplines, how they are linked, and how they may interact with these different disciplines, like positive and negative impacts and how they affect other disciplines"* (Supervisor 2). However, there were difficulties for the students: *"During the development of the project, the developers understood that the socio-economic data could simply be collected and* [was] *easier than the ecological data collection process. That was a misunderstanding, I can say, and then it took a high burden for me to integrate data* ... *and having to partner with publications with all those five students. That created higher pressure on me than other students"* (Student 2). These difficulties, which might have been due to disciplinary chauvinism (Giri 2002), could have led to underrepresentation of socio-economic perspectives had they gone unaddressed; however, project developers, with the help of the socio-economic Ph.D. student, addressed this limitation through discussions with students and their supervisors and through involvement of MSc students to help distribute the socio-economic research workload more evenly. In the end, the record of integrative publication shows that socio-economic research was well represented in project outputs. Joint data analysis in WW across disciplines and across SES in different countries required standardization of research methodologies and coordination of data collection across study regions, which was a focus of an early student training day that was aimed at planning the joint studies when each student in the first cohort was developing a research proposal. Collecting the same data across three countries enabled comparisons and assessment of context-dependent differences. This provided the students with experience dealing with the full complexity of SES, which is where transdisciplinary skills of individuals and teams are especially required.

<u>Joint graduate student support</u>. When asked about how WW compared with other graduate training, some students talked about the high level of support (e.g., resources, advising),

especially in contrast with typical African graduate education. Several students and supervisors recognized the benefits of joint supervision by scientists from the Global South and the Global North, which gave students the opportunity to build working relationships and integrative consciousness across national, cultural, organizational and disciplinary boundaries. One student remarked, *"We had an opportunity to gain experiences from different scientists of Global North and South who have different deep experiences shared among us"* (Student B in questionnaire survey). Feedback about this indicator was somewhat mixed, however, with some students and supervisors criticizing the level of support provided by supervisors from the Global South and the differences in priorities between the project and the universities. For example, one student observed, *"The project originated from the north. The goals, the objectives, … the resources, whatever. And then* [the project] *assign[s] you to supervisors from your institution where you are affiliated. But unless* [your local supervisors] *are really interested in that kind of a thing, … they might not be really very [motivated*]" (Student 3). It is difficult to explain these opposing viewpoints that appear to reflect different experiences by project participants. The latter student opinion in particular may suggest that motivation of supervisors (i.e., senior scientists) from the Global South could depend on whether they were involved during project development, i.e., whether the project was co-developed in a way that led to inclusion of their ideas and interests, a desired equivalence of power that may be hampered by lack of time and financial resources during the project development and initiation phases (Eschen et al. 2021).

<u>Pre-meeting training days</u>. Although not planned during project development, the training days were a very successful component of the training that encouraged integration across multiple categories of difference, including difference in project stage. This view was mainly articulated by supervisors during the interviews. One supervisor said of the training days: *"this put together students from all the disciplines represented, strongly promoted interdisciplinarity and enabled students to appreciate ... different backgrounds and variations in understanding and approach"* (Supervisor 5). Another commented positively about *"organizing trainings for the PhD students and master students before our project workshops to encourage them to work together, to exchange data, to encourage them to have an identical data gathering protocol so that they can more easily exchange their data. To encourage them to look beyond their own discipline, if they are economists, they also look at the biologists' view, and so on"* (Supervisor 3). The additional time spent by students together was useful for building relationships and exchanging knowledge: *"there was ... quite a lot of interaction between the students, and a lot of opportunities for the students to meet and discuss and share information"* (Supervisor 4).

<u>Team building activities</u>. The project embedded a number of opportunities for students to build their integrative capacity as a team, including informal activities like dinners among students during project meetings and more formal opportunities such as joint field work. The students and supervisors appreciated joint field work and other opportunities to spend time together. *"There was quite a lot of … interaction between the students,"* reported one supervisor, *"and a lot of opportunities for the students to meet and discuss and share information"* (Supervisor 4). These opportunities were especially valuable in building interpersonal relationships, but they also encouraged interdisciplinary, intercultural, and international connection. These interactions led "*students to start seeing the problems more holistically*", according to another supervisor (Supervisor 6). The interactions led to lasting, valued personal relationships, as highlighted by

one student: *"The key opportunity was the chance to get to know – to connect with different colleagues from different countries. We have been keeping contact up until today. And this would be impossible if it was not Woody Weeds [that had] connect[ed] us"* (Student 1). Building the team is a critical socio-political part of strengthening integrative capacity, and the long-term relationships suggest that this has been successful.

Integration in the WW program: Weaknesses and Limitations

There were also less successful aspects of the WW training program, which is not surprising given its complexity and seven-year duration. For example, some training elements were rarely mentioned as most useful for integration, such as disciplinary lectures during project meetings or the development of an interdisciplinary vocabulary. This may be explained by the fact that the disciplinary lectures didn't specifically address integration and development of an interdisciplinary vocabulary wasn't emphasized during the project. Also, institutional and cultural differences among students led to variable speeds at which they were involved in the project. For example, students at eastern African universities experienced delays due to regulations that forced them to defend their research proposals to faculty members before being allowed to collect data; to a large extent, these situations were resolved after intervention by project leadership. In addition, some eastern African students had family or professional obligations that added a burden which the other students didn't experience. One student commented, *"you find that the responsibilities that we have from our African context are different from people from Europe, for example. So whereas, for me, I had work responsibilities, I also had other responsibilities. I had family responsibilities and as you well know in the African context, we may have even extended family responsibilities"* (Student 3). The relational, socio-cultural consideration raised in this comment points to a structural inequality between students from the Global South and the Global North that made the time-intensive work of project integration more difficult to pursue. Almost all WW students were from the Global South, though, and the project addressed this inequality through additional support, when necessary, that helped them finish their studies and lead impactful publications.

This comment about different responsibilities in the African context, along with a few earlier comments (e.g., concerning the imbalance between socio-economic and ecological research), underscore the fact that multi-national, transdisciplinary projects like WW will invariably embed structural inequalities and cultural differences. These inequalities and differences generate hierarchies of power that can divide project personnel and stakeholders, leading to asymmetries in participation and contribution that undermine their ability to integrate perspectives and achieve project objectives. The political nature of knowledge co-production requires careful attention during project design and selection of project partners and students, as well as during the project lifetime when the effects of such power differences may become evident and project changes may be needed to address them.

Some students remarked that the supervisors lacked interdisciplinary skills or experience, which probably limited the integrative training the students received. For example, one student remarked, "*It would have been better if we could have interdisciplinary professionals among us"* (Student B in questionnaire survey), and two supervisors indicated that they were more interdisciplinary as a result of participating in WW than they had been at the beginning. Some of the WW training elements involved the participation of both students and supervisors (e.g., several of the Toolbox workshops), but this was not a consistent feature of the training. That senior scientists are often narrowly knowledgeable in their field of expertise and need training in interdisciplinarity is an issue that has been described in the literature and deserves emphasis in future projects (Boix Mansilla and Duraising, 2007).

Although students had control over details of their specific research projects, they indicated that they had little input into the integrative macro-design of their studies. While this may be regarded as negative, we believe it was actually a good thing, for three reasons. First, the students came into the highly dimensional space of WW with many things to learn about their own disciplines and about integrative collaboration with other students. A predefined, integrative study design that emphasized teamwork provided research structure to the students that reduced the complexity of the experience and gave them time to grow into their roles in the project (cf. Bosque-Perez et al. 2016). Second, WW was bigger than any one student's research project, given the team-based design of each cohort's contribution and the inter-stage contributions of the first cohort to the research done by the second cohort as well as the implementation aspects of the second project phase that were expected by the donor. Third, the pre-defined, integrative study design made it clear from the start what integrative skills would be needed for the students to contribute successfully to the overall effort. Ultimately, a successful training program should balance the design necessary for planning and coordination with the autonomy necessary for students to shape their own research experience.

Conclusion and Recommendations

In this article we present a framework for understanding integration in transdisciplinary education in terms of integrative consciousness and integrative capacity in the context of multiple categories of difference. We examine this framework with reference toa training program for graduate students in a highly complex project where the students had an essential role in delivering project outputs. A central part of the student work in WW was research that required special efforts from students, supervisors and project leadership throughout the project lifetime to ensure that data from biological and socio-economic disciplines could be integrated using remote sensing. The project required students to integrate across several categories of difference: nations, organizations, disciplines, cultures, individual researchers, and project stages. WW carried out similar studies across three countries that required coordination of research methodologies and joint analyses of data, resulting in synthesis of patterns across these complex SES by teams of graduate students. The success of the training is evidenced by the large number of interdisciplinary research papers written by the students, the use of student-driven research knowledge by local and national stakeholders, and interview feedback from students and scientists.

Few published studies address the practicalities of the knowledge and planning needed to integrate across the large number of differences in play in inter- and transdisciplinary projects like WW. In a few cases, publication of papers based on interdisciplinary project work has been used as a metric for assessing success (e.g., Luetkemeier et al. 2024), but these papers don't typically describe how interdisciplinary integration was achieved. For example, only a minority of the papers describes whether students or supervisors were involved in joint study design and data analysis (e.g., Graybill et al. 2006; Lyall and Meagher 2012; Wagner et al. 2012), and few address whether and how data from different disciplines were integrated to produce interdisciplinary knowledge and outputs (e.g., Graybill et al. 2006; Lyall and Meagher 2012; also see Supplementary Material). Furthermore, a requirement for students to write interdisciplinary papers as part of their interdisciplinary training program is rare (although see Bosque-Pérez et al., 2016), and without something like that, it is difficult to assess how the students have exercised their acquired integrative skills. This paper fills some of these gaps, but while the approach we propose and the analyses we conduct are not unique to this project context, the trustworthiness of our interpretations is limited by the focus on a single project, the small number of students, and the specific geographic location of the project.

We conclude by offering several recommendations, grounded in the WW experience, to those who seek to engage in complex projects that require integration across multiple categories of difference:

- Make explicit the differences that are relevant to the project objectives and across which integration must occur for the project to be successful

- Develop training opportunities for senior scientists to become familiar with these differences and with strategies and techniques for integrating across them (e.g., provide training that strengthens collaborative interdisciplinary skills throughout the project)

- Involve faculty from the Global South in designing projects at the proposal stage before they are funded by agencies in the Global North; this should include active involvement in proposal writing. Donor agencies should avail funds to prepare proposals by international and transdisciplinary teams.

- Be explicit about how a given training element will support integration across project differences, thinking of this in terms of what inputs are involved in the training element, such as disciplinary understanding or datasets, and how the training supports relating those inputs in producing an integrated output

- Integrate *disciplinary* inputs from the planning phase onward, i.e., consider how disciplinary data will be collected in comparable spatial and temporal units, to ensure that the results can be analysed and published together, for example, as required inter- or transdisciplinary papers

- Stimulate student collaboration from planning of joint research to publishing by designing joint studies and investing in student collaboration and team building across multiple dimensions of difference.

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Box 1 - Introduction of Woody Weeds as a research project

The Woody Weeds project (www.woodyweeds.org) aimed to assess and mitigate environmental and socio-economic impacts of woody IAS in Ethiopia, Kenya and Tanzania. Although all societies require high levels of ecosystem services, rural people in low-income countries are often more directly dependent on the services provided by nature, such as food, fuel, fibre and water, and have more limited capacity to compensate for reductions in service supply (TEEB 2010). Alien shrubs and trees have been introduced in many African countries with the aim of providing socio-economic benefits, but some of these species have become widespread and cause environmental or economic damage where they occur. As a consequence, a broad understanding of the impacts and management options for IAS requires simultaneous assessment of diverse aspects of the socio-economic system where they occur. Funded by the Swiss National Science Foundation and the Swiss Department for Development and Cooperation through the r4d program, the project in its first three years primarily focused on science to understand impacts and in the latter three years on impact mitigation through a deliberative decision process involving a variety of stakeholders and testing implementation measures selected by stakeholders.

The project consortium included partners from the three Eastern African countries, South Africa and Switzerland with diverse disciplinary backgrounds, including ecology, socio-economics, genetics and remote sensing. Students were a central part of the project, as most of the research needed to fulfil the project's objectives was carried out as part of PhD and MSc theses. To jointly assess the ecological and socio-economic impacts of IAS, the project collected primary data on ecosystem service supply, such as herbaceous biomass as a proxy for forage production, and their use, such as income from livestock selling, using a nested sampling design during the first three years of the project that allowed students to collect paired environmental and socio-economic data at the same spatial scales, i.e., the smallest administrative units in each study region. Because the ecological and socio-economic data were collected from different units (replicated field plots for ecological data and household interviews for perception data), the students used remote sensing for upscaling in each target region the data collected at the local scale to the subnational scale, thereby generating data sets relevant for policy decisions.

This complex design required teamwork involving students and senior scientists, and it enabled the pursuit and publication of interdisciplinary research, but it required each student to fully understand the sampling units that allows both analysis at the local scale and upscaling to the subnational scale, the importance of standardized data sampling protocols, and the coordination of data entry and analysis across student projects. During the conceptual phase of WW, emphasis was therefore put on offering the students an enabling learning and work environment that increased the likelihood of successful and timely data collection and that helped them increase their capacity in understanding other students' disciplines.

The results of the research conducted in the first three years were published in international peer reviewed journals and were used to inform the decision-making process of stakeholders at the local level in the second half of the project, as well as in reports requested by the Kenyan and Tanzanian governments to inform the development of policies to manage IAS.

Box 2 – Data integration in the Woody Weeds project

The PhD student projects in the first three years of Woody Weeds each related to one of the project activities, which were all interlinked and coordinated by a different project partner. As a result of the interlinked design of the activities within the project, it was expected that none of the six students could finish their project without effective teamwork, as each project required data collected by at least one of the other students. In many cases, the integration of data collected at different spatial scales was achieved using remote sensing data. The project also required each student to publish at least one interdisciplinary first author manuscript in an international peer reviewed journal.

During the first training days, which were held half a year after the project started during the period when the students developed their research proposals, lectures were given that covered data analysis in different disciplines, including socio-economics, remote sensing and ecology. An introduction to the use of the R software for statistics was also given. These lectures aimed to establish a similar basic level of knowledge among the students to facilitate data exchange and integration.

To facilitate planning of data collection and integration, the students were tasked to think about what information they needed from whom and when in order to meet their deadlines. To assist in fulfilling this task, the students were given a matrix to be filled with required datasets, the person responsible for delivering the data and by when. The exercise, while important for delivery of the project, was also important as it led to a constructive discussion about common units needed for exchange of information. For example, the need to relate a variable to an area for use with remote sensing data led to discussions about the appropriate spatial unit for data collected through household interviews in an area where many households rely on communal or open access grazing land. The results of the exercise revealed the many planned data exchanges among the students that were required to address the project and student objectives (Box Figure 1).

The integration of data across student projects largely went as planned and the student projects resulted in many interdisciplinary, student-led papers with co-authors from diverse disciplines (Box Figure 2). Two papers using data from student projects were led by senior project scientists but were developed with active involvement of the students who generated the data. Furthermore, results of the student research have been instrumental in informing national strategies for managing *Prosopis* or invasive alien species more generally in Kenya and Tanzania.

Table 1. Categories of difference in WW that present integration challenges for the scientific team and the student trainees, along with sub-categories and their specifications.

Category	**Subcategory**	**Specification**
International	Nation of origin	Research collaborators were based in countries in the Global South (Ethiopia, Kenya, Tanzania, South Africa) and the Global North (Switzerland, the United States)
	National locations of research	WW research was conducted in Ethiopia, Kenya, and Tanzania
Interorganizational/ Interinstitutional	Academic partner institutions	Students and supervisors represented different academic institutions in Africa and Europe, including universities in each of the participating countries
	Non-academic partners	WW was a transdisciplinary project that involved partners from outside the academy, governmental and parastatal organizations (e.g., KEFRI, TAFORI, CETRAD), communities (e.g., villagers in Kahe, Tanzania) and other groups (e.g., charcoal producers' associations in Baringo, Kenya)
Interdisciplinary	Disciplines	Disciplines in WW included invasion biology, ecology, agricultural economics, and remote sensing
	Methods	WW combined plot-based data collection methods of the biological sciences with interview-based methods of the social sciences, which differ in the way data are collected, geographic specificity (i.e. exact locations vs administrative level), as well as commonly used statistical analytical approaches
Intercultural	Culture	Cultures within and across countries differed and included sedentarist as well as pastoralist cultures as well as different ethnic groups with different cultures, entailing differences in behavior, values, expectations, etc.
	Natural language	English was the primary language of research spoken during the project, but there were many languages spoken by project partners in the African and European countries where project work was performed
Interpersonal	Career stage	The project included graduate students, post-doctoral researchers, and professional scientists from early to late career, all collaborating on the research
	Personality	There were more than 40 different people involved in this project from different cultural backgrounds who had different tendencies and different sensibilities
Interstage	Work packages	The project was divided into three semi-sequential work packages: local processes and effects, spatial models of threats and impacts, and mitigation strategies
	Collaborators	Different people led the work in different stages, which meant that researchers had to rely on people they didn't know to shepherd their data and findings through the next project stage

Table 2. The elements in the WW training program that focused on enhancing the ability of students to integrate across categories of differences. The table lists the focal and peripheral categories of difference across which each element is intended to support integration and the impact each element is intended to have on integrative ability, both individual (i.e., integrative consciousness) and collective (i.e., integrative capacity). For more detail about each element, see Supplementary Material B.

Training element	**Focal/Peripheral**	**Individual/Collective**
Disciplinary lectures by experts	<u>Focal</u>: Interdisciplinary (revealed disciplinary differences) <u>Peripheral</u>: International (different nationalities of speakers and audience members)	<u>Individual</u>: provided information that enabled trainees to understand relationships among project disciplines <u>Collective</u>: N/A
Stakeholder days	<u>Focal</u>: Intercultural (finding common ground with different stakeholder groups in country), Interorganizational (working with a number of different stakeholder organizations) <u>Peripheral</u>: International (Opportunity for all students to work with stakeholders in different countries), Interpersonal (Interaction with different people)	<u>Individual</u>: provided host country students with opportunities to practice communication with different stakeholder groups <u>Collective</u>: develop integrative capacity with stakeholders who will collaborate during field work
Pre meeting Student training days	<u>Focal</u>: Interdisciplinary, International, Intercultural, Interpersonal (the cohort of graduate students was diverse, representing different disciplines, nations, and cultures) <u>Peripheral</u>: Interstage (one training day involved interaction between the first cohort and second cohort of graduate students)	<u>Individual</u>: enhance integrative consciousness by supplying information about different disciplines, cultures, and nations that could be used to build common ground <u>Collective</u>: build integrative capacity by revealing ways to make connections across differences to support research collaboration that would advance the project toward its objectives
Joint student supervision	<u>Focal</u>: International, Intercultural, Interdisciplinary, Interorganizational (each student had to coordinate input from supervisors whose perspectives reflected different cultures, nations, and organizations) <u>Peripheral</u>: Interpersonal	<u>Individual</u>: enhance integrative consciousness by requiring students to coordinate advice and direction that reflected a number of categories of difference <u>Collective</u>: N/A
Joint data analysis	<u>Focal</u>: Interdisciplinary (the focus of training and experience in the field was on data types that differed across disciplines) <u>Peripheral</u>: International, Intercultural, Interpersonal (by creating meaningful opportunities for students to collaborate, they learned how to work with different	<u>Individual</u>: training day exercises and fieldwork increased individual awareness of disciplinary differences <u>Collective</u>: exercises and fieldwork enhanced integrative capacity by

	people who represented different cultures and nations)	enabling students to better integrate across their disciplinary differences
Joint manuscripts	Focal: Interdisciplinary (these papers required the integration of data from different disciplines), Interpersonal (students had to develop collaborative capacity as co-authors) Peripheral: International, Intercultural (these experiences exposed them to national and cultural differences that could influence the collaboration)	Individual: Manuscript writing enhanced integrative consciousness necessary for perspective-taking, which could then be applied in future integrative contexts Collective: co-authoring manuscripts with students built integrative capacity across the student team
Write shop for PhD students	Focal: Interdisciplinary, Interpersonal (this was an intensive opportunity to pursue the integrative goals associated with the joint manuscripts) Peripheral: International, Intercultural (this was an intensive opportunity to pursue the integrative goals associated with the joint manuscripts)	Individual: it was intended to help individuals improve their collaborative, interdisciplinary writing skills Collective: since they worked together as a group, it was intended to increase the integrative capacity of the team by building cohort cohesion
Student-led paper	Focal: Interdisciplinary, Interpersonal (this was an intensive opportunity to pursue the integrative goals associated with the write shop for PhD students) Peripheral: International, Intercultural (this was an intensive opportunity to pursue the integrative goals associated with the write shop for PhD students)	Individual: it was intended to help individuals improve their collaborative, interdisciplinary writing skills Collective: it was intended to increase the integrative capacity of the team by helping them collaborate effectively, sharing leadership, and making decisions collectively
Meeting of student cohorts	Focal: Interstage (the focus was on knowledge transfer between the two cohorts, which occupied different stages), Interdisciplinary (all project disciplines were involved in the meeting) Peripheral: International, Intercultural, Interpersonal (opportunities were presented to learn more about different people from different nations and cultures)	Individual: it was expected that the integrative consciousness of individual students would be enhanced by the meeting Collective: the meeting increased the number of disciplinary differences the students were asked to integrate across beyond what was included in their cohort
Toolbox workshops	Focal: Interdisciplinary, Intercultural, Interorganizational, Interstage (Toolbox prompts structured dialogue about these categories of difference in regular workshops) Peripheral: International, Interpersonal (dialogue encourages engagement and deep listening that enhance communication and builds relationships)	Individual: structured dialogue about collaborative research encourages reflexivity that builds self-understanding Collective: structured dialogue also encourages perspective-taking that builds mutual understanding and collaborative capacity.

Other activities	Focal: Interpersonal, Interdisciplinary (all of these focused on building interpersonal relationships, and most focused also on disciplinary differences) Peripheral: Intercultural, International (Cultural and national differences were also salient during these experiences)	Individual: these experiences helped students learn how to collaborate with their colleagues Collective: these activities built integrative capacity by strengthening relationships

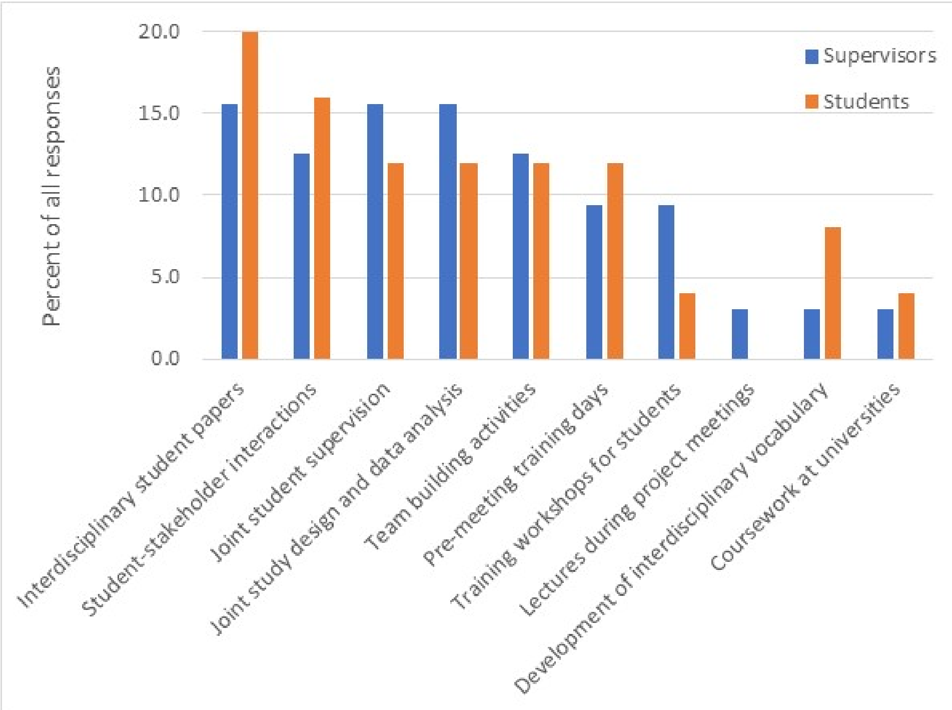
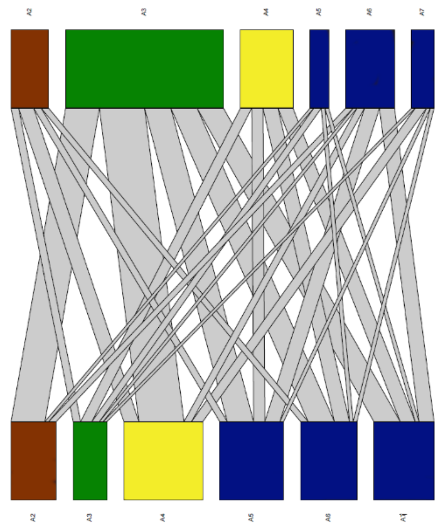


Figure 1. Summary of most valued Woody Weeds training elements in helping students integrate different disciplinary approaches, based on the frequency each was mentioned by student (n=8) and supervisors (n=10) during the interviews. Frequencies were converted into percentages to highlight patterns irrespective of differences in the number of responses from students and supervisors.



Box Figure 1. The number of information types that beginning PhD students in Phase I, each working on one of the six Activities, expected to exchange. The top and bottom boxes represent the six students. The colours of the boxes represent the four disciplines of the students leading each activity: brown = genetics, green = ecology, yellow = economics, and blue = remote sensing. The top of the figure shows information providers and the bottom receivers. The thickness of the lines connecting boxes is a crude indication of the number of information types provided to another Activity. The information in the figure was collected during the first training days, when the PhD students planned their joint studies to determine who would provide which information to whom, and when.

Box Figure 2. Publications in peer-reviewed journals based on research conducted by students of the Woody Weeds project until the end of 2023. All publications have a student as first author, except for three. Colors indicate different disciplines, and how those different disciplines were integrated in the paper is also described. MSc and PhD students are identified in the codes and each other author is identified with letters.

doi	Co-authors	How integration resulted in outcomes of these co-authored publications
10.1016/j.indic.2023.100284	MSc4, MSc5, C, D, E	A social scientific study of willingness to adopt land management practices using a socio-economic methodology informed by ecological understanding of invasive plant species
10.1016/j.scitotenv.2022.160833	PhD2, G, H, I, J, K, D	An ecological study that compares an invasive tree species to a native tree species in terms of water consumption, combining concepts and techniques from forest ecology and hydrology, yielding socio-economic implications for rural livelihoods
10.1186/s43170-023-00163-5	L, PhD1, MSc3, O, P, Q, R, S, T, U, PhD8, W, X, Y, D	An ecological study of management and restoration practices used on *Prosopis* in three countries in Eastern Africa, with economic impact on livelihoods integrated as motivation for the study and evaluation of the findings
10.3390/land11040550	PhD7, D, AA, AB, PhD3, AD, AE, AF	Geographic study that uses remote sensing results from a previous project study to identify study areas and then a model integrating socio-economic, environmental, and economic factors to understand land use decisions and determine policy recommendations
10.1080/1747423X.2022.2128914	PhD7, D, AA, AB, PhD3, AD, AE, AF	This article integrates ecological understanding of invasion dynamics and mapping techniques from remote sensing to identify spatiotemporal invasion trajectories and argue for a policy conclusion concerning collective management at the landscape scale
10.1002/pei3.10090	PhD6, AH, AD, L, D, Q	This is primarily an ecological study that uses a pot-based experimental design to integrate soil chemistry and soil biology in evaluating the impact of Lantana camara on maize and cassava growth in Tanzania
10.1016/j.ecolind.2022.108748	PhD1, PhD5, L, PhD2, AJ, AK, AE, AD, PhD3, D	This paper integrates ecological data and socio-economic data using an econometric model and a nested sampling design to determine whether local stakeholders' perceptions of the impacts of *P. juliflora* aligned with the ecological data
10.1111/ecog.05541	PhD4, D, AM, AN	This ecological study integrates ecological and genetic methods to assess what characteristics explain why only one of two closely related species is invasive in Eastern Africa
10.1002/pan3.10197	PhD5, D, L, AO, PhD2, AE, G, AP	This study integrates social science data about stakeholder priorities with ecological data about the impact of *P. juliflora* on ecosystem services to assess the net overall impact of this invasive tree on stakeholder benefits
10.1038/s41598-021-81776-6	PhD2, G, H, I, J, D	This eco-hydrological study sequentially integrates ecological and economic methods to determine water use by *P. juliflora* stands and its value, motivating land management recommendations
10.1111/1365-2664.13854	L, PhD1, PhD3, E, AD	Using techniques from ecology, remote sensing, and economics, this paper integrates ecological, social, and economic geodata by modeling the financial impact of land management strategies on local stakeholders
10.1002/ece3.6256	MSc2, Q, AR, AS, D, L	This ecological paper presents three experimental studies of the relationship between the spread of alien plant species and the recruitment of native tree species, integrating results to ground management recommendations
10.1038/s41598-020-77126-7	PhD3, AT, AU, AD, L, AV, AE, PhD5, D	By integrating remote sensing data with methods from soil science and ecology, the authors argue that grassland restoration offers more advantages than the introduction of alien tree species in replenishing soil organic carbon
10.1093/aobpla/plaa069	PhD4, D, AM, AW, AX, AY, AZ, AN	Drawing on information from invasion biology and ecology, this genetic study provides insights into the taxonomic uncertainty of non-native Prosopis species, yielding results with implications for land management
10.1186/s13570-020-00174-1	MSc1, AJ, AK	In this disciplinary study, rural households in the Afar region of Ethiopia were sampled concerning their perceptions of P. juliflora using techniques from agricultural economics, yielding results that grounded sustainable management recommendations
10.1002/ecs2.2987	AD, AG, E, PhD5, BB, PhD3, PhD2, Y, D	By integrating two modeling techniques for niche analysis and data from ecology and remote sensing, this paper generates management implications by identifying the current and future habitats of two invasive alien plant species
10.1016/j.ecoser.2019.101055	PhD5, PhD1, D, AO, G, AE, AD, AJ, BC, PhD3, PhD2, L	By integrating ecological data and sociological data and then scaling up using techniques of remote sensing, this study uses *Prosopis* invasions as a model system to reveal relationships among the supply and use of ecosystem services that are relevant for land use management
10.1111/1365-2745.13268	PhD5, D, L, MSc1, AE, BE, PhD3, PhD2, AO	This study integrates ecological and statistical modeling techniques to assess the direct effects of *Prosopis* invasion and the indirect effects mediated by changes in biodiversity and ecosystem functioning, revealing that both *Prosopis* and biodiversity are drivers of global change
10.3390/rs11101217	PhD3, BB, D, AU, AT, AE, AV, AD	Informed by an ecological understanding of both Prosopis and the region, this study uses remote sensing techniques to investigate the spatial evolution and dynamics of a Prosopis invasion and its effects on land use and land cover (LULC), providing baseline data for policy management
10.1016/j.scitotenv.2019.04.220	PhD2, I, G, J, K, PhD1, D, AD	This study integrates remote sensing techniques to identify LULC changes over the decades of a *Prosopis* invasion, economic techniques to determine its impact on ecosystem services, and social scientific techniques to determine stakeholder perspectives on LULC changes
10.1002/ece3.4919	PhD2, I, AD	Motivated by the need to provide fractional cover information for invasive alien plants (e.g., *P. juliflora*) for management decisions, this paper compares the performance of five machine learning algorithms (MLAs) by integrating remote sensing and ecological methods and data
10.1038/s41598-018-36587-7	PhD2, D, I, G, J, K, AD	By integrating an MLA, remote sensing techniques, and plot-based ecological data, this study determines distribution and cover of a *Prosopis* invasion, explains the current distribution, and identifies drivers of future invasion, yielding critical information for resource management
10.1016/j.jaridenv.2018.07.001	PhD1, AJ, AK, D	Informed by the ecology of Prosopis invasions in dryland ecosystems, this econometric study using the choice experiment method finds that the negative effects of the invasion in two Eastern African regions outweigh the positive effects
10.1186/s13570-018-0124-6	PhD1, AJ, AK, PhD2, D	Using ecological data and remote sensing techniques, this econometric study shows that *Prosopis* has a positive effect on household livelihood up to a certain invasion density, after which it becomes negative, yielding a complex set of integrative management recommendations

Genetics
Ecology
Economy
Remote sensing
Geography
Outside consortium