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Training macrosystems scientists requires both interpersonal and technical skills

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Macrosystems science strives to integrate patterns and processes that span regional to continental scales. The scope of such research often necessitates the involvement of large interdisciplinary and/or multi-institutional teams composed of scientists across a range of career stages, a diversity that requires researchers to hone both technical and interpersonal skills. We surveyed participants in macrosystems projects funded by the US National Science Foundation to assess the perceived importance of different skills needed in their research, as well as the types of training they received. Survey results revealed a mismatch between the skills participants perceive as important and the training they received, particularly for interpersonal and management skills. We highlight lessons learned from macrosystems training case studies, explore avenues for further improvement of undergraduate and graduate education, and discuss other training opportunities for macrosystems scientists. Given the trend toward interdisciplinary research beyond the macrosystems community, these insights are broadly applicable for scientists involved in diverse, collaborative projects.

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Macrosystems science – the study of the complex interactions of ecological systems over large spatial and temporal scales (sensu Heffernan *et al*. 2014) – has flourished over the past decade, largely catalyzed by funding opportunities from the US National Science Foundation (NSF) to support macrosystems science (eg the Macrosystems Biology program). A major goal of macrosystems research is to advance understanding of interconnected ecological patterns and processes that operate from regional to continental scales, which are difficult to identify through individual studies conducted over short time periods. Consequently, macrosystems research requires collaboration among scientists who collect, manage, and analyze complex, multivariate datasets using advanced computational, statistical, and modeling techniques (eg Cheruvelil *et al*. 2014; Goring *et al*. 2014; Heffernan *et al*. 2014). Such collaborations are most effective and productive when open communication is fostered, conflict management skills are put into action, and shared goals are integrated into research activities (Cheruvelil *et al*. 2014; Cheruvelil and Soranno 2018). These interpersonal skills, along with core research-based technical skills, increase individual and group efficiency and consequently the probability of success of macrosystems projects, which are often composed of heterogeneous teams of researchers spanning multiple disciplines, institutions, and career stages. However, formal training in the interpersonal skills needed to cultivate high-performing teams, including leadership, communication, and conflict resolution, is rarely included in US undergraduate and graduate training programs (but see Read *et al*. [2016]), much less acknowledged or rewarded at later career stages (eg Goring *et al*. 2014). As such, whether or how macrosystems researchers – especially early career scientists – are gaining experience and proficiency in the suite of skills needed to conduct macrosystems research remains largely unknown.

Here, we propose a conceptual framework outlining the skillsets that are crucial for high-quality, interdisciplinary research on complex systems, such as macrosystems research

In a nutshell:

- The multi-institutional, interdisciplinary, and collaborative nature of macrosystems research requires a set of distinctive but infrequently taught skills
- Interpersonal skills, project and data management prowess, and sound leadership were consistently identified as necessary to carry out successful macrosystems projects and for group members to thrive
- Early career macrosystems participants reported receiving more training than senior personnel in many of the necessary skills, but indicated these skills were often self-taught
- Training initiatives that blend interpersonal and technical skills are crucial for improving career-readiness, project efficiency, and diverse and high-impact macrosystems science

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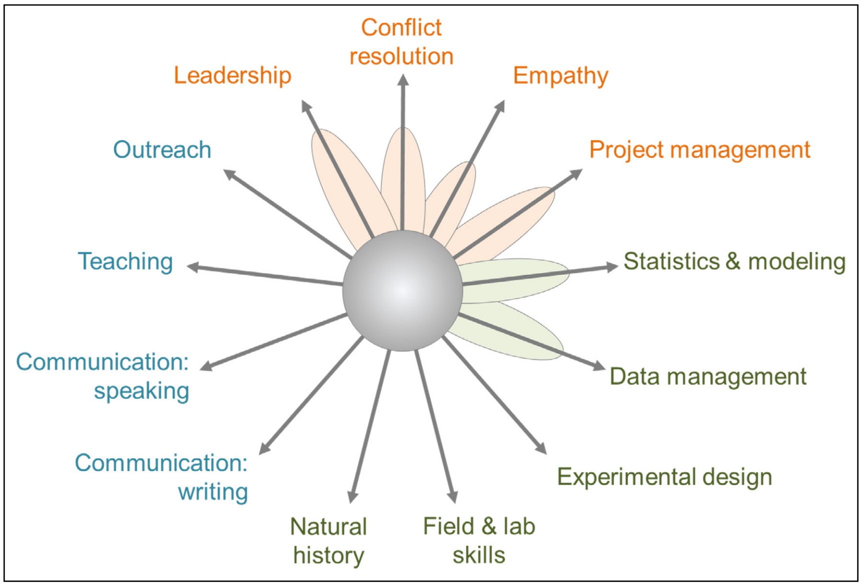

Figure 1. Conceptual framework: important skills for conducting macrosystems research. A level of core competency (gray circle) is needed in a range of skills related to personnel and management (orange), technical and scientific research (green), and communication and outreach (blue), but among these, training in certain interpersonal and technical skills may need to be supplemented (colored ovals) to thrive in macrosystems projects.

(Figure 1). The framework, which was developed by early career and senior participants at the 2018 Macrosystems Biology Principal Investigators meeting based on their experiences in macrosystems projects, proposes that a level of "core competency" (that is, minimum working knowledge and capability; sensu Brewer and Smith [2011]) is needed in a range of skills related to personnel and management, technical and scientific research, and communication and outreach (Figure 1). Among these focal areas, we hypothesized that education in certain interpersonal skills is least likely to be available in early career training programs. We present the results from a survey of participants in macrosystems research about the importance of these skills, as well as the availability and sources of training to become proficient in these skills. We then explore models for effective ways to provide this crucial training for conducting collaborative and interdisciplinary research, paying special attention to early career scientists and opportunities to enhance teaching approaches that provide students with early exposure to macrosystems science.

Macrosystems participant survey

To assess perceptions of the types of skills identified in our conceptual framework (Figure 1) as necessary to thrive in macrosystems research and to understand the availability of skills training, we conducted a survey of past and current NSF-funded macrosystems participants. The survey collected experiential data on the opportunities for and challenges of training participants in macrosystems research, using a combination of closed- and open-ended questions (see WebPanel 1 for formatted survey questions). The survey asked for general information about the research backgrounds and career stages of respondents at the time they participated in macrosystems projects. Career stages were grouped as early career (5 years or less post-PhD or other terminal degree), senior (more than 5 years post-PhD), or both in cases where involvement in macrosystems projects spanned both early career and senior roles. This career stage cutoff was based in part on the initiation of NSF Macrosystems Biology funding in 2010, to roughly divide respondents into primarily trainees on macrosystems grants or primarily principal investigators (PIs)/project leaders on those grants. Specific questions about the skills needed for macrosystems projects and the degree of training received in those skills were also included in the survey (Figure 1).

Survey responses were collected (via Survey Monkey) over a 3-week period in April and May 2018. Respondents were solicited by distributing the survey link to 50 current and former PIs of NSF-funded macrosystems projects with a request that it be distributed to their project members. We do not have data on whether and to how many project members the survey was shared. The survey was also sent directly to 54 predominantly early career macrosystems project participants who were members of our (the authors of this paper) current and previous macrosystems research teams. Participation was voluntary and responses were kept confidential, in accordance with Institutional Review Board protocols.

Of the 60 respondents who returned at least partially completed surveys, 51 completed all of the questions. Survey respondents encompassed a range of macrosystems participation in terms of career stage, duration of involvement with macrosystems projects, project size, and disciplinary expertise represented in their projects (WebTable 1). More than half of all respondents ($n = 44$ of 60, 73%) were working on macrosystems projects at the time of the survey. Projects tended to be large; a majority of the 60 respondents reported that their macrosystems team had ten or more participants ($n = 44$, 73%), and there was usually at least one other project member at the same career stage at the time of project initiation ($n = 53$, 88%).

Training challenges in macrosystems-relevant skills

Technical and management skills are key in macrosystems research

Survey responses revealed commonalities among early career and senior personnel macrosystems participants regarding the suite of skills that were identified as most important for success in a macrosystems project (Figure 2), as well as whether and where training in the skills was obtained. Both technical and management skills were ranked highly for their importance, with four of the top five most critical skills shared among early career and senior macrosystems participants (WebFigure 1a). These skills – project management, data management, written communication, and statistical analysis and modeling – were all rated as "Very important" or "Extremely important" (WebFigure 1a). Respondents who had participated as senior personnel in macrosystems projects also included leadership in their top five skills, while respondents who had only participated as early career personnel included spoken communication in their top five skills. Some skills were consistently ranked as less important for success in macrosystems projects, including natural history, outreach, and teaching. These three skills were consistently rated as "Slightly important" or "Moderately important" to macrosystems success by respondents across career stages.

Respondents also identified a number of skills that they consider important for macrosystems researchers that were not explicitly included in the survey. Many of these focused on interpersonal skills; for example, facilitation, teamwork, and collaboration, as more nuanced aspects of leadership and conflict management, were noted as being particularly valuable skills. Numerous respondents also identified communication across disciplines as a specific skill they saw as necessary for working within a macrosystems research team. Only one respondent emphasized additional technical skills as important for their macrosystems research, highlighting the importance of version control and reproducible research as essential sub-skills of data management and statistics.

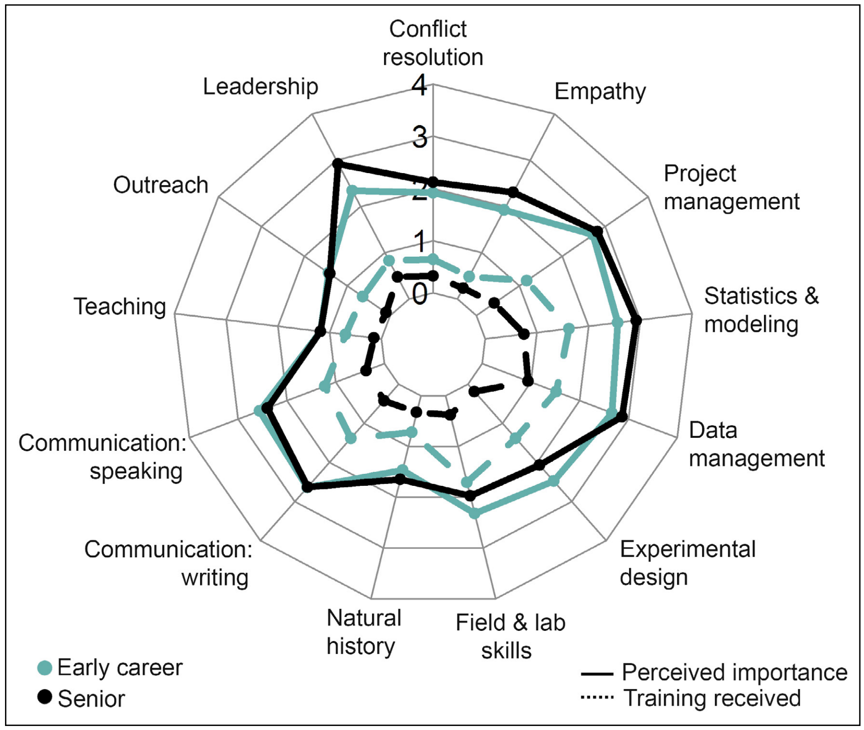

Figure 2. Perceived importance (solid lines) and training received (dashed lines) for selected skills among survey respondents. Points represent weighted average scores per skill for each career stage; responses were based on a Likert scale from 0 (not important/no training received) to 4 (extremely important/extensive training received). Colors correspond to respondent career stage while participating in macrosystems projects (teal = early career only; black = senior only).

Mismatches exist between skills needed and training received

Our survey results revealed gaps and mismatches between the skills perceived as most important for success in macrosystems projects and whether there was training available and received in those skills (Figure 2; WebFigure 1b). For senior personnel, the five skills for which they received the most training as part of their macrosystems projects mirrored the top five skills deemed most important; however, the average level of training reported for those skills was very low. Furthermore, "no training" was the most frequent response for most skills (Figure 2; WebFigure 1b). For example, despite the importance of leadership skills reported by senior personnel, the majority indicated that they had received very little leadership training (Figure 2; WebFigure 1b), most of which was self-taught (Figure 3).

Early career participants reported higher levels of training in all skills than did senior personnel (Figure 2; WebFigure 1b). Among both early career and senior participants, the amount of training provided by institutions in the form of formal courses was low and tended to focus on a small subset of skills, including teaching, experimental design, and statistics and modeling (Figure 3). For interpersonal skills, including leadership, conflict resolution, and empathy, early career participants received more training than did senior personnel. However, overall training in these skills remained low, with over half of early career participants reporting that their training was self-taught or that they did not receive training (Figure 3). In cases where interpersonal skills were not self-taught, early career participants tended to receive training through short workshops and training sessions, or through advisors and other project personnel in informal settings (Figure 3). However, as one early career participant noted, ongoing practice in these skills was limited: "outside experts were brought into our workshops for brief sessions on interdisciplinary team training, conflict resolution, statistical training, and data management, which were very helpful. The training was brief and not necessarily sustained, though".

Overall, the experiences shared by survey respondents suggest that formalized training and sustained practice in management and interpersonal skills could advance the capacity of macrosystems researchers at all career stages. Specifically, senior participants recognized the importance of mentor training to support early career personnel on their projects. One

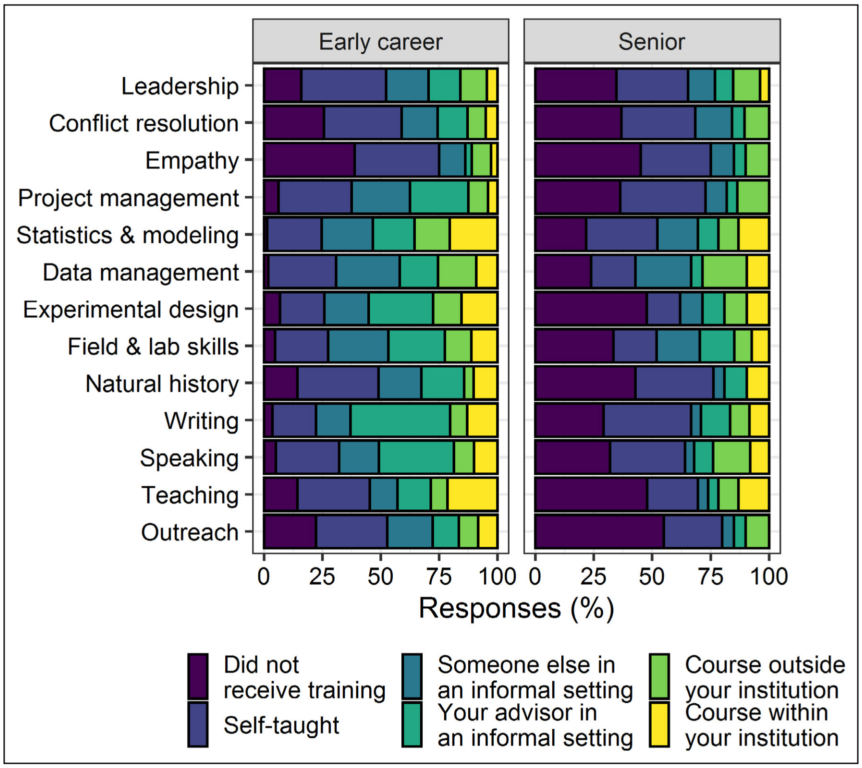

Figure 3. Ways in which survey respondents received training in surveyed macrosystems-related skills. Panels represent respondent career stage while participating in macrosystems projects.

respondent shared that they lacked training in "organization, project management, [and] leadership", and filled that gap by "reading and emulating successful peers". More generally, senior personnel acknowledged that they would benefit from training in the suite of skills needed to thrive in macrosystems research; according to one respondent, "generally speaking, it was assumed one had the skills needed for macrosystems [research] going into a macrosystems [project]. Often, this is not the case". To ensure early career macrosystems participants are primed to thrive in their respective research, "we must find ways to supplement/complement the training that can happen within an institution or lab or group that match the needs of the team", because "given the trend in ecology toward 'working groups', particularly remote, interdisciplinary ones, team facilitation is becoming increasingly important for research success". (Readers' note: each quote in this paragraph was from a different respondent.)

While our survey data provided valuable insights into the experiences and perceived training needs of macrosystems project participants, and early career participants in particular, there are limitations to our dataset that constrain the scope of our interpretations. Our primary limitation is the number of respondents (60 responses, 51 of which were complete) relative to the number of participants in NSF-funded macrosystems research to date (there were approximately 105 NSF-funded macrosystems projects, workshops, and research coordination networks as of the survey date). In addition, the survey results may have been biased toward participants funded by NSF macrosystems grants at the time of the survey, as contacted PIs and project leaders may have been more likely to share the survey with members of their macrosystems team and researchers active in macrosystems projects may have been more likely to have responded to the survey than those who have completed their projects. Moreover, the survey was not designed to catalogue courses or workshops that did address diverse training needs. Nonetheless, this first snapshot of needs and gaps is useful for motivating the development of future training programs.

Opportunities to improve and expand macrosystems training

Skill development plans help focus training priorities

Although survey respondents ranked many skills as being "Very important" or "Extremely important" for success in macrosystems research (WebFigure 1a), because both time and resources are limited during early career training programs (ie graduate school and postdoctoral training) it is unlikely that participants will become maximally proficient in all skills during that time. Therefore, to prioritize training efforts, students and mentors participating in macrosystems research should work together to identify the skills that are most relevant to the students' role in the project, as well as to their long-term goals, and focus on development of a blend of technical (eg statistics, data management) and interpersonal (eg project management, communication, empathy, leadership) skills. To encourage this, senior personnel should incorporate strategic planning for skills development early in the involvement of students and other early career participants, using the framework proposed here as a starting point for such discussions. In practice, this planning may include the use of surveys, questionnaires, and interviews to gather information about the experiences and skills of macrosystems project members and the dimensions in which they would like to develop skills. From this, senior personnel can identify gaps in the core competencies of their team (Figure 1) and then plan for targeted trainings.

We recommend the use of customized mentoring plans in which students and supervisors develop timelines and specific steps to learn and practice prioritized skills. While mentoring plans for postdoctoral researchers are already required for macrosystems proposals (eg NSF 2018), the use of mentoring plans for student trainees (eg the American Association for the Advancement of Science [AAAS] Individual Development Plan; Fuhrmann *et al.* 2019) would help senior project personnel ensure that early career team members are gaining the skills needed for both the project and their individual development. Together, these approaches for honing a subset of skills, building collaborative networks of individuals with complementary expertise, and participating in targeted training programs may help to amend the perception commonly held by early career participants that they must attempt to master every skill.

Cohorts help participants hone and practice relevant skills

Early career macrosystems scientists can benefit from working with a cohort of their peers to build and practice team science skills that transcend traditional discipline-specific training received as part of a university or college degree program. Successful teams embrace diversity, promote inclusion, and foster interpersonal skills to help members work toward a shared goal (Cheruvelil *et al*. 2014) while at the same time reinforcing the importance of clear communication and accountability for team members (Bennett *et al*. 2010; Cheruvelil *et al*. 2014). High-performing teams can have greater collective intelligence than individuals, and groups with social sensitivity, active listening, facilitation training, and higher participant diversity tend to be particularly effective (Wuchty *et al*. 2007; Woolley *et al*. 2010; Goring *et al*. 2014).

Funding agencies have become increasingly aware of the need to support new training models that include the development of necessary skillsets by early career scientists to facilitate successful macrosystems research (WebTable 2). Cohorts can consist of groups of graduate students with overlapping interests at the same institutions (eg the former NSF Integrative Graduate Education and Research Traineeship program, replaced by the NSF Research Traineeship program; Morse *et al*. 2007; Moslemi *et al*. 2009) or by students involved in a new multi-institution project. These experiences can provide cohort members with support in navigating graduate school, peer learning opportunities, and idea generation and communication regarding members' individual research projects, even if they are not part of any intra-cohort collaborations.

Cohorts can also be formed as interdisciplinary networks of early career scientists from different institutions, as was the case for participants in the Lotic Intersite Nitrogen Experiments (LINX; LINX collaborators 2014). More recently, the Global Lake Ecological Observatory Network (GLEON) Fellowship Program brought together diverse groups of graduate students to learn both technical and interpersonal skills, with a dual emphasis on data management and analysis and collaborative team science (Read *et al*. 2016). A key to the success of the GLEON Fellowship Program was the integration of team science approaches, which included face-to-face meetings to build trust among the fellows for sharing new ideas, skills, and strategies for tackling challenging scientific questions (Hampton and Parker 2011; Read *et al*. 2016). Each cohort member brought a distinctive skillset to the program formed from their unique background knowledge, institutional training, and prior experience in collaborative research. Although interdisciplinary cohorts have greater potential for conflict than discipline-specific cohorts due to philosophical differences (Eigenbrode *et al*. 2007; Goring *et al*. 2014), GLEON Fellows discussed and practiced specific strategies to minimize this risk (O'Rourke and Crowley 2013). By leveraging a network of peers with different expertise, GLEON Fellows produced multiple scientific products while participating in the program (eg Read *et al*. 2015; Winslow *et al*. 2016; Dugan *et al*. 2017), and established a strong sense of camaraderie among cohort members that has led to ongoing collaborations on research projects and workshops at professional meetings.

Undergraduate education expands scope of macrosystems

Integrating macrosystems ecology into undergraduate education provides a rich opportunity to train students in the skills needed to study complex, real-world systems early in their careers, contributing to preparation for more advanced training during graduate education. Skills identified in the framework as essential in macrosystems research are well aligned with recommendations presented in the AAAS/NSF Vision & Change for Undergraduate Biology report (Brewer and Smith 2011), such as increasing student experiences with scientific practices and developing quantitative competencies. The Vision & Change framework emphasizes the importance of macrosystems-relevant concepts and practices, including systems thinking, modeling and simulation, interdisciplinarity, and connecting science to society (Brewer and Smith 2011). Incorporating macrosystems-scale data into undergraduate curricula can also help build students' skills in data management, statistics, and modeling, which can be translated and applied by students to future careers both within and outside academia.

Data exploration in the classroom contributes to improving competency in data organization, visualization, analysis, interpretation, and other quantitative skills (Aikens and Dolan 2014). Although the availability of open-access data is increasing, the typical barriers to teaching reform (time, training opportunities, and incentives) have affected the adoption of teaching resources that build data skills (Brewer and Smith 2011; Brownell and Tanner 2012; Corwin *et al*. 2019). These challenges are particularly acute for the integration of macrosystems-scale data, as acquiring the skills needed to manipulate and analyze large-scale datasets can be a hurdle for both educators and students. However, incorporating large datasets and research questions into undergraduate biology and ecology curricula provides important value for improving students' conceptual and practical data skills, justifying the investment of time and resources needed to develop teaching materials and capacity (Langen *et al*. 2014; O'Reilly *et al*. 2017; Farrell and Carey 2018). Indeed, some macrosystems projects have already begun developing resources to integrate systems thinking, modeling, and simulation into undergraduate curricula (WebPanel 2).

The multidimensional skills embedded within macrosystems research (Figure 1) also present opportunities for undergraduates involved in macrosystems research to personalize their professional development goals by emphasizing strengths and identifying areas for growth. We suggest that the framework depicted in Figure 1 could be used as a mentoring tool to help students "see their whole selves" as scientists, recognizing in particular that technical skills represent a subset of components necessary for successful collaborative and interdisciplinary research. For example, this framework could help students who have developed strong skills in leadership or empathy, but lack technical expertise, to recognize that their skills are a valuable component of scientific research.

Faculty mentoring networks build communities of practice

The development of faculty mentoring networks (FMN) can help provide training and support for instructors interested in teaching macrosystems skills to their students. While the importance of mentoring and collaborative peer communities for educational reform in higher education is well documented (Lindholm 2003; Zellers *et al.* 2008), these initiatives typically occur within individual academic centers and departments (eg Calderwood and Klaf 2015). To address this need, the FMN model of the Quantitative Undergraduate Biology Education and Synthesis (QUBES) project creates distributed communities of educators by providing online professional development in quantitative teaching strategies and classroom resource implementation (eg Bonner *et al.* 2017). The advantages of this approach include continued guidance throughout the development and use of new teaching strategies and building a community where participants both gain and share new resources. In addition to the development of new teaching modules, faculty can customize published modules to match the skill level of students in their courses. These adapted materials can then be republished and shared with the teaching community, creating a teaching resource library that allows materials to be updated, shared, and tracked over time. Building this online community allows for the wider implementation, continuous cycling, and iterative improvement of data-centric educational resources (LaMar and Donovan 2017).

In spring 2018, members of the National Ecological Observatory Network (NEON) partnered with QUBES to create a Data Education FMN, which allowed faculty participants to leverage QUBES project infrastructure (Donovan *et al.* 2015) to gain experience developing modules that build data skills using NEON data. The quantitative skills range from introducing students to large datasets to best practices in managing and summarizing data to advanced explorations using coding to manipulate, analyze, and visualize NEON data. To date, NEON Data Education FMN members have produced and adapted at least 14 teaching modules that are available for use by the macrosystems and education communities (https://qubeshub.org/community/groups/neon/educational_resources). Future iterations of this FMN will expand the range of available modules each semester, as the full catalogue of NEON data is now available across the US. The NEON Data Education FMN highlights how curriculum development, faculty training, and student engagement can be successfully integrated to increase the inclusion of macrosystems-scale data and skills in the classroom at an earlier stage.

Additional strategies for macrosystems training

From workshops to multiyear fellowships, there are numerous opportunities to hone the specific macrosystems-relevant skills included in our framework (WebTable 2). Senior personnel in macrosystems projects have also developed strategies to help their project's early career participants gain the skills needed to succeed. Survey respondents reported integrating lectures, workshops, and hands-on activities into their macrosystems projects in topics ranging from team science skills to advanced statistics. In addition, coordinated initiatives at NEON, for example, are providing early career researchers with opportunities to learn data skills and experience macrosystems research through internships and other trainings (WebPanel 2).

Benefits of macrosystems involvement for early career scientists

Despite the challenges early career participants may face, involvement in macrosystems projects represents an opportunity for experiential learning in collaborative, interdisciplinary science (Goring *et al.* 2014), with potential long-term benefits for career development. Large projects can introduce early career researchers to a broader array of scientific topics, as well as provide more opportunities to contribute to scientific products (eg collaborative manuscripts, conference presentations, statistical packages; Read *et al.* 2016) and develop larger networks of potential collaborators for future projects. As one survey respondent noted, "My involvement in macrosystems projects helped me build the network of collaborators [and] cohorts of colleagues with whom I hope to continue to [work] throughout my career". Respondents often remarked on how participation in macrosystems projects led to increased proficiency in data management, writing, project management, and leadership: skills that were reported among the most beneficial and most frequently used in the respondents' current positions (Figure 2; WebFigure 1c). Specifically, respondents shared that macrosystems project experience gave them "confidence to know that I could succeed in large, complex projects, by providing the skills in both R-based data analysis and project management/leadership/empathy that have kick-started my work in my current position" and that "the collaborative and technical skills were viewed very favorably when interviewing for jobs". Working on macrosystems projects can therefore be helpful in preparing early career participants for the next stage of their career when project leaders promote training in technical and interpersonal skills to foster high-performing collaborative teams (Cheruvelil *et al*. 2014).

Conclusion

Participants in macrosystems projects represent a group of researchers who tend to work in particularly large and interdisciplinary teams. As such, learning from their experiences can provide insights about training needs for interdisciplinary scientists more broadly, beyond the macrosystems community. We used our conceptual framework of core competencies and focal skills for interdisciplinary research to survey participants in macrosystems research. Our survey highlighted that researchers require training in both technical and interpersonal skills to thrive in interdisciplinary, multi-institutional macrosystems teams. Although gaining high levels of expertise in all skills may not be possible, attaining core competency is important to facilitate effective collaboration among team members. Formal training in interpersonal skills is lagging compared to training opportunities in more technical skills, but opportunities are increasingly available through short courses and fellowship programs to hone leadership, project management, and other essential interpersonal skills. On the basis of our survey results, as well as our personal experiences, we identified an increasing need for inclusive, sustained skills training opportunities, especially for graduate students. In addition, further development of training programs focused on undergraduate education and faculty mentoring networks is needed to facilitate continued macrosystems science discovery and meet the need for technically proficient and collaborative researchers.

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Supporting Information

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Wrapped up in plastic

Plastic is a versatile material appreciated for its durability and wide applicability in everyday products like food containers, beverage bottles, and medical devices. However, mismanaged plastic waste frequently washes into streams and rivers, where it is consumed by various organisms. To help avoid mortality from potentially crushing predators such as juvenile dragonflies (Odonata) and brown trout (*Salmo trutta*), the aquatic larvae of caddisflies (Trichoptera) build protective cases. Interestingly, we recently discovered that caddisfly (*Lepidostoma basale*) larvae use plastic waste as a material for case-building (*Aquat Biol* 2019; doi.org/10.3354/ab00711). During a laboratory experiment, the caddisfly larva shown here was offered blue microplastic particles (<5 mm) of polyethylene terephthalate (PET, a plastic type commonly used in beverage bottles), along with gray sand grains. After having been removed from its original case composed of natural materials, the larva immediately started building a new case using the PET particles, and then later incorporated the sand grains into its case. The experiment revealed that caddisfly case stability decreased with increasing PET particle load (*Environ Sci Pollut R* 2020; doi.org/10.1007/s11356-020-08790-5), suggesting that plastic waste incorporation in caddisfly cases may reduce protection from predators and, thereby, influence predator–prey interactions. Fish often consume caddisfly larvae along with their cases, and microplastics are known to cause inflammatory responses in fish. The question that remains unanswered is how microplastics in caddisfly larval cases may affect predatory fish.

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