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Synthesis

Toward an ecology of disasters: a primer for the pursuit of ecological research on disasters

Nathaniel L. Gibson [1], Elizabeth A. Green [1], Guido A. Herrera-R [1], Sarah J. Love [1], Sophia C. Turner [1], Maryrose Weatherton [1], Alexandra S. Faidiga [1], Amy R. Luo [1], Michael L. Ngoh [1], Eric Shershen [1], Hyun Seok Yoon [1] and Michael J. Blum [1]

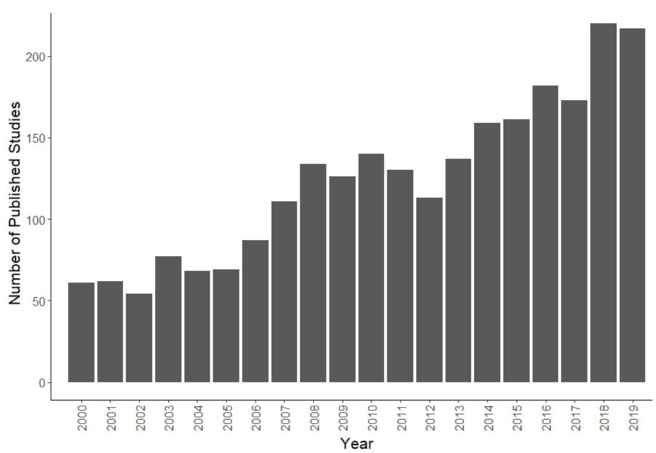
ABSTRACT. Ecologists are increasingly becoming interested in disasters, reflecting growing recognition that disasters can present exceptional opportunities to advance fundamental knowledge and appreciation for how ecological research can aid affected communities. Attempts to achieve both objectives can, however, create fractious tensions that result in unfavorable opinions about ecologists and diminish the perceived value of ecological research. Here we outline the merits and perils of "disaster ecology." We first examine how ecologists have engaged in the disaster cycle, focusing on trends in training and education, research funding, and the prevalence of community engagement in ecological research. We illustrate the global asymmetries in educational opportunities, how funding of opportunistic pursuits can engender discord, and how the discipline has not yet widely embraced approaches that foster community engagement. We then provide a prospectus for improving best practices to advance knowledge and support humanitarian missions. Pathways toward improvement and innovation begin with taking steps to increase interdisciplinary coursework and trainings that prepare ecologists to work with first responders and stakeholders. Expanding the base of funding sources and supporting research spanning the disaster cycle would foster broader integration of ecological expertise into decision making. Greater adoption of community-engaged research approaches also would better address community and stakeholder concerns as well as strengthen the discipline by broadening representation and participation.

Key Words: *community engagement; disaster cycle; global change; pedagogy; research funding trends; social-ecological systems*

INTRODUCTION

Scholars and practitioners pursuing work on ecology, i.e., the study of relationships among organisms and of organisms and the environment, are increasingly becoming interested in disasters, as reflected in the growing number of topical studies published over the past 20 years (Fig. 1). Interest is on the rise in part because it appears that disasters are becoming more frequent and intense with global trends in climate and human demography (Webster et al. 2005, Coleman 2006, Khan et al. 2008, Bender et al. 2010, Banholzer et al. 2014). Increasing interest also reflects greater recognition that disasters can present exceptional opportunities to advance fundamental knowledge of ecological phenomena, including coupled dynamics that can arise from human-environment interactions (McGinnis and Ostrom 2014). Moreover, as work on disasters has grown, so has appreciation for how ecological research can aid affected communities. It is becoming evident that ecologists can assist with humanitarian missions by supporting first responders, affected communities, and decision makers who shape public policy, evidenced in part by the synthesis of translational ecology (Hallet et al. 2017) and well-established practices within conservation ecology (Berkes 2004). There is also growing appreciation, however, for the possibility that naïve and fractious interactions (intentional or not) can marginalize valuable contributions and lead to unfavorable public opinions about ecologists and ecological research. Here we outline both the merit and perils of "disaster ecology" by first examining how ecologists participate in disaster response efforts with a focus on education, funding, and research paradigms. We then provide a prospectus for how ecologists can advance knowledge and promote social equity before, during, and after disasters.

Fig. 1. The number of disaster-related ecological studies has increased by > 350% over the past 20 years.



Though natural (e.g., hurricanes and earthquakes) and technological (e.g., oil spills) disasters often transform the social-ecological landscapes of affected areas, it is unusual to find ecologists embedded among first responders or to otherwise find ecologists directly assisting with recovery efforts in a professional capacity. Although this could (and arguably should) be more common, oftentimes ecologists adopt a more conventional role of conducting discovery-driven research. Doing so may sometimes afford secondary opportunities to pursue nominally defined sociocultural goals, e.g., restoring affected ecosystems to foster recovery and reduce the likelihood of future disasters. In

[1]Department of Ecology and Evolutionary Biology, University of Tennessee

part, decisions made to assume the conventional role of a research scientist can be attributed to structural constraints related to the availability of (1) training in disaster preparedness and response, and (2) funding for ecological research before and following disasters. It also reflects (3) the relative novelty of community engaged research paradigms, which have yet to be widely adopted by the ecological research community. Understanding and resolving these and associated concerns could increase the likelihood that discovery- and challenge-driven research yields more meaningful sociocultural outcomes and promotes broader integration of ecological expertise across the full disaster cycle.

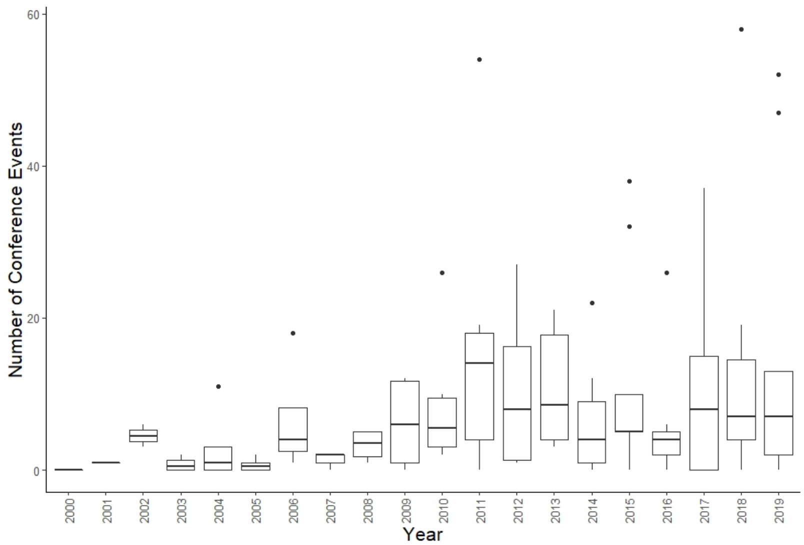
Disaster ecology is not disturbance ecology

Ecologists tend to view disasters through the prism of disturbance theory, even though conditions often depart from general theoretical constructs, including expectations that humans are effectively absent from affected areas (Rael et al. 2016). Understanding how disturbance and disaster differ can lead to more informed research and more cogent support of humanitarian missions. Disturbance is broadly defined as “any relatively discrete event in time that disrupts ecosystems, community, or population structure and changes resources, substrate availability or the physical environment” (Pickett and White 1985:7). More severe events, such as volcanic eruptions or catastrophic hurricanes, have been characterized as large, infrequent disturbances (LIDs) that can result in abrupt and persistent alteration of whole landscapes (Turner and Dale 1998). These and other definitions of disturbance do not adequately capture the human dimension and coupled dynamics of disasters. Definitions of disasters implicitly consider residential communities that are embedded in affected areas. For example, disasters have been broadly defined as “a sudden event, such as an accident or a natural catastrophe, that causes great damage or loss of life” (Wirasinghe et al. 2013:3), or more specifically “a sudden, calamitous event that seriously disrupts the functioning of a community or society and causes human, material, and economic or environmental losses” (Galindo and Batta 2013:202). Examples include Hurricane Katrina in 2005 and the 2010 Haiti Earthquake, which disrupted physical, biotic, and sociocultural landscapes, resulting in widespread destruction of infrastructure and loss of life. Thus disasters can be viewed as a driver of state change, with outcomes of subsequent recovery, i.e., re-assembly, of biotic and residential communities, being contingent on site legacy, shared responses to common drivers, and potential interactions that can give rise to reinforcing feedbacks (Gotham et al. 2014, Rael et al. 2016, Sovacool et al. 2018, Hewitt 2019).

Although the timing and magnitude of disasters are difficult to predict, the progression of pre-disaster to post-disaster conditions has been well characterized and captured in a conceptual framework widely referred to as the “disaster cycle.” The conceptual framework describes the cyclical relationship between (1) pre-disaster prediction and warning, i.e., mitigation and preparedness, (2) disaster impact and immediate post-disaster relief, i.e., response, and (3) rehabilitation and reconstruction, i.e., recovery (Jayaraman et al. 1997, United Nations 2002). The preparedness-response-recovery phases of the disaster cycle are not mutually exclusive, as phase duration can vary depending on a suite of complex site-specific factors. For instance, recovery can overlap and sometimes subsume pre-disaster mitigation efforts, which often receives less attention and resources (Kates et al. 2006, Waugh 2006, Khan et al. 2008). In part, this is because it can take years to decades of resettlement and reconstruction before affected areas come to resemble pre-disaster conditions (Kates et al. 2006). Resource expenditures may, consequently, align more with the post-disaster recovery phase and overlap with pre-disaster mitigation efforts. Deficits in support for disaster mitigation and preparedness are a well-recognized concern, particularly with expectations that the frequency and intensity of catastrophic disasters are likely to rise in the future (Webster et al. 2005, Khan et al. 2008, Bender et al. 2010, Banholzer et al. 2014). This increases the associated probability that one disaster will catalyze others, as illustrated by the Fukushima Daiichi nuclear disaster being precipitated by a catastrophic earthquake and tsunami (Ohnishi 2012). Compounding disasters effectively reset the cycle and extend the recovery timeline, possibly leading to an enduring state of concurrent disaster response and recovery. As a result, there might be even stronger emphasis placed on recovery efforts, further reinforcing disparities with disaster mitigation.

Disparities in emphasis are also evident in the balance of research that ecologists have so far conducted on disasters. Ecologists have tended to focus on the recovery stages of the disaster cycle, likely because associated conditions of post-disaster environments offer opportunities to examine long-standing questions about ecosystem resilience and emerging questions about social-ecological feedbacks (Walker and Salt 2012). Increasing interest in “resiliency thinking” also has led to a boom in research aiming to improve understanding of social-ecological resilience and the rise of “new normal” conditions. For example, Hurricane Katrina triggered a surge in research on community resilience (e.g., Campanella 2006, Colten et al. 2008, Gunderson 2010) and ecological resilience (e.g., Chapman et al. 2008, Middleton 2009, Wang and Xu 2009). This work precipitated a subsequent wave of studies examining social-ecological dynamics including research on how post-disaster resettlement and land management policies have reinforced legacies of sociocultural disparities in the availability and distribution of ecosystem services and hazards (e.g., Gulachenski et al. 2016, Rael et al. 2016, Lewis et al. 2017, Peterson et al. 2020). In comparison, questions related to disaster relief, mitigation, and preparedness during earlier stages of the disaster cycle have not received as much attention from ecologists. Asymmetries can prove to be problematic; not only might it limit understanding of social-ecological dynamics, e.g., lags and feedbacks, it might also inadvertently inhibit the study of post-disaster conditions, i.e., because of limited knowledge of pre-disaster reference conditions. Practically speaking, it is not feasible to conduct baseline, i.e., monitoring and assessment, ecological research in all areas in anticipation of a future disaster, particularly unprecedented disasters like the 2020 derecho that struck the Midwestern United States. Nonetheless, advancing research to characterize baseline conditions in disaster-prone areas could prove beneficial. Further development of best practices in disaster ecology could stave off inadvertent limitations and thus afford greater opportunity to advance understanding of events and conditions with broad ecological and societal relevance.

Fig. 2. Distribution of disaster-related conference events across all sampled conferences from 2000 to 2019 (n = 113). The middle horizontal line represents the median, bars represent the first and third quartiles, vertical lines represent the minimum and maximum range relative to the quartiles, and dots are outliers.



CURRENT PRACTICES IN DISASTER ECOLOGY

An overview of current practices

Herein we provide an overview of the landscape of current practices in disaster ecology related to (1) training and education; (2) the availability and pursuit of research funding; and (3) community engagement. We first assess the nature of training and education opportunities to better understand the roles that ecologists have assumed over the course of the disaster cycle, and to guide the advancement of disaster awareness. We then characterize recent trends in the availability and distribution of funding to better understand the nature of support and the pursuit of disaster-related ecological research over time. Finally, we examine how ecologists have interacted with disaster-stricken communities when conducting research with comparisons drawn to peers working in other fields of study involved in disaster-related work.

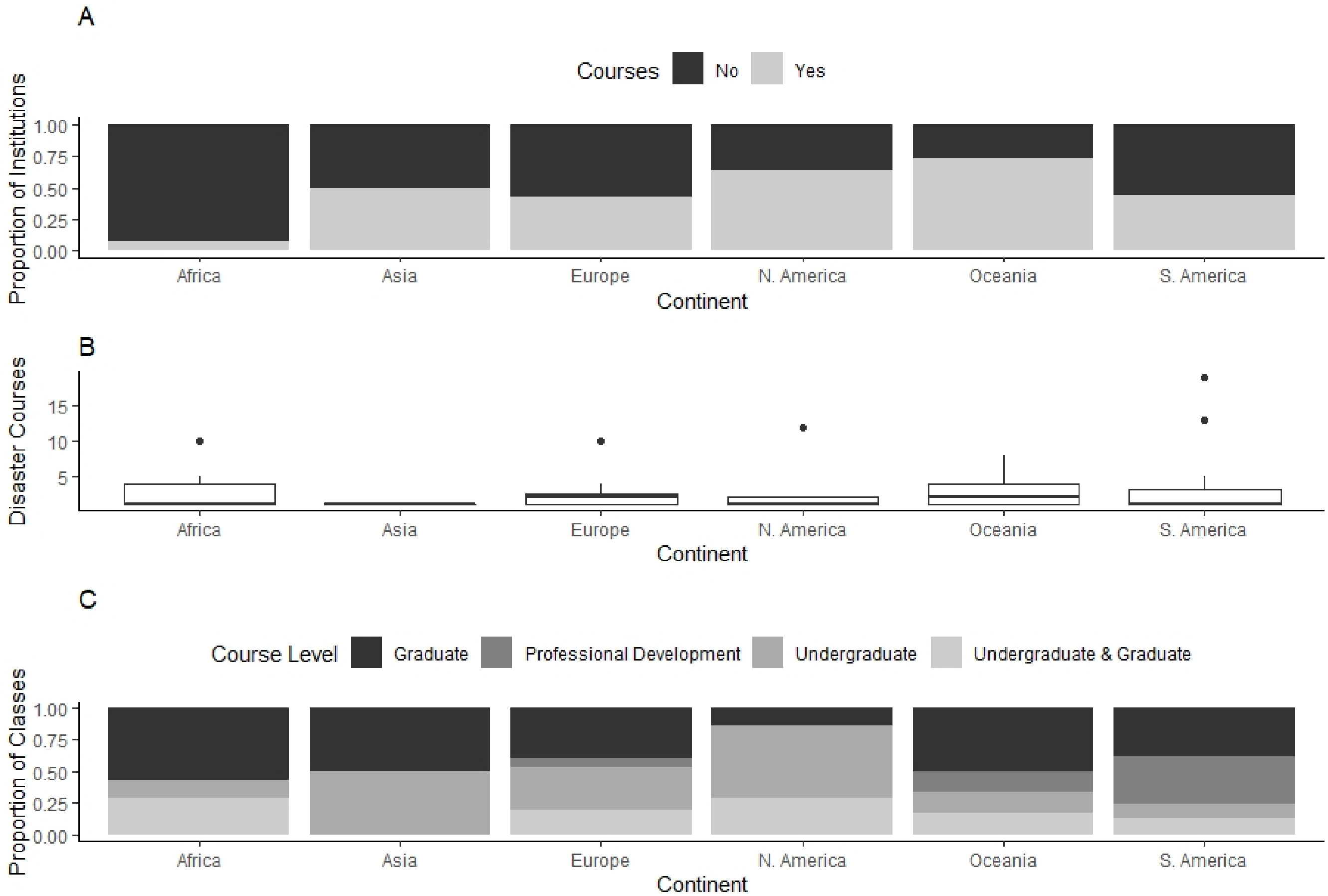
Leading by example: training and education for ecologists

Negotiating the complexities of disaster mitigation, response, and recovery requires substantive education and training to achieve favorable outcomes. A review of educational opportunities in the United States and Europe indicates that training for disaster management is not standardized (Khorram-Manesh et al. 2015), and varies by subject matter, content, and delivery (Kirsch et al. 2019). Most current educational programs are largely structured around the disciplines of public health, psychology, social work, and related humanist, e.g., economics or urban planning, disciplines. Limited effort so far has been made to (re)formulate educational and training programs explicitly for ecologists aiming to pursue disaster-related studies. More concerted efforts to do so would help ensure that ecologists gain awareness of roles and responsibilities, i.e., command and control structures, during and after disasters. Likewise, well formulated training would offer ecologists greater insight into how timely research can meet the immediate needs of affected communities and inform decision making that shapes public policy. Accordingly, disaster management education and training could increase capacity to put ecological skill sets and knowledge into service when it might otherwise be ignored or underutilized.

Professional conferences serve as premier venues for communicating new, field-specific ideas and findings among members of a research community, and thus can offer excellent opportunities to deliver disaster-related training programs targeted for ecologists. We assessed the extent to which conferences have served as a venue for disaster-related training by surveying conference programs from nine national and international ecological societies between 2000 and 2019. We searched the conference programs for disaster-related events including symposia, workshops, oral sessions, plenary sessions, special sessions, and contributed talks (Appendix 1), retrieving 974 total hits representative of 113 events (Table A2.1). Although not every conference offered a topical event every year; overall, the surveyed conferences averaged ≥ 1 topical event per year. This suggests that disciplinary conferences have served as a consistent venue for training and educational opportunities for ecologists. Notably, there has been a significant increase in the average number of topical events across all conference programs over time ($R^2 = 0.52$, $P < 0.0001$; Fig. 2), though it should be noted that archival databases covering the early part of the study period were unavailable for several conferences (Appendix 1).

University-based programs also can afford exceptional opportunities to deliver disaster management education and training for ecologists. Examination of a randomly sampled subset of 120 of the top 500 universities worldwide based on the

Fig. 3. (A) The proportion of universities offering disaster-related course offerings, by continent (n = 120 universities of the top 500 universities worldwide); (B) The number of disaster-related courses offered per institution, by continent, where the middle horizontal line represents the median, bars represent the first and third quartiles, vertical lines represent the minimum and maximum range relative to the quartiles, and dots represent outliers; (C) The proportion of disaster-related courses taught according to education level, by continent.



Leiden Ranking (LR) revealed that 47% of surveyed institutions offered courses relating to disasters (Appendix 1). Course offerings were distributed across a range of faculties, including: the arts and humanities, environmental science, geography, information technology, public health, and public policy (Fig. A2.1). Notably, only a handful of disaster course offerings were hosted by ecology departments or similar disciplines in the biological or natural sciences. Only one course, offered by the University of Regensburg (Regensburg, Bavaria, Germany), is explicitly focused on ecology. Many if not all the other courses are open to ecologists, however, including courses offered as part of graduate and undergraduate programs as well as stand-alone courses, e.g., pertaining to disaster planning, risk management, mitigation, and recovery, offered by departments of "sister" disciplines like geography and environmental science.

The availability of disaster-related training does not appear to differ according to institutional attributes. For example, there is no relationship between university rank and the number of disaster-related course offerings (S = 0.15158, r = -0.1772, P = 0.228), even though more highly ranked universities tend to focus more on fundamental rather than applied disciplinary topics (Moed 2017). We also did not find a relationship between the number of offerings and the type of institution, e.g., public versus private, though this likely reflects the predominance of public institutions (91.7%) among the surveyed universities. It is notable that a higher proportion of universities located in the Southern Hemisphere offer disaster-related courses (Fig. 3A). Likewise, Southern Hemisphere institutions also offer a larger mean number of disaster-related courses (Fig. 3B) and have a larger number of related graduate and professional programs (Fig. 3C). In contrast, institutions located in the Northern Hemisphere offer more undergraduate programs (Fig. 3C). Using the World Risk Indicator as a proxy for country risk to disaster, we also found that there is a significant correlation between the number of courses per institution and country-level risk of experiencing a disaster (S = 2035, r = 0.3402, P = 0.0096), indicating that areas more prone to disasters offer greater opportunity for disaster-related education and training. Though provocative, further evaluation of this trend is warranted, perhaps focusing on region-specific indices, because the availability of information that we examined was skewed toward universities with websites in English or that are readily translated into English. This is particularly true of universities in Asia.

While of limited scope, some important insights can be gained from our survey of conference and university-based educational opportunities. Conferences, which ranged in topical specificity from gatherings focused on fisheries and biogeography to broader meetings like the Ecological Society of America, offer routes for ecologists to disseminate disaster-related research despite differences in focus and reach. Interestingly, though perhaps fittingly, conferences with some of the highest average number of relevant events were more aquatic and coastal-oriented societies such as the American Fisheries Society (20.9 ± 15.8) and the biennial Coastal and Estuarine Research Federation (20.8 ± 15.9) conference. Larger and more topically comprehensive societies were also among the leading edge, highlighted by the Ecological Society of America (25.9 ± 12.7), whose 2018 annual meeting focused on the intersection of extreme events and human well-being. On the other hand, it is evident that disaster-related courses are not offered by all universities or widely offered by ecology departments. At universities that do have topical courses, offerings are spread across a range of disciplines that may not appear relevant or accessible to ecologists, e.g., philosophy courses. Notably, differences in course levels between universities, e.g., in the Southern and Northern Hemispheres, not only reflect geographic variation in coursework availability, but the mission and focus of each respective institution, e.g., fundamental vs. applied research. This suggests that there are opportunities for programmatic development. Institutions may not be nimble enough, however, to meet growing need and interest. With the frequency and severity of disasters expected to rise, it might be necessary for ecologists to seek non-traditional educational opportunities, through universities or professional societies, for developing the knowledge and skills to effectively engage in the disaster cycle.

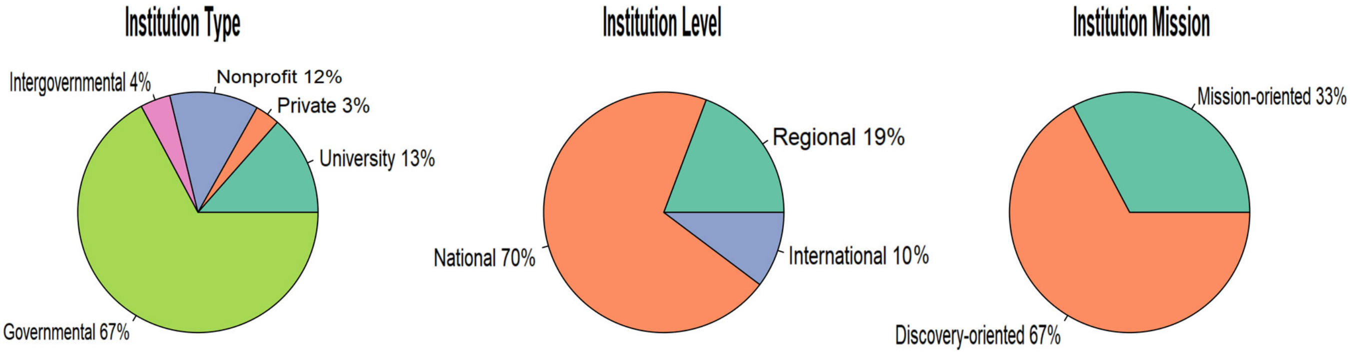
Have money, will travel? Funding for disaster ecology research

The capacity for research communities to support the needs of policy makers and the broader public in part depends on the nature and pursuit of available funding, especially following a disaster. Accordingly, we evaluated whether the current research administrative infrastructure and funding procedures deliver the capacity, focus, and form of inquiry necessary to improve post-disaster outcomes. Across the discipline, ecologists largely rely on funding streams from governmental entities, with support awarded based on merit review (Courchamp et al. 2015). Yet the mission and goals of traditional funding entities such as the U.S. National Science Foundation ("NSF" hereafter) and other governmental institutions are not necessarily structured to support research designed to meet acute needs of policy makers and disaster-stricken communities (Kirsch and Keim 2019). Even programs or mechanisms created by funding institutions to provide support for time-sensitive research in response to a disaster often fall short of the mark (National Research Council 2006, Lindemayer and Likens 2009).

Work undertaken in response to a disaster, particularly during the immediate wake of an event, requires an agile and mission-driven funding framework with balanced consideration of research goals and place-based concerns of stakeholders and affected communities. Disasters often progress over timelines that quickly supersede those of conventional merit-review (National Research Council 2006). Consequently, traditional funding frameworks can fall out of step with unfolding conditions, with the distribution of funding lagging behind critical periods of opportunity and need. This well-recognized concern has motivated the development of mechanisms that allow for more timely and efficient review and disbursement of funding for disaster-related research, and more broadly, for translational ecology (Hallet et al. 2017). For example, the NSF has issued Rapid Response Research (RAPID) awards for time-sensitive research for more than a decade. Though RAPID funding (and parallels at other federal agencies like the U.S. National Institutes of Health; "NIH" hereafter) is a timelier mechanism for disbursing support, awards are relatively small, of limited duration, and are not necessarily directed toward topically relevant work (Lindenmayer et al. 2010). Indeed, support might be awarded for discovery-driven research that has little if anything to do with a disaster, such as some of the research funded through awards made during the Deepwater Horizon oil spill (e.g., DEB-1059236, which supported work on nitrogen cycling in south Florida mangrove swamps not directly impacted by the spill). Other entities with missions that may align more closely with disaster response and recovery (e.g., the United States Environmental Protection Agency and Federal Emergency Management Agency; "EPA" and "FEMA" hereafter) often have comparatively little funding that can be made available to support challenge-driven and time-sensitive disaster-related research. Disparities between funding availability and aims can thus be an administrative barrier that limits the capacity of research communities to meet urgent topical needs, which may consequently result in lamentable and arguably avoidable knowledge deficits. Disaster ecology might thus advance, as a practice and scholarly sub-discipline, by the availability and pursuit of more responsive funding frameworks that provide support for other disciplines, e.g., public health, that are already well-embedded across the disaster cycle.

To better understand the availability and pursuit of support, we performed a literature search to evaluate trends in funding of ecological research on disasters. We used the Web of Science (WoS) to characterize funding source(s) listed in peer-reviewed studies published between 2000 and 2019 (Appendix 1). Overall, the search returned 2481 articles listed in 290 source titles, e.g., peer-reviewed journals, book series, etc. Of these, 1320 articles listed funding agencies, and of the total of 2112 agencies listed, we examined 1045 funding entities to characterize trends in disaster-related research support. Many of the surveyed studies received support from national government institutions (Fig. 4A, B), with support originating from entities, e.g., the NSF, that traditionally focus on discovery-based, as opposed to mission-oriented pursuits (Fig. 4C). Consistent with this, the top funding agencies were the NSF (U.S.), the United States Department of Agriculture ("USDA" hereafter; U.S.), the National Natural Science Foundation of China (China), the Environment Research Council (United Kingdom), the Natural Sciences and Engineering Research Council (Canada), the Ministry of Education, Culture, Sport, Science and Technology (Japan), and the United States Geological Survey ("USGS" hereafter; U.S.).

Fig. 4. Distribution of 1045 funding entities supporting peer-reviewed studies focusing on disaster-related ecological concerns differentiated by (A) type of institution, (B) geographic scope of the institution, and (C) aims of the institution.



A smaller proportion of studies acknowledged funding from regional agencies, e.g., state-level entities in the U.S. (Fig. 4B).

We also assessed how discovery-oriented entities have supported ecological research through programs that have served as a mechanism for timely disbursement of funding in response to disasters. We focused on funding distributed by the NSF through Small Grants for Exploratory Research (SGER) awards as well as exploratory Early-Concepts for Exploratory Research (EAGER) and RAPID awards. All three programs were designed to support research with an acute urgency related to the availability or access to facilities, specialized equipment, or data. Between 2000 and 2019, approximately 1869 awards (~$214M) have been awarded by the NSF for disaster-related research through the SGER, EAGER and RAPID programs (Appendix 1). Of these awards, 312 projects (~16%) that received ~$28M (~13%) were readily identifiable as ecological research. Respectively, the average size of awards for ecological research was $56,457 (SGER, SD = $42,777), $155,085 (EAGER, SD = $88,490), and $92,326 (RAPID, SD = $58,860). SGER and EAGER awards were primarily made through the Division of Environmental Biology (16 and 24 awards, respectively), while the Division of Ocean Sciences issued the largest number of RAPID grants (59 awards). Notably, an average lag of only 6.7 days (SD = 59.32, min = -1117 days, max = 741 days) between the reported award date and project start date suggests that RAPID grants have been made in a timely manner (Appendix 1). It is important to note, however, that the process of seeking support can multiply the time necessary to secure funding. Some compensatory mechanisms are available to expedite work, though some involve assuming risk, such as spending against accounts in anticipation of receiving funding.

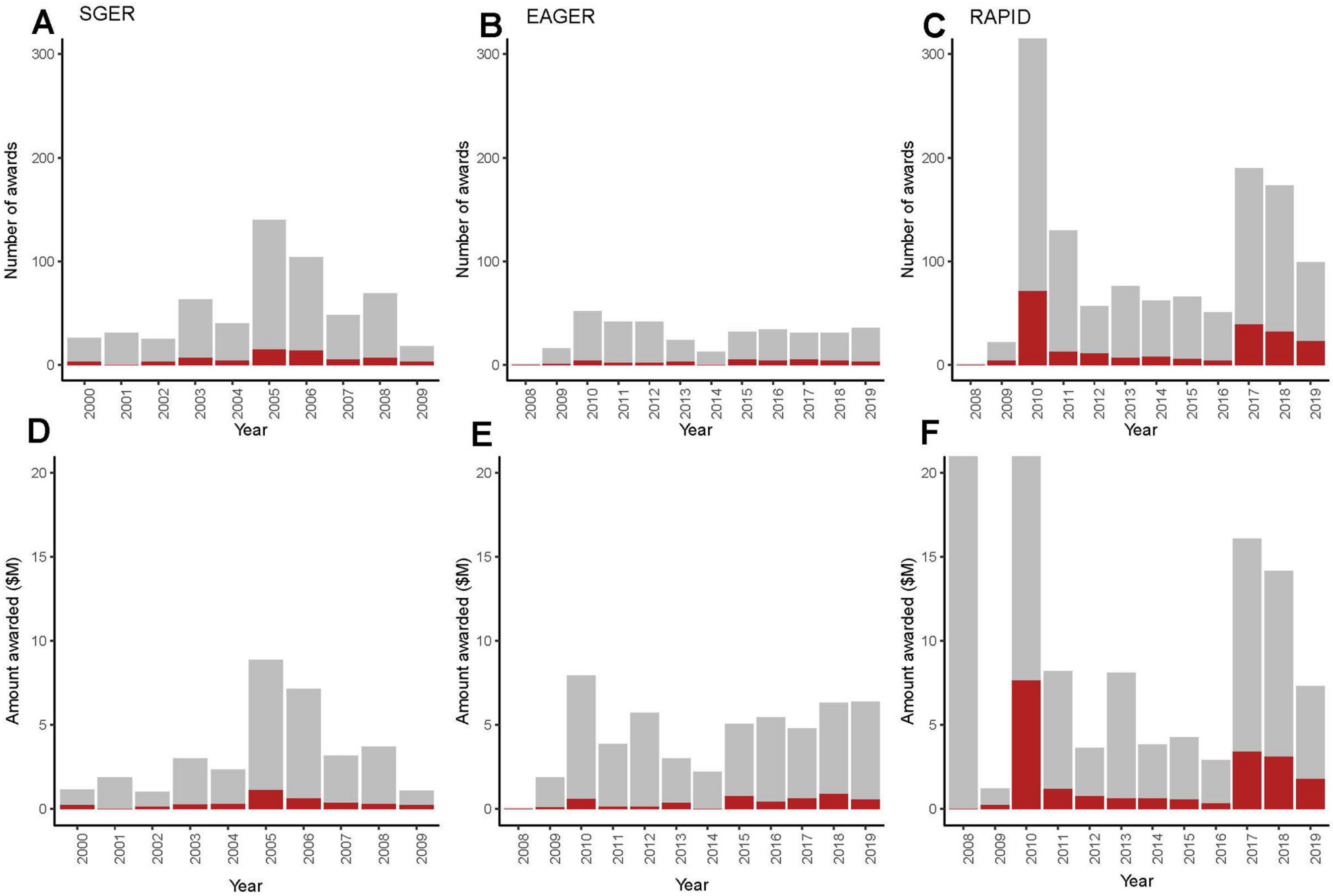
Trends in annual funding might be expected to track the prevalence and magnitude of catastrophic events considering that awards are often made to support post-disaster pursuits. Although no trends were discernible for the EAGER program, large increases were evident for the RAPID program in 2010 and 2011, coinciding with notable events such as the Deepwater Horizon Oil Spill (2010), the Haiti and Chile Earthquakes (2010), and Hurricane Irene (2011; Fig. 5C, F). RAPID grants also increased following a bevy of destructive hurricanes in 2017 (Hurricanes Maria, Harvey, and Irma) and 2018 (Hurricanes Florence and Michael), as well as historic wildfires in California during 2018 (Fig. 5C, F). Institutions in disaster-affected areas, such as Texas (153), California (170), North Carolina (69), and Florida (83), received the most RAPID awards across all divisions (Appendix 1). An increase in SGER funding also occurred in 2005 and 2006, coinciding with notable events such as Hurricane Katrina (2005) and flooding across the mid-Atlantic region of the U.S. (2006; Fig. 5A, D). Interestingly, institutions in affected areas of Louisiana and Mississippi received far fewer SGER awards related to Hurricane Katrina (49 and 21, respectively) than those in unaffected states such as California (333), New York (192), Massachusetts (193), and Texas (123; Appendix 1). Such discrepancies, i.e., between where funding is being directed compared to where a disaster has occurred, highlight well-recognized concerns about disparities in place-based expertise and capacity building, particularly in areas that are becoming increasingly prone to catastrophic disasters.

Partnering up before the get go: working with affected communities

Pursuing scientific research in disaster zones is not an abstract exercise because it can be an unwanted burden on affected communities. Ecologists conducting research during or following disasters often prioritize engagement with institutional decision makers rather than communities in affected areas. This can indirectly disconnect ecological research from the well-being of affected communities, in part because research methods and objectives do not align with community interests (Mukherji et al. 2014). Consequently, community priorities may not be acknowledged (let alone met) by ecologists, which can depreciate the perceived value of research and increase reluctance to support future work despite potential long-term benefits, e.g., science-informed policy, improved understanding of ecosystem services, etc. (Jacobs et al. 2005, Enquist et al. 2017). Appreciation for the potential for discord is growing, but it nonetheless has remained largely unaddressed by the ecological research community.

Discord can potentially be avoided by following some basic principles when working in disaster zones. Besides adhering to common ethical standards for conducting research (Anderson et al. 2012, Browne et al. 2014), care should be taken when entering and engaging affected communities (Ferreira et al. 2015). Institutional relationships are certainly important in shaping communication networks during disasters, but well-established

Fig. 5. Estimated number and amount of SGER (A, D), EAGER (B, E), and RAPID (C, F) grants awarded by the U.S. National Science Foundation for disaster-related studies in general (gray) and specifically for ecological research (red) between 2000 and 2019.

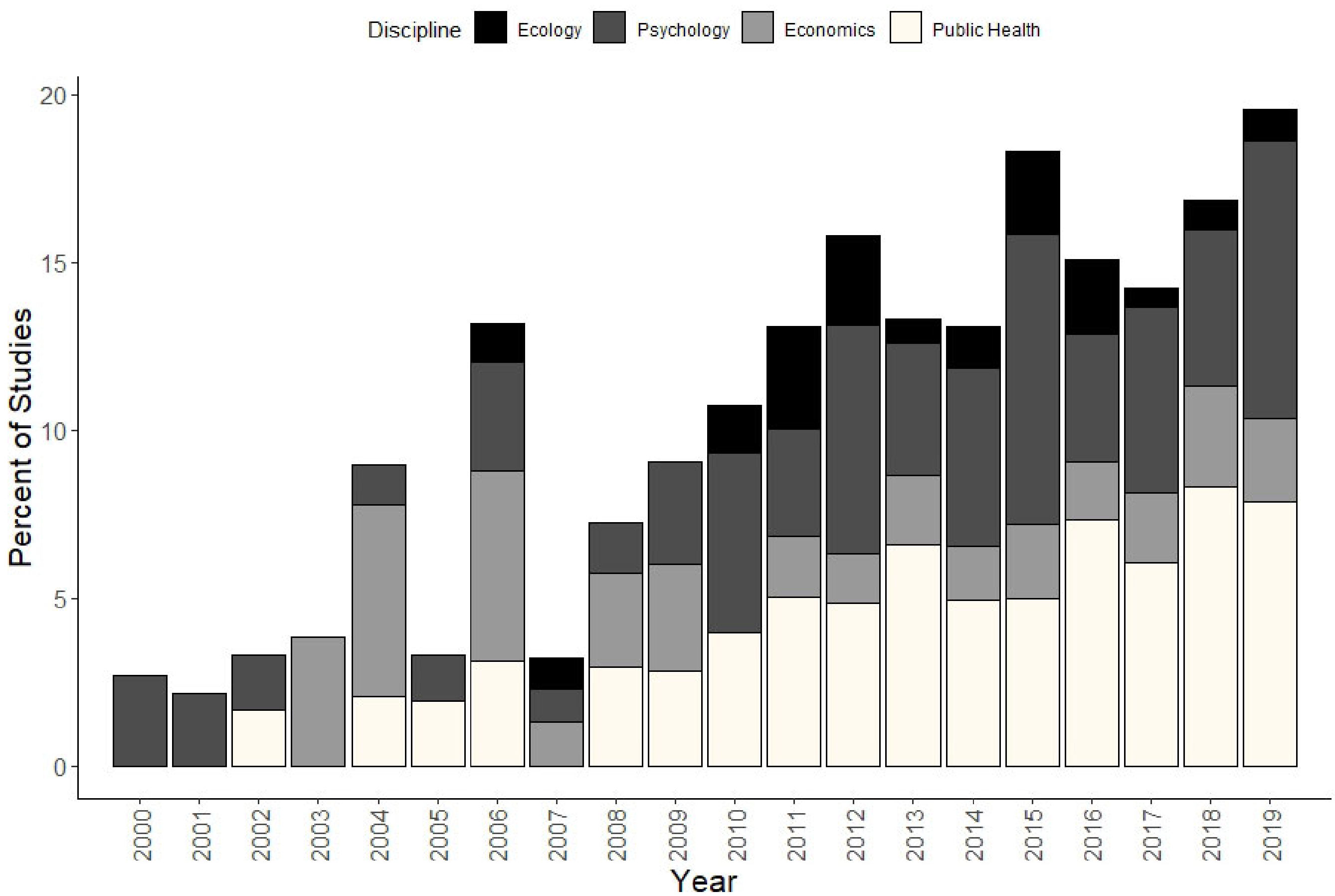


interpersonal relationships with stakeholders and community members often can have greater influence on the ability of scientists to coordinate and execute research (Nowell and Steelman 2015). Thus, if relationships have not been established prior to a disaster event, priority should be placed on establishing relationships with community members to build trust and foster communication. Social capital can be generated and sustained through interpersonal relationships that are based on a sense of transparency (Mukherji et al. 2014) and a clear understanding of the reciprocal benefits that can be gained from research being conducted in an affected community.

Implementing a community engaged research (CER) framework can be one of the most effective approaches for working with local communities and stakeholders. CER is formally defined as "the process of working collaboratively with and through groups of people affiliated by geographic proximity, special interest, or similar situations to address issues affecting the well-being of those people" (Centers for Disease Control and Prevention 1997). Informally, CER offers opportunities to build and develop trust, generate beneficial partnerships, and increase the efficacy of communication while generating improved outcomes (Centers for Disease Control and Prevention 1997, Chandra et al. 2013, Oetzel et al. 2015). By establishing relationships with community members, research can be conducted in a manner that respects the affected community, is informed by their needs and sociocultural factors, and sustains meaningful relationships that may lead to novel scientific findings and a better understanding of the study area and topic.

Though not yet widely adopted by ecologists (Fig. 6), CER approaches have been implemented across the disaster cycle by peer researchers in related disciplines like public health. As a discipline, public health has been at the forefront of defining and executing CER to concordantly meet the goals of researchers and needs of community members. The purpose and value of CER approaches have been particularly well illustrated in post-disaster public health research focusing on community resilience (Chandra et al. 2013, Wells et al. 2013, Ramsbottom et al. 2018). Public health researchers and practitioners have aspired to help communities better prepare for disasters by promoting greater understanding of coping capacity across a spectrum of vulnerability (Chandra et al. 2013, Wells et al. 2013, Ramsbottom et al. 2018). Some evidence suggests that sustained engagement with the public health sector can foster greater recovery of disaster-affected communities (Ramsbottom et al. 2018). Benefits might similarly be derived from broader adoption of CER frameworks by ecologists, where community engagement is

Fig. 6. Percent of disaster-related peer-reviewed studies executing community engaged research (CER) methods in the fields of ecology, psychology, economics, and public health between 2000 and 2019.



viewed as iterative and fundamental rather than as an ancillary aspect of ecological research. It has been found, for example, that CER strategies improve disciplinary outcomes like increasing the efficacy of biodiversity management and restoration (Reyes-Garcia et al. 2019). CER can also provide for beneficial sociocultural outcomes over time, ranging from intermediate objectives, e.g., creating shared governance of research and equity in research infrastructure, to long-term goals, e.g., alleviating disparities rooted in racism, sexism, or classism that may exist between research institutions and communities (Isler and Corbie-Smith 2012). It thus stands to reason that greater awareness and appreciation for the gains that could be achieved might foster a disciplinary-wide embrace of CER approaches.

To better understand trends in the adoption of CER frameworks, we performed a WoS-based literature search to determine the prevalence of CER in disaster-related ecological studies in comparison to topical work conducted by researchers in other fields. Our search of peer-reviewed ecological research (Appendix 1) returned a total of 27 papers published from 2000 to 2019. Parallel searches of work by researchers in other relevant disciplines (Appendix 1) returned a range of totals, as follows: public health, 287 papers; psychology, 120 papers; and economics, 53 papers. An analysis of variance (ANOVA) revealed a significant difference in the number of peer-reviewed papers between fields (df = 3, 76, F = 9.274, $P < 0.0001$). A post-hoc Tukey test, however, showed that public health was the only discipline to have significantly more publications than ecology ($P < 0.0001$). An ANOVA also recovered significant differences in the percent of studies involving CER among disciplines (df = 3, 76, F = 8.702, $P < 0.0001$), with post-hoc Tukey tests showing that both public health ($P < 0.00001$) and psychology ($P < 0.00001$) had significantly higher percentages of CER-based studies compared to ecology. It becomes more evident how ecology has lagged public health over the past 20 years after standardizing for the difference in the total number of disaster-related papers published by each respective discipline (Fig. 6, Fig. A2.2). Linear regression revealed that the prevalence of CER in public health ($\beta = 2.417$, $R^2 = 0.8334$, $P < 0.00001$) and psychology ($\beta = 0.7835$, $R^2 = 0.7289$, $P < 0.00001$) has increased over time more so than it has in ecology ($\beta = 0.1692$, $R^2 = 0.4693$, $P < 0.001$; Fig. A2.2). This trend suggests that ecologists are falling behind researchers in other fields who are engaging in parallel work on disasters, and thus are likely overlooking elements of community engagement and outreach that can improve both the quality and outcomes of ecological research.

A PROSPECTUS FOR DISASTER ECOLOGY

Guidance for participating in the disaster cycle

The current landscape of ecological education and training opportunities, funding trends, and community engagement indicate that there are notable deficits that can be addressed to improve the value and impact of ecological research across the disaster cycle. Taking action to promote greater value would address potential complications that can arise because of practical decisions made by first responders and stakeholders unfamiliar with ecological principles and research findings (Gulachenski et al. 2016, Rael et al. 2016, Lewis et al. 2017). Likewise, individual and disciplinary advancement could help prevent potential discord with affected communities that can feedback to diminish perceived value and adoption of ecological guidance (Mukherji et al. 2014).

Improvement of current practices, ranging from vocabulary use to data collection methods to information dissemination, is vital for ensuring that ecological research aligns with conceptual and practical frameworks relevant to disaster response, recovery, and mitigation (e.g., Hobbs et al. 2011, Suding 2011). We offer guidance for how ecologists can more effectively navigate the disaster cycle.

Learning to lead through education and training

Ecologists can provide guidance for addressing conditions of concern across the disaster cycle, from vector transmission to biological invasions to biodiversity loss (Mukabana et al. 2006, Nuñez et al. 2020), but doing so requires placing ecological knowledge within an appropriate sociocultural context. The World Health Organization (WHO) estimates that 160 million people are affected by natural disasters every year worldwide (Adams 2002), which underscores the need for ecologists to effectively and respectfully place their work within the context of place-based concerns. Yet ecologists often do not have formal training in disaster response, recovery, and preparedness, including practical skillsets that can prove critical during the aftermath of a disaster. Accordingly, gaining greater interdisciplinary knowledge and logistical capacity can help increase the impact of ecologists pursuing research, particularly following a disaster. For example, undergoing first-responder training (and maintaining certification as needed) would enable an ecologist to better contribute to medical emergencies or search and rescue efforts that may occur when conducting research in disaster-stricken areas. Likewise, undergoing wildfire training would help ensure that ecologists safely conduct research and support local communities in wildfire-prone areas. Research efficacy and engagement could be further improved through more comprehensive coursework and training tailored for the discipline.

Universities are the logical host for educational programming because most ecologists are associated with an institution of higher education at some point in their career. University-based course work might be incorporated into degree-granting programs, covering a curriculum that reflects global trends and regional concerns so that ecologists can gain a shared yet hierarchical understanding of the disaster cycle. Programs might be structured following templates developed by organizations like the WHO to address public health emergencies (Adams 2002, Wright et al. 2020). Importantly, training must be nimble, iterative, and continuous to incorporate novel ideas and keep pace with unfolding trends in disasters and capacity to respond, e.g., post-disaster operational logistics. Thus, opportunities for continuing education must be available to support and complement degree-granting programs. Focused training opportunities could also be offered in coordination with discipline-based meetings like scientific conferences and symposia, and via specific training programs oriented toward professionals in the field, like programs in disaster preparedness offered by the Red Cross (Braman et al. 2010) and the United States Centers for Disease Control and Prevention ("CDC" hereafter; https://emergency.cdc.gov/coca/trainingresources.asp).

It is important to give careful consideration to the possibility of complications and constraints arising because of poor coordination across education venues. Ensuring a unified and coordinated approach to disaster preparedness, response, and recovery requires that educational benchmarks and standards be consistent at a national or preferably global level. Educational competencies establish benchmarks that enable ecologists to meet occupational competencies (Markenson et al. 2005). We suggest that ecologists should have proficient knowledge in a suite of core topics to competently prepare for and respond to disasters, including coupled human-natural ecosystem dynamics, the epidemiology of vector-borne pathogens, as well as the outcomes and drivers of global change. Likewise, it would be valuable to gain greater proficiency through additional coursework on more focused topics like wildlife-human interactions and ecological, i.e., trophic, cascades. Educational programs should also encourage ecologists to gain greater understanding of other topics that are circumscribed by disaster-adjacent disciplines. Such disciplinary topics might include place-based history, structural violence, social capital, and environmental racism (see Shultz et al. 2007 for a more in-depth discussion of these and additional subjects that would strengthen a core education in disaster ecology). These recommendations are not meant to be a comprehensive prescription of subjects that ecologists must learn to engage in disaster-related research. Rather, we encourage educators to consider the recommended topics in the context of developing a broader curriculum that is dynamic and iteratively refined to keep pace with ever-evolving nature and complex outcomes of disasters.

Although there is value in tailoring educational programming to focus on disciplinary and trans-disciplinary knowledge, it is equally important for ecologists to gain technical and logistical skills to properly respond and conduct research in the field. Foundational skills like research design and implementation, grant writing, and communication with non-scientists can be highly beneficial, and thus should be made broadly available to established and early career ecologists. The dynamic and complex nature of disaster response, well characterized by short decision-making timeframes and resource constraints, highlights the need for ecologists to gain proficiency in skillsets that enable effective engagement. Many current disaster preparedness programs exemplify this type of skill-based competency training. For example, Tulane University's Disaster Resilience Leadership Academy (DRLA) offers graduate training led by an interdisciplinary team of faculty from the schools of Social Work, Architecture, Business, Law, Public Health and Tropical

Medicine, as well as Science and Engineering (https://tssw.tulane.edu/disaster-resilience). The DRLA works to train students of all disciplinary backgrounds on skills like risk management, development of qualitative and quantitative research projects, community engagement, policy development, and leadership, with the aim of integrating education and research with practice to foster effective, humanitarian disaster response and research. Training in disaster-specific skills should be made readily accessible through cross-departmental course offerings, perhaps hosted or coordinated by accredited programs like the DRLA. As with our recommendations for gaining topical knowledge, our recommendations for gaining topical competency are meant to be a starting point for ecologists to acquire the skills and awareness necessary to contribute to disaster response, recovery, and mitigation.

Finally, educational programming should incorporate place-based training so that ecologists gain an understanding of regional and location-specific concerns complemented by broadly applicable competencies. Although important perspectives can be gained from courses focusing on general principles, many elements of the disaster cycle, e.g., the pace of recovery or the extent of human impact, can be contingent on geography and society. Place-based training can afford greater awareness and appreciation for this, in part by drawing distinctions among local communities, e.g., according to history, environment, socioeconomics, etc. This can help illustrate the potential for social and environmental nuances, providing ecologists with necessary context for pursuing relevant research and effective community engagement. Programs like the Community Engagement Academy (CEA) at the University of Tennessee (https://gradschool.utk.edu/2020/08/11/community-engagement-academy/) offer examples of how to achieve these learning objectives. The CEA is a program designed for early-career researchers to gain skills in community-engaged research and to facilitate connections between University of Tennessee faculty and communities in eastern Tennessee. Training through programs like the CEA can help ecologists better learn from historical precedents to understand the challenges of tomorrow. The evolving responses of ecologists to disasters like the eruption of Mt. St. Helens in 1980, Hurricane Katrina in 2005, the Ebola outbreak in 2014, and the ongoing COVID-19 pandemic shows that, as a discipline, knowledge, awareness, and skills are progressively improving. Collectively establishing educational and professional competencies in part by leveraging and expanding existing educational programs will foster further advancement so that ecologists approach disasters with a more expansive sense of scientific curiosity supported by commensurate humanitarian values.

Seeking support for timely, topical, and long-term research

Though current funding paradigms have provided considerable support for ecologists to work on disasters, concerns about institutional mission and administration, the duration of funding availability, and the feasibility of securing funding during critical periods of the disaster cycle highlight opportunities for improvement. For example, funding institutions could work to centralize or coordinate disparate resources via multi-agency funding opportunities. Ecologists can also take additional steps to secure support by partnering with regional and local funding entities to guide resource availability and support for at-risk and disaster-stricken communities throughout the disaster cycle.

National-level funding entities often play an important and arguably outsized role in providing resources for disaster-related research but may nonetheless fail to realize their full potential because of limited coordination within and among institutions. Funding opportunities for disaster-related ecological research are often spread across disparate offices and institutions that vary in topical focus and intent. Although some specialization is warranted and should be expected in some cases, e.g., earthquake research support through the USGS, greater consideration should be given to increasing accessibility and broadening participation to encompass a wider range of topically relevant research. This is particularly important for programs like the joint NSF-NIST (U.S. National Institute for Standards and Technology) Disaster Resilience Research Grants (DRRG) competition, which is among the largest disaster-specific research funding programs worldwide. Since early 2015, the vast majority of DRGG awards (86 of 94) have been made through the Division of Civil, Mechanical, and Manufacturing Innovation. No awards have been made through the Division Environmental Biology, which includes core offices that direct support to ecological research. Although DRGG awards have in part funded ecological research, this disparity in resource administration suggests that ecology is not a priority consideration of the program. Broadening participation in competitions like the DRRG, i.e., with more ecologists serving as principal investigators, would undoubtedly enhance a broader range of disaster-related ecological research and perhaps also sustain longer term interdisciplinary research programs on disasters. Of course, a partnership between the NSF and NIST may not be the most suitable route to achieve this objective. Thus, consideration should be given to expanding or developing other inter-agency partnerships to increase funding availability and accessibility. There are excellent precedents that could guide this process. For instance, the Ecology and Evolution of Infectious Disease (EEID) program is a well-respected, interdisciplinary program that draws on funding from the NSF, the NIH, and the USDA as well as international partners based in the United Kingdom and Israel. Shifting the funding model for the DRRG to something closer to that of the EEID program would probably support a broader research community, which would very likely translate to greater support of larger national and international constituencies that face similar disaster-related risks.

Consideration should also be given to expanding the roles of regional funding entities in supporting disaster-related research. Most regional funding sources do not have resources like marquee entities like the NSF and NIH but may nonetheless support research that delivers greater benefit to affected areas. Large, national funding institutions are generally guided by priorities that do not emphasize placed-based concerns and specific, challenge-driven objectives (Tierney 2007). Funding priorities of regional institutions, on the other hand, are often innately linked to resident community and stakeholder needs, including those that relate to disasters. Regional funding entities can also more nimbly respond to shifting needs to better address the priorities of local communities, while reducing the time needed to mobilize their response. Thus, research funded from regional sources may be more likely to result in actionable, translational science that aligns with agency missions (Arnott et al. 2020), perhaps aiding in the development of strategies to reduce vulnerability and increase resilience (Henstra 2010). This is particularly true given the nature of research produced through mechanisms like the NSF RAPID program that have supported projects that are only tangentially related to disasters.

The Louisiana Coastal Protection and Restoration Authority (CPRA) is an excellent example of a regional funding entity that supports research offering globally relevant insights while also addressing placed-based needs (https://coastal.la.gov/). The current iteration of the agency was established after Hurricanes Katrina and Rita in 2005 to address issues of coastal restoration and protection, including those related to subsequent disasters like the Deepwater Horizon Oil Spill in 2010. The CPRA has funded a wide range of disciplinary and interdisciplinary research, from post-disaster oil spill restoration to disaster mitigation focusing on flood resilience and risk. Notably, in contrast to federal programs that typically award support during the wake of a disaster, the CPRA funds research across the full disaster cycle. The CPRA also has demonstrated a propensity to support long-term research agendas, including those focusing on adaptive monitoring (Lindenmayer and Likens 2009). By funding research that spans the disaster cycle, funding agencies like the CPRA can enable ecologists and other researchers to achieve more robust outcomes that reflect baseline measures of pre-disaster conditions. Fostering participation in research throughout the disaster cycle can also facilitate better integration of ecological research into disaster-related policy and decision making, while simultaneously creating opportunities for ecologists to develop relationships with local communities that can promote translational outcomes (i.e., broader impacts) of their research.

A shift toward a more holistic funding paradigm- at the regional and national levels- could also yield more impactful and effective research by broadening participation. Current funding paradigms often place disproportionate emphasis on providing support for time-sensitive data collection, which can disadvantage researchers from disaster-stricken areas. Preparing proposals, i.e., for research, to replace lost infrastructure and instrumentation, etc., can come at a real cost, by requiring a shift in attention away from meeting immediate family or community needs (Richardson et al. 2009). This burden is not shared by researchers based elsewhere, who might elect to seek support for opportunistic pursuits, potentially limiting support for researchers who arguably could be pursuing more substantive place-based work. One partial remedy for this is for researchers based in disaster-prone areas to invest time in pre-proposal scenario planning, though this approach has thus far not been widely adopted by ecologists (Lindenmayer et al. 2010). Although strategic, preemptive proposal planning nonetheless would not address potential trade-offs that local researchers might face, i.e., when deciding whether to prioritize research over relief efforts. Thus, funding entities might consider taking steps to support research communities and build greater capacity in disaster-prone or disaster-affected areas. Even providing stop-gap measures would be a valuable step forward. For example, temporary assistance could be provided through mobile research infrastructures like those that have been developed through the National Ecological Monitoring Network (Lindenmayer et al. 2010), which can sustain research capacity while efforts are made to seek more long-term remedies. Notably, not only would this provide timely support to local researchers to help address concerns about reduced capacity and lost infrastructure, but it could also inject money into local economies, which can aid in rebuilding affected communities (Richardson et al. 2009).

Working with affected communities: lessons learned from public health

Ecologists intent on engaging in the disaster cycle may achieve greater success by adopting a CER approach for working with affected communities. Often, ecologists who elect to pursue research do so shortly after a disaster hits, without much understanding of preceding conditions and without pre-existing relationships with affected communities (Faas et al. 2019). This can yield outcomes that personally and professionally fall short of the mark, i.e., contributing knowledge and expertise to promote recovery and well-being, that may reflect ethically questionable research practices, e.g., asking survivors recovering from displacement, death, and destruction to participate in research projects (Mills et al. 2007, Richardson et al. 2009). Socially informed CER approaches can be much more rewarding, particularly for those researchers working in embedded or nearby institutions aiming to establish and maintain long-term research programs (Richardson et al. 2009). Adoption of CER strategies can also improve social equity, which should be an imperative objective considering that disasters often more strongly impact marginalized and vulnerable communities (Park and Miller 2006, Ahmed et al. 2012, Dominey-Howes et al. 2014), including communities that are strongly dependent on natural resources (Flint and Luloff 2005).

Important lessons can be learned from other disciplines, like public health, that are increasingly adopting CER approaches. Although our analyses revealed that CER approaches are also often employed in disaster-related psychology research (Fig. 6), topics in public health, e.g., epidemiology, are more readily relatable to ecological research. The number of CER-based public health studies of disasters has steadily increased over the last 20 years (Fig. 6, Fig. A2.2). This trend in part reflects the development of disciplinary standards and best practices for community engagement and integration of disciplinary expertise into disaster response efforts (Miller et al. 2016). Ecologists could similarly establish an operational, disciplinary definition of "community engagement" and community engagement best practices. Definitions and practices could be crafted to align with precedents set by public health and other fields while also accounting for the disciplinary focus of ecology, including aspects that are not centered on the human experience. Doing so could better position ecologists to respond to the needs of disaster-affected communities by building stronger, more equitable partnerships based on ethical and professional norms (Adams et al. 2014).

Outreach and community engagement are not necessarily intrinsic components of ecological research (Hampton et al. 2013), which can present challenges that require careful consideration to overcome (Groffman et al. 2010). Public health researchers and officials, such as social workers, primary care physicians, and first responders, are often in positions to understand the immediate pressures acting on disaster-affected communities, and what resources may be required to ameliorate community concerns. Providing or facilitating access to necessary resources can aid in disaster mitigation, relief, and response by promoting community resilience (Morton and Lurie 2013, Wells et al. 2013, Miller et al. 2016, Pollock et al. 2019). Although ecologists may have a greater understanding or familiarity with specific disaster-related environmental hazards or outcomes, ecologists are not often in positions that foster communication with affected or at-risk communities. Deficits in community engagement and outreach can lead to ineffective communication about the potential value of ecologists and ecological expertise across the disaster cycle. Steps can be taken, however, to overcome this challenge. For example, ecologists can elect to work closely with public health practitioners to adapt tenets of public health (and CER more broadly) to build trust and community support for mutually beneficial research pursuits. Likewise, ecologists can partner with knowledge brokers or boundary spanners (Weerts and Sandmann 2010, Newman et al. 2016). By facilitating community engagement and outreach, partnering with brokers and spanners can help ecologists find sound footing and thus more effectively work with and for affected communities.

Adopting CER frameworks can also improve well-being and future outcomes by broadening sociocultural representation and participation. CER approaches offer opportunities for community members to help establish and define research objectives. This process can help ensure that community interests and priorities are reflected in the research, which can foster more equitable representation in scientific research and outcomes thereof. Likewise, CER approaches encourage participatory support, with community members actively involved in research efforts. Besides serving in an advisory capacity, community members can readily assume the role of citizen scientist to support data collection and analysis. Citizen science can help meet specific research objectives, help establish baseline conditions, and sustain long-term monitoring in support of disaster response, recovery, and mitigation (Deguines et al. 2020). It can also improve community relations by allowing residents meaningful opportunities to help restore affected areas, which can alleviate persistent issues of research fatigue and concurrently improve public perceptions of value and consideration for ecology and ecologists across the disaster cycle (Clark 2008, Marshall et al. 2012). Importantly, expanding community engagement and citizen science can help promote diversity and inclusivity across the discipline (Enquist et al. 2017, Adler et al. 2020). Trends indicate that the discipline of ecology is becoming more inclusive (Beck et al. 2014), reflecting continuing efforts to address well-recognized yet long-standing concerns about the need for greater diversity across the discipline. By complementing other efforts (e.g., Sealey et al. 2020), greater engagement of disaster-affected communities, which are often socioculturally marginalized and underserved (Park and Miller 2006, Ahmed et al. 2012, Dominey-Howes et al. 2014), would help broaden the basis of participation in the discipline, while also potentially building resilience and capacity to address disparities that can be generated or reinforced by disasters (Gulachenski et al. 2016, Lewis et al. 2017, Peterson et al. 2020).

CONCLUSIONS

Trends of disasters increasing in frequency and intensity (Webster et al. 2005, Coleman 2006, Khan et al. 2008, Bender et al. 2010, Banholzer et al. 2014) have seemingly motivated ecologists to gain greater understanding of how disasters affect organisms, ecosystems, and human well-being. The prospectus provided here outlines some important steps that can be taken to meet disaster-driven challenges as the scope of topical research is likely to increase into the future. Importantly, further guidance could be derived from more detailed reviews of education, funding, and community engagement. Not only could this better define disaster ecology as a topical pursuit, but additional evaluation would also offer a stronger basis for disciplinary and societal advancement. More expansive reviews of educational opportunities could, for example, help identify institutions that can best serve as hubs for training future generations of disaster ecologists. Finer grain examination of disaster-related grants awarded by regional agencies would help improve research funding paradigms. Drafting formal best practices for community engagement would not only offer clear and consistent guidance to ecologists working in disaster-affected areas, it would also encourage participation and inclusivity, helping to ensure that the discipline addresses community and stakeholder concerns.

Responses to this article can be read online at:
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Data Availability:

The data/code that support these findings are available upon request from the corresponding author, NLG. The data were derived from the following resources available in the public domain: the American Fishers Society (https://fisheries.org/events-page/past-afs-meetings/); the Association for the Science of Limnology and Oceanography *(https://www.aslo.org/meetings/); the Association of Tropical Biology and Conservation (https://tropicalbiology.org/atbc-meetings/annual-meetings/); the Botanical Society of America (https://cms.botany.org/home/meetings.html); the British Ecological Society (https://www.britishecologicalsociety.org/events/past-bes-meetings/); the Coastal and Estuarine Research Federation (https://www.cerf.science/past-cerf-conferences); the Ecological Society of America (https://www.esa.org/events/meetings/past-meetings/); the International Biogeography Society (https://www.biogeography.org/meetings/); the Society for Integrative and Comparative Biology (https://sicb.burkclients.com/meetings/past.php3); Leiden Ranking (https://www.leidenranking.com/); World Risk Index (https://weltrisikobericht.de/english/); Web of Science (https://app.webofknowledge.com/author/); National Science Foundation (https://www.nsf.gov/awardsearch/).*

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Appendix 1: Literature and institutional review search terms and statistical methods

METHODS

Education and training institutional review

To evaluate the prevalence of disaster-related training in the field of ecology, we reviewed the number of topical workshops, symposia, and special sessions offered over the past 20 years during the annual conferences of nine topical societies: the American Fisheries Society (AFS), the Association for the Sciences of Limnology and Oceanography (ASLO), the Association of Tropical Biology & Conservation (ATBC), the Botanical Society of America (BSA), the British Ecological Society (BES), the Coastal and Estuarine Research Federation (CERF), the Ecological Society of America (ESA), and the International Biogeography Society (IBS). No meeting programs were available for the year 2000 for any conference. The search terms "disaster", "hurricane", "typhoon", "earthquake", "landslide", "eruption", "tsunami", and "spill*" were used to find and validate hits on relevant education opportunities for ecologists. If a title received a hit, the event was counted and the abstract, if available, was searched for relevance. If an abstract received a hit, the title was reviewed and counted only if the event was relevant. Canceled events were excluded from consideration.

To explore extant practices in training and education related to disaster response and community engaged ecological research, we used the Leiden Ranking (LR) to identify the top 500 universities worldwide based on bibliometric indicators such as publication output, citation impact, and scientific collaboration. The LR was chosen for its transparency and recognition of limitations. We randomized the list of universities so that we could get an unbiased subset for our analysis (i.e., not only taking the top universities from each continent). Thereafter, the first twenty universities from Europe, Asia, Africa, Oceania, and the Americas respectively were identified from the randomized list (based on the randomized numerical order, not rank), thereby allowing a balanced and random list of 120 universities for the analyses. Each university website was mined to gather information on whether the university offers courses related to disasters, and if so, how many courses are offered, the level at which such courses are offered (graduate or undergraduate), within which departments they are offered, the location of the university and whether it is a private or public institution. This information was used to examine i) how common it is to have courses relating to disasters in higher education, and i) at what academic level, ii) which departments provide such courses, ii) and if there were any trends based on the risk of each country to disaster. To quantify "risk to disaster", we used the World Risk Index, which is a percentage metric that measures each country's risk to natural disasters based on 28 indicators and globally accessible data.

Literature review: funding and engagement

We performed a systematic literature review coupled with a bibliometric analysis to identify disaster-related ecological studies and funding sources thereof. We performed an Advanced Topic Search through Web of Science (WoS) in July 2020 using keywords for high impact disasters ("disaster, "earthquake*", "hurricane*", "typhoon*", "landslide*", "eruption*", "spill*", and "tsunami*") and in the WoS Category "Ecology". We selected these keywords because each is highly identifiable through the scientific literature over time, while terms such as “wildfire” and “flood” that often focus on purely disturbance ecology perspectives were not used for searches. We limited our search to studies published in the last 20 years (2000-2019), that were written in English, and that were classified within the category “Ecology” as defined by WoS. This search yielded a total of 2,481 studies, including 1,320 (53.2%) articles reporting standardized information regarding funding sources. Information on these entities was manually standardized given the disparity of names used to refer to the same institutions. Based on this information, we classified all reported funding entities depending on type of resource (public, non-profit, university, private, or intergovernmental), level of administration (international, national, or regional) and mission (fundamental or missional).

To further characterize institutional practices in funding disaster ecology research, we gathered funding data made available through the NSF awards database (https://nsf.gov/awardsearch/advancedSearch.jsp). We retrieved records of all the RAPID (Rapid Response Research), SGER (Small Grants for Exploratory Research), and EAGER (Early-Concept for Exploratory Research) grants awarded between 2000 and 2019. We classified a project as disaster-related if the title or abstract contained one or more of the following keywords: “disaster”, “earthquake”, “eruption”, “hurricane”, “typhoon”, “tsunami”, “landslide”, “flood”, “tornado”, “fire”, “wildfire, “spill”, “mudslide”. Disaster-ecology research was identified by including identifying those with abstracts having a combination of disaster-related keyworks and ecology-related keywords (e.g., “ecolog”, “species”, “assemblage”). To investigate Katrina-related SGER funding, keywords “Katrina”, “Hurricane Katrina”, and “post-Katrina” were search for in either the title or abstract of awards.

To determine the prevalence of community engagement and community-engaged practices in disaster-related ecology research, we modified the aforementioned approach to include terms such as: engag*, “community-engaged framework", “community engagement”, “community-engagement”, “community-engaged research”, "community-engaged scholarship", "community engaged research", "community-engaged participatory research", "CER", "CEnR", and "CBPR" in the WoS defined “Ecology” category in articles published between 2000 and 2019. To compare ecology to other fields of study, we used the same search terms in the following WoS defined categories: “Public, Environmental, and Occupational Health”, “Economics”, and “Psychology”.

Statistical methods

We performed Spearman’s rank-order correlation analysis to assess the strength of associations between World Risk Indicator measures and the availability of disaster-related education opportunities at higher-education institutions, as well as university rank (according to Leiden Ranking) and the number of courses offered. One-way analysis of variance was used to determine how the estimated number of papers published using CER methodologies varied among disciplines, with post-hoc Tukey HSD tests for pairwise multiple comparisons between individual disciplines. Data pertaining to trends over time were examined first using Pearson’s correlation to determine possible associations, and then analyzed using general linear models to determine the magnitude and significance of change over time. We would like to note that our estimate of the minimum lag between reported award dates and project start dates is negative because it accounts for projects that start early through pre-award funding. All data were analyzed in R version 4.0.2.

Appendix 2: Supplementary table and figures for the manuscript.

Table A2.1. Disaster-related educational and professional development events from conference programs including symposia, workshops, oral sessions, plenary sessions, special sessions, and contributed talks between 2000 and 2019.

Conference Name	Number of Years Surveyed	Total Number of Hits	Average Number of Hits	Standard deviation
Association for the Sciences of Limnology and Oceanography	20	165	8.25	10.7
The Society for Integrative and Comparative Biology	18	58	3.22	2.69
Botanical Society of America	17	34	2	2.09
Association for Tropical Biology and Conservation	16	78	4.88	4.91
The Ecological Society of America	11	285	25.9	12.7
American Fisheries Society	10	209	20.9	15.8
International Biogeography Society	9	15	1.67	1.66
Coastal and Estuarine Research Federation	6	125	20.8	15.9
British Ecological Society	6	5	0.833	2.04
TOTAL		974	48.05	45.358

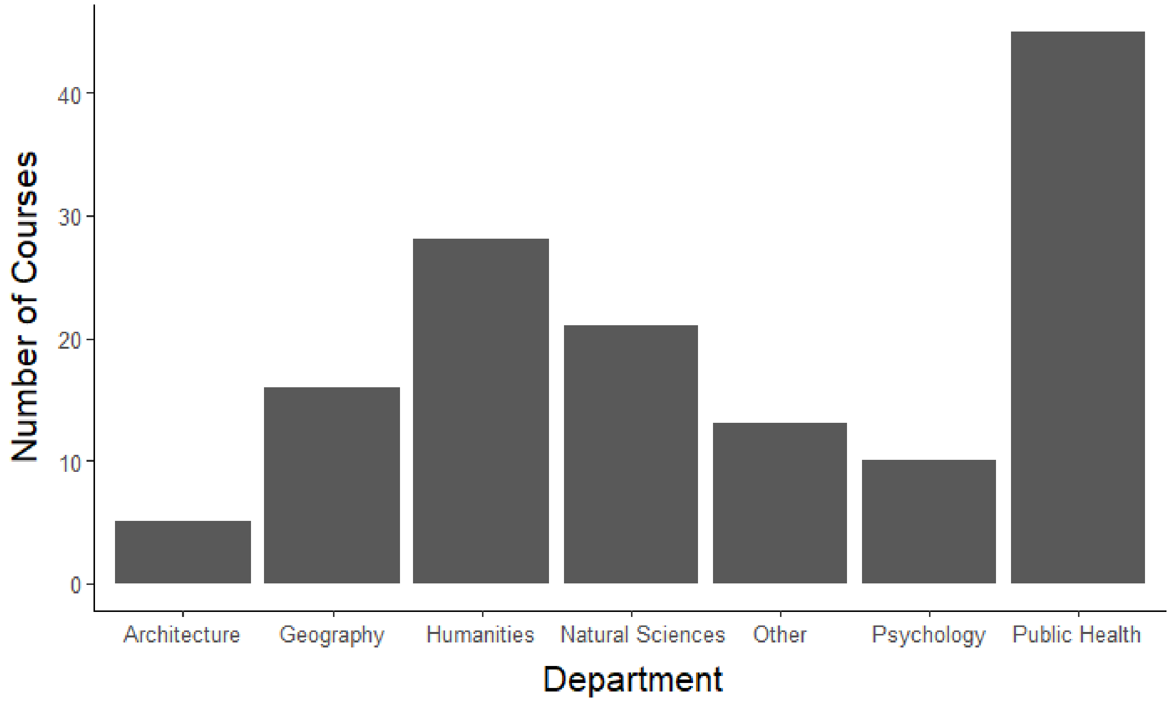

Figure A2.1: Number of disaster-related course offerings per department, based on sampled universities that had courses relating to disasters (n = 68).

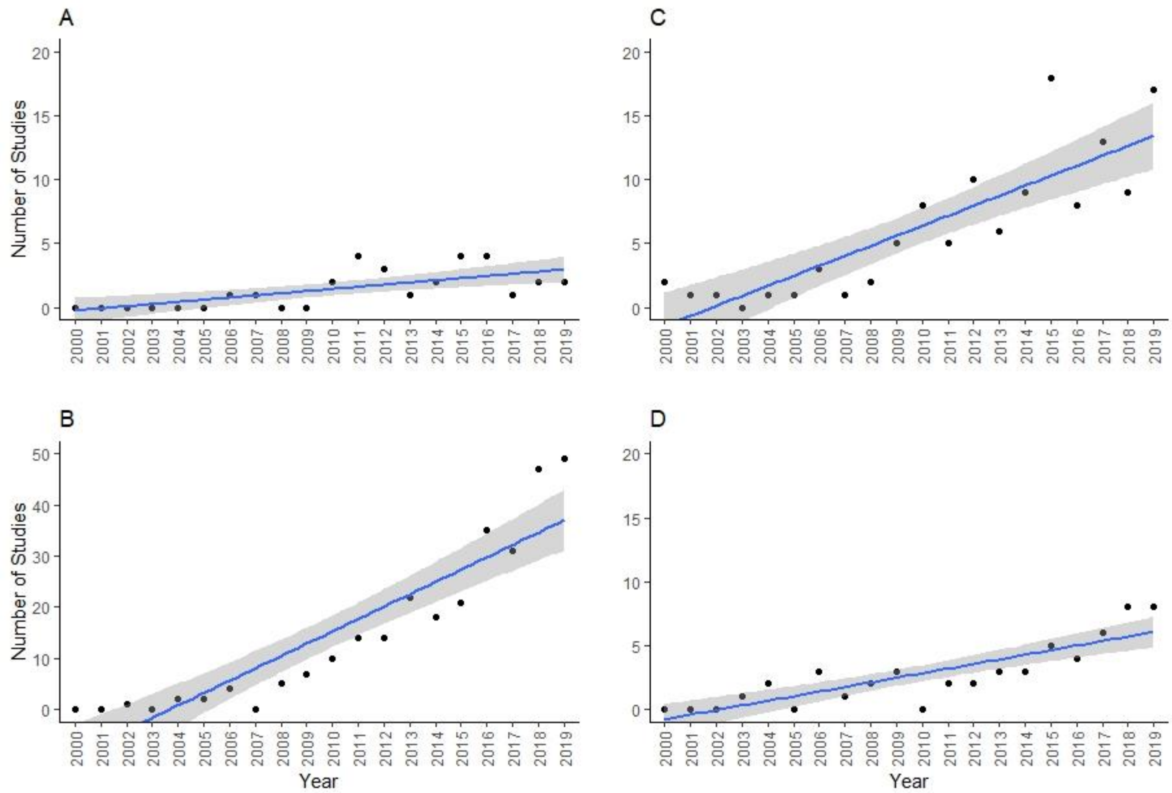

Figure A2.2: Number of disaster-related papers with community-engaged research frameworks or methodologies for the disciplines of ecology (A), psychology (B), public health (C), and economics (D). Each plot has fitted linear regression lines, with shaded areas representing 95% confidence intervals.