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The next generation of *action ecology*: novel approaches towards global ecological research

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Abstract. Advances in the acquisition and dissemination of knowledge over the last decade have dramatically reshaped the way that ecological research is conducted. The advent of large, technology-based resources such as iNaturalist, Genbank, or the Global Biodiversity Information Facility (GBIF) allow ecologists to work at spatio-temporal scales previously unimaginable. This has generated a new approach in ecological research: one that relies on large datasets and rapid synthesis for theory testing and development, and findings that provide specific recommendations to policymakers and managers. This new approach has been termed *action ecology*, and here we aim to expand on earlier definitions to delineate its characteristics so as to distinguish it from related subfields in applied ecology and ecological management. Our new, more nuanced definition describes action ecology as ecological research that is (1) explicitly motivated by the need for immediate insights into current, pressing problems, (2) collaborative and transdisciplinary, incorporating sociological in addition to ecological considerations throughout all steps of the research, (3) technology-mediated, innovative, and aggregative (i.e., reliant on 'big data'), and (4) designed and disseminated with the intention to inform policy and management. We provide tangible examples of existing work in the domain of action ecology, and offer suggestions for its implementation and future growth, with explicit recommendations for individuals, research institutions, and ecological societies.

Key words: action ecology; applied ecology; big data; citizen science; environmental leadership; environmental management; ESA Centennial Paper; planetary stewardship; training; transdisciplinary; translational ecology.

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Introduction

The last decade has witnessed a rapid emergence of tools that facilitate widespread participation in generating scientific knowledge. These advances have shifted the central challenge of producing useful ecological knowledge from "too little data available" to "too much data, too few analyses" (Reichman et al. 2011). In the advent of this new era, ecologists are faced with the challenge of developing new approaches to rapidly and robustly analyze these increasingly large and often multifaceted datasets, and to integrate different forms of data into practicable approaches to ecological problems (Michener and Jones 2012, Hampton et al. 2013).

The shift in availability of data and resources has revolutionized ecology. Major topics of research and principal methodologies are undergoing complete transformations (e.g., spatial ecology, macroecology, genomics), and entirely new fields of ecology are emerging (e.g., macrosystems ecology [Soranno and Schimel 2014] and predictive ecology [Evans et al. 2012]). This shift is also fostering the growth of transdisciplinary work across ecology; large datasets are now allowing ecologists to expand the scope and scale of their analyses, providing broad principles that can be useful across multiple domains (Hampton et al. 2013, Crain et al. 2014).

New technologies now also enable ecologists to discuss their science as it progresses. Preliminary results can be shared on social networks and blogs, thereby allowing the general public, journalists and policymakers to observe and participate in ecological research as never before. Open-access journals provide the coda to this symphony of collaboration (Giles 2005, Davis 2011), and the meteoric rise of this publishing approach is further evidence of this new, enterprising type of scientific action (Norris et al. 2008). This transparent, cooperative method of conducting ecological research is both a consequence of and a catalyst for a trend of increasing globalization in research and research activities (Jørgensen et al. 2015).

It is easy to get caught up in the rapidly changing landscape, but it is also worth asking how these changes affect the practice of our science. Increasing mandates for public access to research publications and underlying datasets (see: Butler 2003, Kenya Ministry of Information and Communications 2011, Rahemtulla et al. 2011, African Development Bank Group 2013, United Kingdom Cabinet Office 2013, United States Executive Office of the President: Office of Management and Budget 2013) mean that analyses often can be done readily and by a wider group of people. This demand, in conjunction with social networks that allow quick access to a broad audience (Nadkarni and Stasch 2013), enables ecologists to rapidly move from idea to implementation. This shift is perhaps the most significant characteristic of *action ecology*, and represents a broader change that is already affecting the very foundations of how ecological research is being and will be carried out in the future.

In this paper, we highlight how advances in the acquisition and dissemination of knowledge over the last decade have shaped the way that ecological research is conducted. We (1) discuss the factors that have led to the emergence of action ecology, (2) identify future directions in its evolution, and (3) outline how action ecology can be taught to the next generation of ecologists.

What Is Action Ecology? An Expanded

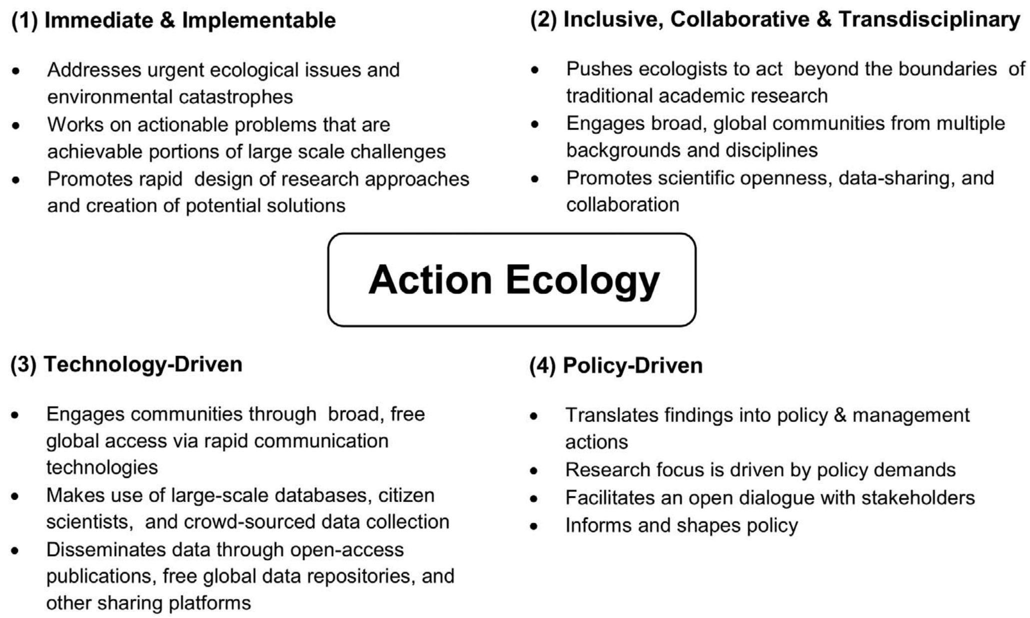

Fig. 1. Overview of the four key defining characteristics of action ecology. See *The four characteristics of action ecology* section for details and examples.

Definition

Action ecology has become in the last five years the flagship objective of the Ecological Society of America's (ESA) program on Strategies for Ecology, Education, Development and Sustainability (SEEDS; Rivera et al. 2010). First coined by A. E. Pérez and L. Calle in 2009, action ecology was first formally described in Bonilla et al. (2012) as follows:

> "*Action ecology is conducting research that has broader socio-ecological implications for the welfare of society as well as the ecosystems, and it requires collaboration with other disciplines, stakeholders, and any sectors that compose the socio-ecological system*".

In its most current iteration, action ecology emphasizes the impact-oriented synthesis of large-scale datasets to inform evidence-based management and policy that impacts ecosystems (Colón-Rivera et al. 2011, Marshall et al. 2011). Passionate support for action ecology has come from the leadership of the ESA, whose SEEDS student program was home to Pérez and Calle when they coined the term. Here, we, as part of the working group of the International Network of Next Generation Ecologists (INNGE; Jørgensen et al. 2015), have taken the original definition of action ecology and expanded it to include a greater emphasis on the rapidity of data collection, analysis, and implementation; and to accommodate recent developments in the fields of data management, ecological leadership, and scientific outreach.

We define action ecology as research explicitly targeted at providing relatively fast but effective analyses of diversely scaled and multifaceted datasets to support and inform policy and management decision-making about on-going ecological problems. Thus, action ecology is an approach to ecological research that is fundamentally and explicitly (1) geared towards providing immediate, implementable and targeted solutions to urgent ecological problems, (2) socio-ecological, inclusive, collaborative and transdisciplinary, (3) technology-driven, innovative, and aggregative (i.e., reliant on 'big data' sources and global, rapid communication platforms), and (4) designed and disseminated with the intention to specifically inform policy and management (Fig. 1).

These four characteristics of action ecology, which are further detailed below, distinguish this subfield from related subfields in conservation ecology, ecological management, and applied

Table 1. Glossary of subfields in ecology that are related to but distinct from action ecology.

Ecology subfield	Formal definition, and differences from action ecology	Source
Applied ecology	Applied ecology is ecological research that informs management practice—it therefore encompasses an extremely wide range of topics and approaches. It differs from action ecology in that it makes recommendations for application ex post facto, rather than integrating the goal of implementation into the entire process.	1
Conservation ecology	Conservation ecology is a branch of applied ecology that aims to improve the knowledge and preservation of biological diversity. It differs from action ecology in that it is a values-driven discipline, wherein solutions are devised primarily within a framework of biodiversity preservation.	2
Ecosystem stewardship (and environmental management)	Ecosystem stewardship is long-term management planning to maintain a region or system in its current status (often, partially or wholly protected). It differs from action ecology in that it relies on a predetermined baseline (i.e., maintenance of current status) to direct management activities.	3,4
Revolutionary ecology	Revolutionary ecology describes the transition towards, and promotion of, action ecology.	5
Translational ecology	Translational ecology connects end-users of environmental science to the field research carried out by scientists who study the basis of environmental problems. Translational ecology differs from action ecology in that it focuses heavily on the *process of translation*, necessitating a structural division between scientists and other stakeholders. This differs from action ecology's structural integration of both parties and process.	6

Note: Sources are: 1, Freckleton et al. (2005); 2, Sodhi and Ehrlich (2010); 3, Worrell and Appleby (2000); 4, Chapin et al. (2010); 5, Cólon-Rivera et al. (2011); 6, Schlesinger (2010).

ecology. For additional clarification, Table 1 briefly summarizes several subfields in ecology that are related to—but are distinct from—action ecology. The implications of these characteristics, as well as some examples of action ecology in practice, are outlined in the following sections.

The Four Characteristics of Action Ecology

1. Immediacy and efficacy

The challenges addressed by action ecology are immediate and actionable. These may be a part of larger trends (e.g., climate change), but nevertheless address problems that are proximate and exigent (e.g., shifts in commercial fish stocks [Sumaila et al. 2011], changes in coastlines [Johnson 2012]). The ability to approach pressing environmental problems in a rapid, actionable way demands a particular set of skills and necessitates special training. In order to be effective at the type of rapid, transdisciplinary work that action ecology therefore necessitates, practitioners must be trained early and effectively.

Training next-generation ecologists for immediacy and efficacy: seven tenets for action ecology.—In order to prepare the next generation of ecologists for the needs of action ecology, we make the following recommendations:

1. *Foster transferable skills:* This includes mastering data (and metadata) management (Michener and Jones 2012, BES 2014, Costello and Wieczorek 2014), statistical and computational tools (Joppa et al. 2013, Barraquand et al. 2014), and the ability to synthesize data from multiple sources (Michener and Jones 2012). A recent study by Barraquand et al. (2014) highlighted the unmet need for quantitative training among early-career ecologists; this becomes ever more urgent as the changing landscape of data collection requires ecologists to be trained in state-of-the art analysis and modelling (Hobbs and Ogle 2011). Some private institutions and volunteer-led groups have taken the initiative in making quantitative training more available (see: *Software Carpentry*, http://software-carpentry.org; *Data Carpentry*, http://datacarpentry.org; and *Mozilla Science Labs*, http://mozillascience.org). We laud these efforts, and believe that universities can and should play a more active role in the progressive training of quantitative ecologists by providing greater opportunities in coursework and research support.

2. *Train students for communicating ecology:* Action ecology requires effective and engaging conversation with many stakeholders from a variety of backgrounds and disciplines (Hobbs 2006). To support this as a training goal, we advocate for universities and professional societies to develop supportive outreach programs. These include coursework and training in effective public outreach; professional experience opportunities in public affairs; and reward systems to recognize high achievement in effective public dialogue and engagement (Pace et al. 2010). As an exemplar, the British Ecological Society (BES) rewards outstanding performance in public engagement with their annual Ecological Engagement Award; further recognition in the UK comes from the STEM (Science, Technology, Engineering and Mathematics) Ambassador scheme.
3. *Develop transdisciplinary collaboration and engage with evidence-driven solutions:* Action ecology requires a clear and familiar understanding of many other disciplines (among them: sociology, political science, economics). To support this type of integrated learning, we advocate for universities and professional societies to expand transdisciplinary training opportunities (e.g., transdisciplinary research programs, such as the National Socio-Environmental Synthesis Center (SESYNC) operated by the University of Maryland; the Graduate Degree Program in Ecology at Colorado State University; the University Program in Ecology at Duke University; and the Center for Science and Policy at the University of Cambridge); to support and reward researchers who work across disciplines; and to create joint conferences with parallel professional societies (e.g., Yale's Theology & Environmentalism conference; the Alliance of Artist Communities' Arts + Ecology conference). Action ecology further necessitates the advance of evidence-based solution design (originating in the medical literature, expanding through global health and development, and now best characterized in ecology by Sutherland et al. 2004).
4. *Learning opportunities in science-policy and science-business interfaces:* Coursework alone will not satisfy the skill development required for successful careers in transdisciplinary work; training must include experiential learning in the form of internships, externships, and immersive professional learning opportunities. We advocate for the expansion of joint degrees and course offerings (e.g., Duke University's Master of Forestry/Master of Business Administration degree), for the expanded funding and promotion of transdisciplinary opportunities (e.g., the Natural Environment Research Council policy internships [UK]; the American Academy for the Advancement of Science [US] policy fellowships), and for relationship-building with key leaders in business and policy fields to recruit ecologists into existing professional learning opportunities (e.g., Goldman Sachs summer internship programs; White House internships). Not only will this broaden the career prospects of ecologists trained in this way, but it will also serve as a valuable long-term bridge between professionals in these fields (May et al. 2008).
5. *Broaden benchmarks of success and merit in ecology*: Traditional university training emphasizes "pure" research and quantitative benchmarks of success (e.g., publication impact factors) (Lawrence 2003). This is incompatible with measuring efficacy in action ecology, for which effective and impactful solutions may not meet traditional standards of scientific value (Morgan et al. 2008, Salguero-Gómez et al. 2009). Action ecologists may have an impact that is not well captured by their number of publications, grant support awarded, or number of students graduated. Critical contributions such as improved relationships, increased student and organizational opportunities, better mentoring, and strengthened public positioning, provide value in themselves and must be evaluated as such (Goring et al. 2014).
6. *Recognizing and expanding non-traditional qualification programs:* Non-traditional training and mentoring schemes are becoming increasingly popular among early-career researchers in developing countries. Such

programs enable young researchers who may not have formal academic qualifications to effectively engage in action ecology. The Association of Tropical Biology (ATBC), Flora and Fauna International (FFI), and Tropical Biology Association (TBA) now provide opportunities for students in these regions to participate fully in the creation of new scientific knowledge through research and study. Similarly, field programs such as the Xishuangbanna Tropical Botanic Garden ecological training courses (AFEC-X) provide crucial opportunities for developing world researchers to learn the skills needed to conduct independent ecological research. Giving greater recognition (and specific, titled qualifications) to programs like these provides the benefit of greater opportunity to both the students whom they engage and the larger ecological community.

7. *Expanding and supporting early education programs:* Although the focus of this manuscript has been on graduate and early career research opportunities, we also advocate the expansion of training at the elementary and secondary school level (or equivalent). With appropriate mentorship, schoolchildren can contribute significant scientific data (e.g., via SciStarter), which will not only enhance STEM education but bring greater awareness of ecological and environmental issues surrounding sustainability and resilience to the "next generation" of citizens.

2. Inclusivity, collaboration and transdisciplinarity

What do transdisciplinarity and inclusivity mean, in the context of action ecology?—In order to successfully address real-world environmental issues, collaboration across disciplines is vital. The terms *multidisciplinary, interdisciplinary* and *transdisciplinary* are increasingly used in scientific literature with regards to integrative research approaches, but are often ambiguously defined and interchangeably used (Tress et al. 2005). Where differentiated, these terms are typically defined as follows (adapted from Pooley et al. 2014). *Multidisciplinary* projects involve different disciplines researching a single problem or theme but working in parallel with little integration. *Interdisciplinary* projects involve dissimilar fields in a way that requires them to bridge traditional boundaries in order to create new knowledge and theory in pursuit of a common research goal. *Transdisciplinary* projects integrate multiple types of stakeholders (e.g., academic researchers; citizen scientists; policymakers) in pursuing a common goal of creating new knowledge and theory.

Action ecology urges researchers to take action beyond the pursuit of knowledge. In doing so, it requires that ecologists reach out of the realm of academia and into a multitude of other spheres, most commonly: policy, advocacy, economics, print and digital media, healthcare, education, and urban planning. Action ecology is therefore inherently transdisciplinary, and must retain this characteristic in order to achieve any degree of success (see section *The four characteristics of action ecology: immediacy and efficacy*).

Furthermore, the open and collaborative nature of the technology underlying action ecology broadens the participant base. This means that some community members may have little or no traditional training in ecology; their primary work may be unrelated to ecological science; and they may be members of groups historically underrepresented or under-engaged in ecology. Thus, action ecology is not only inherently transdisciplinary, but also intrinsically reliant on a global, inclusive community.

Why are inclusivity and transdisciplinarity important to action ecology?—The primary motivation of action ecology is to provide immediate, effective, implementable solutions. Thus, any measures that improve the feasibility or increase the scope of solutions to ecological challenges are valuable to action ecologists. The inclusive, transdisciplinary participation of diverse stakeholders in action-oriented ecological work directly improves both feasibility and scope of action ecology outcomes in the following ways:

1. *Improved research design and direction:* Effective ecological research often requires expertise from multiple, complementary disciplines. This multi-perspective research forms the baseline, giving a strong foundation on which action can subsequently take place. Collaborations across disciplines within the natural sciences have long been a part of the ecological research framework.

For example, restoration ecologists frequently partner with limnologists to understand the mechanics of polluted stream remediation (Walsh et al. 2005); reintroduction biologists partner with community ecologists to predict the success of ferret releases (Russell et al. 1994); soil scientists collaborate with biologists to investigate heavy metal influences on microbial communities (Kandeler et al. 1996). Action ecology extends these traditional forms of collaboration to include stakeholders in community leadership (Lysack 2012, Wageman et al. 2012), environmental policy (Cardinale 2011), communications/media (Davison et al. 2014), and other fields that can provide critical contextual analysis of research design, direction, and conclusions.

2. *Improved communication, implementation, and support:* Inclusive, transdisciplinary work has the potential to enhance and promote communication between different regions, communities and different disciplines (Fischhoff 2012). This improved communication can provide value by itself (as in the above-described research collaborations), or it can lead to helpful political or managerial outcomes. This is because of the strongly positive relationship between direct engagement and support for scientific initiatives and policies (Greenwood and Riordan 2001). Public groups that are well-represented and engaged in the discernment, discovery, and decision-making process surrounding an ecological issue are most likely to support the implementation of new and potentially valuable solutions (Roe 1996, Carr and Hazell 2006).
3. *Improved efficacy and knowledge:* Action ecology relies on large-scale datasets, often provided by individuals working beyond the traditional bounds of the ecological research community. Increasing engagement among these source groups therefore leads directly to a larger database of information from which action ecologists can draw. Furthermore, the broader engagement of participants from multiple backgrounds, knowledge systems, political and personal orientations, and points of view improves the quality of knowledge creation by forcing action ecologists to challenge presumptions, look for blind spots, and press farther at the frontiers of information. Such inclusive, transdisciplinary, and cross-cultural engagement also widens the pool of problem-solvers, enriches the scientific dialogue, and enhances the probability of identifying novel solutions (Buckingham et al. 2012).

Future areas of focus for increasing inclusivity and transdisciplinarity in action ecology.—Goring et al. (2014) suggest that a future of enhanced interdisciplinary work will only be possible with a cultural change; specifically, with the expansion of ecologists' measures of productivity so that collaboration is rewarded, rather than penalized. We agree, and also put forward the following points of focus as critical areas of future growth for action ecology:

1. *Policy:* Ecologists must continue to partner with policymakers and advocates to ensure future opportunities for ecological action are supported at a foundational level.
2. *Innovation:* As experimental, innovative biological approaches continue to advance and grow in both popularity and efficacy, it is critical that ecologists join in the conversation with emerging fields of research like synthetic biology and biological design (Redford et al. 2013).
3. *Funding:* Venture investment and environmental entrepreneurship have presented new avenues to bring funding and support to ecological work, and to drive the field towards action. The expansion of impact investment and growth of environmental investment opportunities (e.g., Credit Suisse's Sustainable Products & Investment Services, launched in 2013), as well as the arrival of advisory firms geared specifically toward ecological investment (e.g., Synchronicity Earth, founded in 2009) have opened more avenues of support to ecologists than ever before.
4. *Near-peer partnership:* Despite fundamental differences in approach, both action ecology and its cousin disciplines (see Table 1 for a detailed accounting of these) can profit from joint action toward mutually beneficial goals. Strengthening bonds between profes-

sional societies on matters of critical advocacy, such as seeking federal funding for basic science research, can produce cascading rewards for all near-peer partners. One potential avenue that has demonstrated potential value is in the shared support of cross-societal, multinational guidance groups such as INNGE or the International Association for Ecology (INTECOL).

5. *Developing world engagement:* Stakeholders and researchers from developing countries are under-represented in the global ecological community (Jørgensen et al. 2015). This is an unfortunate missed opportunity, since the support and scientific insight of ecologists from developing regions has the potential to greatly improve the body of knowledge in ecology. Several challenges hinder developing world ecologists from participating more fully in the larger research community; among the most prevalent are: (a) lack of fiscal allocations for research and development, (b) limited access to costly scientific literature, (c) few opportunities for training, and (d) lack of physical infrastructure to support ecological work (Watson et al. 2003, Altbach 2009, UNESCO 2010). Collectively, this has resulted in historically lower scientific output than in developed countries (although this gap is closing [Holmgren and Schnitzer 2004]). Redressing these issues will be one of the chief challenges facing action ecology as we seek greater inclusivity in the decades to come.

Successful examples to increase inclusivity and transdisciplinarity in action ecology.—In recent years, increasing efforts have been made to reduce barriers to full participation in ecology, thereby better engaging participants from under-represented groups and the developing world. To wit, a number of major professional bodies have long-established support programs for researchers from developing countries (e.g., the Ecologists in Africa grants from the BES and the developing world student grants made by the Student Section of the ESA). These large professional societies have also supported outreach to underrepresented groups (e.g., the ESA SEEDS program; the Doris Duke Conservation Scholars program; the National Science Foundation's Institute for Broadening Participation [IBP]). Collaborative research projects and degree programs between countries across the development spectrum (e.g., Horizon 2020) are also on the rise.

In addition, provision of access to paid literature through online portals is helping to bridge the global information divide by enabling developing countries to gain access to vast amounts of previously inaccessible publications. Examples include the UN-led initiatives OARE (Online Access to Research in the Environment), HINARI (Health InterNetwork Access to Research Initiative), and AGORA (Access to Global Online Research in Agriculture). Finally, widened opportunities for communication and networking with researchers in developing countries via social media networks have helped to narrow under-representation from developing countries (Jørgensen et al. 2015). Some globally distributed experiments have begun to operate with decentralized budgets that permit local innovation in science funding to support local research (e.g., NutNet, http://www.nutnet.umn.edu and eBird).

Support for transdisciplinarity has also grown, and this growth is best represented through the proliferation of forums, meetings, conferences, and seminars that bring together stakeholders from divergent disciplines. The recent *Ecology and Economics* open online seminar series, a joint initiative between INNGE and the Institute for New Economic Thinking—Young Scholars Initiative (INET-YSI) is a key example of a relatively rare partnership crossing the natural and social sciences. Another key transdisciplinary meeting was Goldman Sachs' recent Environmental Finance Innovation Summit—an event of particular importance, as it was originated and organized by stakeholders in business and finance.

Other prominent examples of transdisciplinary and inclusive action are global research hubs and partnerships. Here it is worth highlighting Applied Environment Decision Analysis (AEDA, http://www.aeda.edu.au/) and Centre of Excellence for Environmental Decisions (CEED, http://ceed.edu.au/), as they both are formed by a transdisciplinary team of ecologists, economists, mathematicians and social scientists. Their multifaceted composition and wide collaborative networks allow them to produce environmental solutions which are realistic and manageable options (Wilson et al. 2006, Guisan et al. 2013). Such groups showcase the value of working with a diverse array of fields to affect real and sustained ecological change. In this vein, some other particularly inclusive and transdisciplinary examples from the USA include:

1. The Eco-Vision Festival of the Student Section of the ESA: Begun in 2008, this event takes place at the ESA annual meeting, and celebrates the communication of ecological research through the universally accessible outlets of visual media.
2. The Eco-Service award of the ESA: Funded in 2009 in partnership with the Union for Concerned Scientists, this award recognizes the actions of young members of the ESA who directly improve the broader global community through work in applied ecology, outreach, education and action ecology (Salguero-Gómez et al. 2009).
3. The Parks & People Foundation and the Student Conservation Association both engage with underrepresented youth in urban centers to teach fundamentals of ecology while developing collaborative, innovative solutions to local ecological management challenges.

3. Technology-driven

Action ecology is driven by, reliant on, and evolves alongside technological advances. These influential advances can be split into the following three categories: (1) communication technologies, (2) data collection and analysis technologies, and (3) data dissemination and open-access publication platforms. Below, we detail some of the most impactful technological advances within each category.

Global communication and collaboration.—1. Online communities and social networks. The rise of social networks (e.g., Twitter, Facebook, and Weibo) and free blogging platforms (e.g., Dynamic Ecology) allow for broad participation in science as never before. Communication on these platforms is direct, simple, and allows ecological stakeholders from multiple groups worldwide to engage in instantaneous dialogue with other groups, entities, and traditional researchers. In addition, the recent, explosive growth of social networking sites for scientists (e.g., ResearchGate, http://www.researchgate.net; [5 million users as of August 2014] and Mendeley, http://www.mendeley.com) and ecologists (e.g., the African ecology-specific SafariTalk, http://www.safaritalk.net) have created new, global platforms for scientists and ecological stakeholders to communicate. These online networks provide tools to synchronize and interlink across networks where scientists can rapidly generate, share and refine new ideas in a community of peers and public stakeholders (Darling et al. 2013).

2. Free online surveys, questionnaires, and datasheets. The proliferation of free data collection and organization platforms (e.g., Google Forms, Qualtrics, SurveyMonkey) has facilitated the collection of data from globally scattered ecological practitioners. This has expanded opportunities for large-scale metastudies of scientific communities themselves (Barraquand et al. 2014, Sutton and Lopez 2014).

3. Free online collaboration and project management platforms. The above opportunities, when combined with the collaboration power of free voice and video meeting programs (e.g., Skype, Appear.in) and online document/task sharing (e.g., Google Docs, Trello, Slack) mean that more scientists and ecological stakeholders are able to meet and work together than ever before. Global collaboration is no longer restricted by geography or physical access, but instead can take place at any time and in (almost) any place.

Data collection and analysis across technological platforms.—1. Crowd-sourced citizen science and participatory action research. Collaborative research that relies on the shared collection and reporting of data related to scientific or social issues is a hugely useful and increasingly critical aspect of knowledge discovery in ecology. Collaborative work of a one-way communication type (referred to as crowd-sourced science, or citizen science) involves the collection of data by members of the general public, and the subsequent contribution or relinquishment of that data to a larger database or dataset under analysis by scientific groups.

Collaborative work of a two-way communication type (referred to as participatory action research) typically involves the collection of data by members of the general public as part of a collaborative dialogue with professional scientists, in which citizens are also educated and empowered to influence and redesign the research program and questions (Krasny and Bonney 2005).

Over recent years, the growth in number, scale and significance of both types of citizen science initiatives has been substantial within ecology (Silvertown 2009), providing both numerous benefits and new challenges as an ecological research tool (Dickinson et al. 2010).

Recent successes in crowd-sourced science (e.g., iNaturalists' *Observations By Everyone; mPing*, developed by NOAA; *Loss of Night*, developed by Cosalux GmbH; and *What's Invasive!*, developed by the University of Georgia; *eBird* [Sullivan et al. 2009]) are evidence of the previously undervalued potential of the general public for making single-point contributions to a massive, open dataset (Dickinson et al. 2012). For further reference, the Citizen Science Alliance (CSA) maintains a list of other projects in this vein.

2. Statistical and spatial analysis packages. The use of statistical/spatial analysis software packages now allows the rapid analysis of massive volumes of data which were formerly unapproachable. Increased processing power and open-source software (particularly in the popular programming languages of *C++*, *R*, *Python*, and *Ruby*) have rapidly advanced the speed and complexity of scientific analyses (Green et al. 2005, Luo et al. 2011).

Such analyses allow large datasets to be interrogated with respect to spatial relationships, eco-climatic conditions, and temporal scales simultaneously (Irschick 2003, Salguero-Gómez and de Kroon 2010). These techniques lend new understanding to the patterns and processes which underlie many ecological phenomena. For this reason, skills in geospatial analysis and programming/coding are becoming increasingly critical for ecologists (Barraquand et al. 2014).

3. The genomic revolution. The transition to genome-scale ecology is ongoing and rapidly evolving; sequencing rates have been doubling every five months (Stein 2010) with a corresponding halving of costs in the same time frame (Bonfield and Mahoney 2013). This exponential growth means that ecological questions can be asked at the genome level with ever-greater resolution, particularly as the full potential of recombinant studies is explored (Sousa and Hey 2013). Being able to consider ecosystems directly with meta-genomics approaches (e.g., Allen and Banfield 2005), as well as allowing investigations of adaptive processes in non-model species (Ekblom and Galindo 2011) greatly expands the impact of contemporary evolutionary ecology. Collaborative solutions between genomics and ecology will be a critical part of the future of ecological problem-solving. The future of such collaborations is likely to lie within specialized forums like Conservation Genetic Resources for Effective Species Survival (CONGRESS; Hoban et al. 2013), and will rely on taking full advantage of large data repositories (e.g., Dryad). In ecological genomics, as in the broader field of ecology: more data means more opportunity to identify ecological solutions.

Data dissemination and open-access publication.— 1. Online datasets and data repositories. Also critical to action ecology is the principle of scientific openness; scientific data and results should be as widely disseminated and openly accessible as possible (Soranno et al. 2014). Open science and adherence to scientific (meta)data management best practices (e.g., as outlined in Michener 2006, Costello and Wieczorek 2014, and as suggested by USGS Data Management Training Modules) improves not only availability of data and publications, but also the transparency of methods and analyses. With an estimate of less than 1% of data available after publication (Reichman et al. 2011), the need for data access and sharing is self-evident: the scientific method requires constant re-evaluation of results.

Efforts to improve openness, transparency, and accessibility in the scientific process have grown exponentially in the last ten years, hinging largely on changes in attitude toward the process of peer review, open access journals, and data sharing (Reichman et al. 2011). Journals are increasingly supportive of data availability, with some even requiring datasets to be made accessible as a condition of manuscript submission (Reichman et al. 2011, Wulder and Coops 2014).

Such data sharing has been facilitated in part through the growth of free online data sharing and storage platforms. Some great examples of successful repositories include Dryad and the

Knowledge Network for Biocomplexity (KNB).

Shared databases and efforts like the DataONE project (https://www.dataone.org) have also been instrumental by providing a centralized format that brings multiple datasets together. Other similar examples include General Biodiversity Information Facility (GBIF) and Map of Life (Jetz et al. 2012) for species occurrences; YouTHERIA (Jones et al. 2009) for mammal traits, Botanical Information and Ecology Network (BIEN) for plant distributions, abundance and traits; WorldClim for climate and environment data; and GenBank for genetic sequences. Some databases can even be called from within statistical environments such as *R* and processed directly, such as the recent launching of high-resolution demographic records of ca. 600 plant species worldwide via the COMPADRE Plant Matrix Database (Salguero-Gómez et al. 2015).

When appropriately organized, such online data repositories strengthen cooperation between ecology and other disciplines, encourage data retrieval and sharing, and facilitate large-scale, transdisciplinary analysis. Centralizing and making better use of existing data is therefore not only a priority for macroecology, as suggested in Beck et al. (2012), but also an invaluable goal for action ecology.

2. Revised peer-review processes and open-access publication. There have been a suite of recent initiatives seeking to revise the traditional mechanisms of peer-review and paid publication. The process of peer-review is central to the principles of research and is required to ensure the integrity of science. However, classical peer-review approaches are struggling to keep up with the rapid increase in publications and technological advances in the dissemination of research findings. The resulting crisis, where too few scientists are involved in the review of too many papers, is slowing down time-to-publication in peer-review journals, and consequently science as a whole (Alberts et al. 2008, Hochberg et al. 2009, Aarssen 2012). Recently, different solutions have been suggested to resolve this crisis (Aarssen 2008), including pre-and post-publication open-review (Desjardins-Proulx et al. 2013, Soergel et al. 2013), cascading peer-review, and attracting more young ecologists into the reviewing process (Donaldson et al. 2010, Hochberg 2010, Zimmerman et al. 2011, Curran et al. 2013).

In further response to criticisms of traditional publishing, the popularity of alternative publishing methods has grown (van Noorden 2013). These publication alternatives include post-publication review (e.g., F1000 Research), online-only journals (e.g., Ecosphere, Methods in Ecology and Evolution), and open-access publishing (e.g., Public Library of Science; PeerJ). Increasing demands from members of the public have also pressured scientists to make the results of their research broadly available—in the United States, bills proposed to mandate open access to the results of federally funded research (e.g., Fair Access to Science and Technology Research Act of 2013, proposed in 113th Congress, 1st Session) have received widespread, bipartisan support.

4. Policy-ready

The results of action ecology projects are policy-ready; that is, they are clear, simple recommendations that can be transferred directly into critical memos or factsheets to inform policy or management action. While applied ecologists seek to reach out to policy-makers ex post facto, hoping to have some of their findings used to support the decision-making process, action ecologists seek to merge their work with the origination of policy goal-setting, thereby fundamentally influencing the policy-making process (Balmford et al. 2002, Adams et al. 2004). At present, however, the burden of dissemination is shared by a very small group of participants. Shockingly, only 5% of researchers account for 50% of broader engagement activities in the natural and biological sciences (Jensen 2005).

Why is early and consistent engagement of policy stakeholders important to action ecology?—Action ecology is, at its core, oriented toward action. It is guided at such a fundamental level by the desire and need for action that it requires early and complete engagement with policy stakeholders. We therefore advocate an early and aggressive form of integration that brings policy stakeholders to the table long before they would be engaged by traditional ecology. By including these critical stakeholders from the outset, action ecology can engender:

1. *Improved understanding of the scientific process:* One of the chief challenges facing

ecologists and other environmental scientists is a limited public understanding of the process by which scientific knowledge is produced. This limitation has led to significant obstruction of the scientific process, weak integration of scientific findings into policy, and outright rejection of scientific recommendations—particularly with respect to ecology and climate change (Oreskes 2004). Integrating policy stakeholders early and often in the discovery process will help to ameliorate some of these misunderstandings, easing the way for future dialogue and managing expectations of scientific results.
2. *Improved public support for policy and management:* As public demand for evidence-based policies across disciplines ("evidence-based everything", Pawson et al. 2011:519) has grown, policymakers find themselves under greater pressure to provide peer-reviewed, scientifically tested evidence to support their policy design and direction (Pawson et al. 2011, Prewitt et al. 2012). Policymakers who cannot provide this support find themselves at a major disadvantage to opponents, and run the risk of losing constituent support for proposed laws or policy measures. Early integration of policymakers into the process of ecological data collection and analysis relieves this burden and provides a further incentive to policymakers to support future ecological endeavours.
3. *Improved policy outcomes:* Policy that is based on rigorously tested, well-supported evidence is better, safer, and more effective. From the Coalition for Evidence-Based Policy (USA): "Examples of proven effectiveness are rare in part because rigorous studies, such as well-conducted randomized controlled trials, are still uncommon in most areas of social policy. Meanwhile, careful investigations show that the less-rigorous studies that are typically used can produce erroneous conclusions and lead to practices that are ineffective or harmful." (CE-BP 2014). It can be logically assumed that more rigorously tested and critically examined policies will lead to better proposals and implementations, thereby improving outcomes.
4. *Improved research efficacy:* In order for action ecology to provide solutions to immediate needs, it must understand what those needs are. One particularly efficient way to do this is through close integration with policymakers, who represent (or, at a minimum understand) the most pressing needs and concerns of the public which they serve. Close conversation with policymakers early in the research design process (often, at the point of hypothesis origination) can help to direct preliminary inquiries, contextualize data, and define the boundaries of potential recommendations. It can also bring to light new data sources not traditionally known to academics. In this way, action ecologists can help to ensure that their work will be as actionable, useful, and efficient as possible.

An example of the successful and complete engagement between policymakers and other ecological stakeholders came as a reaction to the immense oil spill in the Gulf of Mexico in 2010 (Camilli et al. 2010). Working with the ESA's Rapid Response Team, early-career ecologists were pivotal in the construction of a searchable database of experts and a list of existing datasets on ecological conditions in and around the Gulf prior to the spill. This resource was able to provide critical information to support policy development and decision-making as the spill recovery efforts progressed (Ramos et al. 2012).

Conclusion

The new, more nuanced definition of action ecology that is provided herein describes it as an approach to ecological research that is fundamentally and explicitly (1) geared towards providing immediate, implementable and targeted solutions to urgent ecological problems, (2) socio-ecological, inclusive, collaborative and transdisciplinary, (3) technology-driven, innovative, and aggregative (i.e., reliant on 'big data' sources and global, rapid communication platforms), and (4) designed and disseminated with the intention to specifically inform policy and management. Here, we have provided some tangible examples of existing work in the domain of action ecology, and have offered suggestions for its future growth and implementation.

Action ecology differs from other branches of ecology by its drive to target urgent issues, its use of large-scale datasets, and its reliance on novel technologies for analysis and dissemination. However, it aligns with the traditional ecology in its focus on a better understanding of the natural processes that underlie ecosystems worldwide. There is intrinsic value in promoting action ecology more widely, including greater scientific openness, broadened participation in the global ecological community, more widespread transdisciplinary collaboration, and a forward-pushing energy that will bring renewed vigor and relevance to ecology as whole.

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