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Rethinking the role of ecological research in the sustainable management of freshwater ecosystems

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SUMMARY

1. Despite the dramatic growth in the understanding of freshwater ecosystems in recent decades, many analyses indicate that the magnitude, complexity and urgency of freshwater environmental problems are increasing rather than decreasing. This pattern serves as a sobering reminder that ecological science is necessary but not sufficient for addressing a wide range of sustainability challenges and suggests the need for alternative strategies that can increase the effectiveness of science in environmental problem solving.
2. One key step in efforts to link knowledge with action more effectively is to use a conceptual model that examines factors leading to mismatches between the demand for science to achieve various societal goals and the supply of scientific information by researchers. Some common examples of supply and demand mismatches include instances where scientific information is provided but not needed, is needed but not provided, is not sufficiently trusted or reliable or conflicts with user's values or interests.
3. Recent work in sustainability science and related fields suggests that such mismatches can be reduced by more careful attention to the design of interdisciplinary research programmes and stakeholder partnerships. For example, research should be salient to the concerns of stakeholders. Research also needs to be independent and objective, so that it is credible to stakeholders. Moreover, researchers should work with stakeholders in ways that foster legitimate decision-making processes. We show how such design criteria can help in identifying and overcoming potential obstacles which limit the influence of ecological research on decision making.
4. These strategies are illustrated by a collaborative programme designed to promote the sustainable management of vernal pools in the northeastern U.S.A. These unique ecosystems are vulnerable to multiple stressors associated with urbanisation, forest management and climate change. An interdisciplinary team of researchers with a wide array of expertise (e.g., ecology, economics, communication, institutional governance, regional planning and forestry) has established a long-term partnership with multiple levels of government, the private sector, conservation organisations and citizens. Using a variety of approaches for linking knowledge with action, this programme has helped produce new land use regulations and management practices designed to balance economic development and vernal pool protection.
5. *Thematic implications*: freshwater ecosystems are increasingly impaired by multiple stressors that are usually the product of complex interactions between socioeconomic and biophysical factors. Thus, an understanding of the biophysical causes and consequences of such impairment will rarely be sufficient for achieving sustainable management policies and practices. Rather, we need a more integrative and action-oriented approach that

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explicitly acknowledges the strong coupling between natural and human systems and focuses on reciprocal interactions between knowledge-generating and decision-making processes. We believe that the emerging field of sustainability science holds considerable promise for strengthening connections between knowledge and action.

Keywords: interdisciplinary research, knowledge-to-action, problem solving, sustainability science, vernal pools

Introduction

Scientific understanding of freshwater ecosystems has increased dramatically during the last three decades. Many of these advances have been reported in the pages of Freshwater Biology, and the authors of studies in this special issue have made major contributions to such progress. Despite these scientific advances, growing evidence documented in this special issue and elsewhere indicates that many environmental problems involving freshwaters are increasing in magnitude, complexity and urgency. On local to global scales, we are witnessing mounting challenges associated with water scarcity, coastal dead zones, fishery depletion, invasive species and climate change (e.g. Steffen *et al.*, 2005; Allan *et al.*, 2006; Barnett & Pierce, 2008; Diaz & Rosenberg, 2008). The purpose of our study is to examine why ecological research has not been more effective in contributing to the sustainable management of freshwater ecosystems, and to introduce and illustrate strategies that offer greater potential for linking scientific knowledge with effective action.

Many voices have expressed concern about the widening chasm between available knowledge and effective action (e.g. Speth, 2004). One of the most succinct statements comes from Bocking (2004), who asks ''How can science be so important yet so ineffective in environmental affairs?'' In their summary of the last quarter century of research published in Freshwater Biology, Hildrew & Townsend (2007) lament that ''The gulf between the enormous amounts of science in an academic journal and its uptake in environmental management remains profound''. Examining the looming challenges of conserving freshwater biota, Strayer (2006) expresses doubt that current conservation strategies will be adequate to reduce the alarming rates of population decline and extinction.

Ecologists may experience an unusually personal form of disquiet as they witness this growing divide between the generation of new knowledge and its use in guiding effective environmental action. For many ecological researchers, their work is more than an intellectual quest to understand the complexities of interactions between organisms and the environment. It also represents a desire to create knowledge that leads to more effective protection and management of ecosystems and their biodiversity. If this desire is to be realised, however, we believe it will require the development of novel research strategies and partnerships.

In exploring how science can play a more potent role in affecting societal actions, we begin with a simple observation: ecological science is necessary but not sufficient for improving environmental outcomes. This view is a core principle in the emerging field of sustainability science (e.g. National Research Council, 1999; Kates *et al.*, 2001), which is concerned with the challenge of meeting human needs while protecting the planet's life-support systems. Sustainability science argues that an understanding of the dynamics of coupled natural – human systems requires an explicit focus on interactions among their social, economic and ecological components. In another sense, this integrative approach reflects the conviction that most of the world's pressing problems are inherently multi faceted, and that single disciplines are insufficient for developing the kind of robust understanding needed to support effective problem-solving strategies.

A variety of conceptual models have been proposed to explain why scientific research sometimes fails to inform societal actions (e.g. Sarewitz, 1996; Bocking, 2004). One simple model suggests that the chief barrier to this process is the level of uncertainty associated with scientific understanding and prediction, which impedes effective action. A common scientific response to this challenge is to develop research programmes focused on reducing uncertainty below some presumed threshold at which sufficient confidence exists about future states to facilitate appropriate actions. Although ecological research has generally been accompanied by significant progress in reducing scientific uncertainty, such uncertainty is rarely eliminated. For example, one of the lessons learned in ecological research is that complex interactions among different stressors can hamper efforts to develop accurate and precise predictions. In the face of lingering uncertainty, stakeholders often find ample grounds for disagreement about whether to take action, and if so, how. Scientists can experience confusion or frustration when attempting to address societal concerns about uncertainty, especially if those concerns are entangled with or obscured by stakeholder preferences for particular options, regardless of the scientific merits.

These experiences with societal deliberation and conflict about environmental issues underscore the fact that science is but one of many perspectives that can influence the decisions of individuals and institutions (Bocking, 2004). Many decisions are also affected by values, attitudes and belief systems that are completely unrelated to or in direct conflict with rationales based on scientific information. Although we might wish that science played a larger role in such decision making, it is important to recognise that it will rarely be the sole determinant of decisions.

Strategies for strengthening connections between knowledge and action

There is a pressing need for the development of strategic models to increase the likelihood that knowledge generated from research will contribute effectively to the solution of sustainability-related problems (Speth, 2004; van Kerkhoff & Lebel, 2006). A large literature examines many dimensions of this challenge and draws upon a range of disciplines including ecology, geography, political science, public policy, philosophy, environmental communication and sustainability science (e.g. see reviews in Lee, 1993; Lubchenco, 1998; National Research Council, 1999; Shabecoff, 2000; Dietz, Ostrom & Stern, 2003; Light & de-Shalit, 2003; Bocking, 2004; Speth, 2004; Palmer *et al*., 2005; Acheson, 2006; Cox, 2006; Lawton, 2007; Dietz & Stern, 2008). Rather than attempt to review this extensive and diffuse literature, we highlight several strategies that have emerged from independent analyses in multiple fields and that may hold great promise for strengthening connections between knowledge and action. It is important to recognise, however, that the effectiveness of different problem-solving strategies will vary depending on such contextual factors as the level of problem complexity, the degree of scientific uncertainty and the problem's geographical scale (e.g. Beierle & Cayford, 2002; Sabatier *et al*., 2005). Thus, we recommend that these strategies be viewed as putative 'best practices' for linking knowledge with action. We also suggest that they be analysed via research methods that can facilitate continuous evaluation and improvement based on the comparative, on-the-ground performance of different strategies.

Examining relationships between the demand for and supply of science

One promising conceptual model was recently developed by Sarewitz & Pielke (2007), who focused attention on factors affecting relationships between the societal need for scientific information and the generation of that information. They argue that this relationship can be viewed as a process of matching the demand for and supply of scientific information, and they explore factors that influence the degree of correspondence. In this model, the scientific knowledge and information that are needed by various individuals and institutions as input to their decision-making process(es) can be represented as a 'demand function'. Reciprocally, complex interactions among people, institutions and processes affect the supply of scientific 'products' (e.g. data, assessments, predictive models). Sarewitz and Pielke acknowledge that this model is too simplistic to reflect fully the complex and interactive processes influencing supply and demand. Nonetheless, their model helps to highlight the ways of improving the match between supply and demand, which can in turn increase the potential for scientific research to generate improved societal outcomes.

To illustrate this approach, Sarewitz and Pielke create a 2×2 matrix (Table 1) that examines the correspondence between various attributes of the supply function (e.g. research focus, quantity and quality of information products) and the demand function (e.g. user-specific information requirements). Both supply and demand are represented as binary

Table 1 The missed opportunity matrix for reconciling supply and demand (modified from Sarewitz & Pielke, 2007)

	Demand: can end-users make effective use of relevant research products?	
	Yes	No
Supply: does research process generate relevant scientific information?		
No	Research agendas may be inappropriate	Research agendas and user needs poorly matched; users may be disenfranchised.
Yes	Empowered users taking advantage of well-deployed research capabilities	Unsophisticated or marginalised users, institutional constraints or other obstacles prevent information use.

states to simplify the analysis. For supply, the research process can either produce or fail to produce information that is relevant to the needs of decision-makers. For demand, potential users either can or cannot make effective use of research products to improve decision-making processes.

The four cells of the matrix serve to highlight qualitatively different outcomes associated with the supply of and demand for scientific information. Specifically, the lower left cell represents the optimal situation, in which the research process generates relevant information that end-users can readily use to improve decision-making processes and outcomes. In contrast, the upper left and lower right cells represent mismatches between supply and demand. The upper left cell defines a situation, in which the user can potentially benefit from research, but the research process fails to produce relevant scientific information. This could reflect an 'acute' problem where researchers are largely unaware of the problems that stakeholders are experiencing. Alternatively, the mismatch could arise, because the scientific information produced by research lacks regional specificity is provided in an inaccessible form or the information is unavailable when needed. On the other hand, the lower right cell represents a situation in which the research process produces relevant information, but users are unable to benefit from these research products. Possible explanations include institutional constraints that preclude information use, a lack of trust in the research process or the existence of stakeholder values and interests that conflict with potential actions based on the information. Finally, the upper right cell of the matrix represents a particularly challenging mismatch, in which relevant information is not produced, nor could end-users have made effective use of potentially relevant information. This situation might arise where researchers lack a clear understanding of stakeholder needs, and where potential end-users have limited ability to influence decision making.

This model should not be interpreted to suggest that stakeholders always have a clear understanding of their need for scientific information. Indeed, one critical role of research is to make stakeholders aware of emerging problems that would not otherwise be apparent. Nonetheless, these supply and demand considerations suggest that stakeholders will be less likely to take action to avert or reduce such problems until they understand the nature of the problem and the role that scientific information can play in developing solutions.

Institutional mechanisms for managing knowledge–action boundaries to increase the match between supply and demand

Cash *et al.* (2003) offer valuable insights into mechanisms that can potentially produce a closer match between the supply of and demand for science. They adopt a case study approach to evaluate key characteristics influencing connections between knowledge and action in the context of sustainable development. Together with other researchers (e.g. Hirsch Hadorn, 2002; Bocking, 2004), they seek to identify those characteristics that best account for variations in the success with which scientific information is harnessed to inform sustainability policies and practices. We summarise these characteristics and explore their roles in affecting strategies for linking knowledge and action.

Three characteristics of the information production process (i.e. saliency, credibility and legitimacy) play particularly important roles in affecting the likelihood that scientific research products positively affect decision-making processes (Cash *et al.*, 2003). Saliency is a function of the extent to which the research process and products are relevant to and meet the needs of stakeholders; note that salience is similar to the concept of relevance used by Sarewitz & Pielke (2007). Research credibility is related to the adequacy of the causal understanding of the system or problem. Legitimacy is determined by the way in which divergent stakeholder interests and values are acknowledged and addressed. Cash *et al.* (2003) emphasise strategies for strengthening all three characteristics of the knowledge production process, but they also acknowledge that these strategies will often entail challenging trade-offs.

Saliency can potentially be enhanced by a developing a clearer understanding of stakeholder concerns and needs prior to the initiation of research. Effective steps include the establishment of a constructive dialogue with stakeholders about the nature of the problem(s) they are facing and the goals they are trying to achieve. This dialogue can lead to a clearer definition of information needs of end-users, including the time frame in which information is needed as well as its format, resolution and regional specificity. This process could also probably benefit from efforts to blend science's emphasis on increased understanding with engineering's focus on the development of more useful solutions.

Credibility can often be increased by strengthening the logical basis for and technical adequacy of scientific processes used to generate information, explain relationships and make predictions. Credibility is a function of the ability to generate an adequate understanding of system states and cause–effect relationships for the system in question (Kueffer & Hirsch Hadorn, 2008). Peer-review processes often serve to enhance credibility, especially where these include formal scientific assessments or consensus statements (e.g. Millennium Ecosystem Assessment, 2005; IPCC, 2007).

Stakeholder perceptions of legitimacy can strongly affect the potential for consensus in the face of divergent values and goals (Beierle & Cayford, 2002; Bocking, 2004; Dietz & Stern, 2008). Efforts to measure concepts like legitimacy and representation are inherently difficult (Sabatier *et al.*, 2000). Nonetheless, legitimacy is believed to be a function of the openness of the process to stakeholder input, the extent to which scientific information is viewed as unbiased and the fairness with which diverse and divergent viewpoints are treated. Legitimacy can be enhanced by encouraging the participation of all stakeholders, creating transparent communication processes, developing rules of conduct, establishing criteria for decision making and ensuring that scientific research is conducted in an unbiased manner. Recent research suggests that these practices reduce the likelihood of stakeholder opposition to decisions that result from consensus-based processes (e.g. Dietz & Stern, 2008).

Although Cash *et al.* (2003) document the positive effect of all three characteristics on efforts to link knowledge with action, they also emphasise the inherent trade-offs in attempting to maximise all three goals. For example, efforts to increase the credibility of the research process often emphasise scientific criteria that can cause the research to appear less relevant or transparent to stakeholders. Similarly, stakeholder engagement efforts designed to enhance salience can be viewed by some as potentially jeopardising the unbiased nature of the research process, which risks a loss of legitimacy. Although there are no simple solutions to these dilemmas, careful attention is needed to balance these trade-offs effectively (Cash *et al.*, 2003).

Cash *et al.* (2003) place particular emphasis on the importance of managing the boundaries between the domains in which knowledge is generated and used. The world of expert knowledge generated by scientific research is often very different from the world in which stakeholder deliberation occurs and decisions are made. Active attention to these cultural differences is often required to facilitate productive interactions and increase the potential for positive outcomes. Cash *et al.* (2003) identify three processes that contribute to effective cross-boundary interactions: communication, translation and mediation (see also van Kerkhoff & Lebel, 2006). Effectiveness is enhanced by two-way communication processes that are frequent, sustained and inclusive. Supplementary translation systems can help to overcome cultural differences in language, experience and expectations. Although communication and translation processes often contribute to improved understanding, conflict can still arise because of differences in backgrounds, interests and values. Mediation can help to resolve conflicts that arise from concerns about legitimacy, especially by establishing consensus-based criteria for inclusiveness, transparency and decision making. A variety of organisational models can potentially be used to enhance these interactions. Regardless of their size or structure, such organisations are usually more effective when they are actively engaged with and accountable to all parties.

Potential roles for ecological research in linking knowledge with action

The previous ideas highlight alternative strategies by which ecological research can be conducted and have profound implications for their potential contribution to the sustainable management of freshwater ecosystems. One common strategy is to conduct basic research (*sensu* Stokes, 1997), with minimal attention to stakeholder needs or decision-making processes. This approach has been highly successful in generating new knowledge about ecological and other natural systems. It has been far less effective, however, in generating durable solutions to environmental and other societal problems characterised by high levels of scientific uncertainty coupled with conflicting values and interests (e.g. Sarewitz, 1996; Bocking, 2004; van Kerkhoff & Lebel, 2006). Regardless of what this implies about the value that society should place on basic research (e.g. Sarewitz, 1996; Stokes, 1997), these ideas suggest that the products of such research will often have relatively small near-term effects on decision-making processes and environmental outcomes.

A second strategy is to focus on issues for which end-users appear ready to make use of appropriate research products, but where relevant scientific information is not yet available. This approach is based on the idea that the research process should be shaped by the needs of decision-makers if we hope to increase the likelihood that environmental research will influence decision making. One key element of this strategy is initial, active engagement with stakeholders to understand their perception of the problem and information needs in the context of potential decision-making options.

A third strategy may be useful in situations where potentially relevant scientific products have already been produced but are not being used. In these circumstances, ecologists can collaborate with experts in the human dimensions of sustainability problems (e.g. communication, anthropology, economics, political science and law) to overcome barriers to the use of such potentially relevant information. Such innovative partnerships hold great potential for improving communication, increasing trust, overcoming institutional constraints and changing values.

Overall, these ideas suggest that efforts to link knowledge with action would benefit from much greater attention to potential obstacles which can limit the use of ecological research products in decision making. The missed opportunity matrix (Table 1) and the ''best practices'' identified by Cash *et al.* (2003) offer valuable guidance for strengthening connections between knowledge and action. It is also clear that the development of more effective strategies will require systematic research on the research process itself (van Kerkhoff & Lebel, 2006). Specifically, we need to understand how different characteristics of the problem (e.g. the level of complexity and uncertainty), stakeholders (e.g. the diversity of interest groups and values) and research process (e.g. the expertise and integration of the research team) influence the way in which the problem is framed, potential solutions are developed, and improved outcomes can be achieved.

Application to freshwater ecosystems: vernal pools as a model system

One way to evaluate these approaches for linking knowledge with action is to examine their influence on decision-making processes and environmental outcomes. One context in which we are performing such studies is in an on-going interdisciplinary project focused on interactions between the ecological and social dimensions of vernal pool conservation. In this section, we provide a brief overview of our work to enhance the sustainable management of these unique aquatic ecosystems that has involved various biophysical, socioeconomic and political challenges. This project is a component of Maine's Sustainability Solutions Initiative (http://www.umaine.edu/sustainabilitysolutions), which seeks to enhance connections between knowledge and action which result in improved solutions to sustainability-related challenges. A state-wide programme being led by the University of Maine's Mitchell Center, the Sustainability Solutions Initiative is supported by a $20 million, 5-year grant from the National Science Foundation.

In Maine, vernal pools are typically small (<0.5 ha), shallow aquatic environments that provide critical breeding habitat for a unique assemblage of amphibians and invertebrates. Because of seasonal inundation, these pools are usually fishless, which facilitates the persistence of amphibians and invertebrates that would otherwise be vulnerable to predation by fish. In the northeastern United States, these species include wood frogs (*Rana sylvatica)*, four species of salamanders (*Ambystoma laterale, A. maculatum, A. jeffersonianum and A. opacum)* and fairy shrimp (Calhoun & deMaynadier, 2008).

Incorporating stakeholder concerns and needs through the Vernal Pool Working Group to improve saliency

Effective management of vernal pool habitats (the breeding pool and associated terrestrial non-breeding habitat) is challenging for several reasons. First, they are difficult to identify remotely because of their small size and typically ephemeral hydroperiod. Second, amphibians that breed in vernal pools have complex life histories which require both terrestrial and aquatic habitats. Thus, efforts to protect these species must focus on the distribution and connectivity of multiple habitats within a landscape. Vernal pools are also vulnerable to a combination of stressors associated with human activities that degrade or destroy breeding and non-breeding habitat, including urbanisation, forestry operations, changes in temperature and precipitation patterns (i.e. climate change) and spread of diseases (Gahl & Calhoun, 2008). Thus, an understanding of potential synergistic interactions among these stressors is required for crafting effective conservation strategies.

One important impetus for a new approach to the protection of vernal pools in Maine came from the lack of agreement between federal and state wetland regulations and inconsistencies in policies towards smaller wetlands, particularly vernal pools. In the mid 1990s, Maine legislators and regulators were receiving feedback from frustrated constituents about the lack of coordination between federal and state wetland regulations. In response, the Maine state legislature passed a Legislative Resolve in 1993 setting up a Wetlands Task Force to recommend changes to the state wetland programme. This Task Force recommended formation of the Vernal Pool Working Group (VPWG), a multi-stakeholder group including representatives from various federal and state agencies, biologists/researchers, consultants and non-profit organisations, to address the vernal pool issues that were not adequately addressed in earlier legislation. Although there were no citizens-at-large included in the group, state agencies such as the Maine Forest Service and the Maine Department of Inland Fisheries and Wildlife were expected to bring the perspective of their constituents to the table. Similarly, the environmental consultant was able to bring concerns of developers and other clients forward for discussion. This Group was charged with developing a strategy to fill the gaps in current wetland regulations for small wetlands.

As emphasised by Cash *et al.* (2003), a key step in effective knowledge-to-action initiatives is ensuring that stakeholders play a central role in defining the problem, identifying research needs or information gaps and helping to shape solutions. Therefore, our first step in developing a conservation strategy was to create a working definition of vernal pools which was acceptable to a diverse array of stakeholders. Early in the process, it became clear to the VPWG that there was not a sufficient body of research on Maine vernal pool ecology to establish this working definition. Thus, the VPWG developed a multi-pronged approach to meet the mandate to improve conservation of pools: identify and fill gaps in knowledge (the science), educate stakeholders about the resource and engage them in problem solving and develop mechanisms (regulatory or non-regulatory) to conserve vernal pools. Later, we summarise these three parallel efforts and illustrate how they continue to feed into a comprehensive strategy for vernal pool conservation that arose from both top-down regulatory and collaborative management approaches.

Designing a research agenda to enhance scientific credibility

Numerous research projects were initiated to address gaps in knowledge-to-action identified by the VPWG. Collaborations among state agencies, non-profit organisations and private consulting firms were forged to address research gaps ranging from the best technology for remote sensing of pools to identifying the fine-scale habitat requirements (e.g. soil moisture, soil temperature, leaf litter depth and composition) of each species. We also addressed effects of forest management practices such as partial and clear-cutting on survivorship of larvae, juvenile and adult pool-breeding amphibians and quantified the spatial and temporal movement patterns of adults and juveniles. We quantified the variability in egg mass numbers for each species in breeding pools in different regions of Maine. Regular meetings of the VPWG throughout the period of research allowed for adjustments to research methods, initiation of new research as necessary and opportunity for input from stakeholders. For example, regulators wanted an analysis of species-specific egg mass numbers per pool to develop criteria for relatively productive pools that would be termed 'significant' vernal pools. They needed these data for key stakeholders, including policy makers and private landowners who would be subject to the regulation. Some of these stakeholders made it clear that legislation would be supported only if <50% of vernal pools were deemed 'significant' and hence subject to regulation. This standard was met using our research on egg mass numbers and is a prime example of challenging trade-offs that often occur when two cultures (science and policy) engage in collaborative problem solving (Cash *et al.*, 2003). Credibility was further enhanced through the publication of many studies on vernal pool conservation strategies in peer-reviewed journals (e.g. Calhoun *et al.*, 2003; Vasconcelos & Calhoun, 2004; Calhoun, Miller & Klemens, 2005; Baldwin, Calhoun & deMaynadier, 2006; Patrick, Hunter & Calhoun, 2006; Oscarson & Calhoun, 2007; Patrick, Calhoun & Hunter, 2007; Patrick *et al.*, 2008a; Patrick, Calhoun & Hunter, 2008b). Recommendations for resource management to regulators, resource managers and the natural resource committee of the state legislature would not have been accepted without the rigour of peer-review. Even though these decision-makers may not read the scientific literature, it is always referred to and included in legislative and management discussions. Laying the scientific foundation for action is a fundamental piece of a successful programme.

Engaging stakeholders in the process of communicating scientific results to strengthen legitimacy

Unfortunately, the results of scientific research are often inaccessible to or poorly understood by stakeholders, which reduces the likelihood that results will enhance decision making. Indeed, Cash, Borck & Patt (2006) emphasise the limitations of this ''loading-dock approach'', in which researchers adhere to established professional norms by publishing in academic journals and leaving stakeholders with the difficult task of determining how such research should be used in decision-making processes. Our outreach efforts avoided this traditional academic approach and focused instead on producing a series of non-technical publications on best management practices (BMPs) and conservation strategies for educators and practitioners (Calhoun & Klemens, 2002; Calhoun & deMaynadier, 2003, 2008). These science-based documents were designed to ensure that both economic development and pool habitat conservation could be realised. Stakeholder input was solicited *before* the writing began through workshops, stakeholder meetings and field trips. The forestry publication took 2 years longer to produce than it would have if it were written by researchers without consultation with practitioners. The inclusion of loggers and foresters in designing guidelines increased the level of 'buy-in' by stakeholders, including large industrial paper companies. The final guidelines were written in accessible formats designed for a broad audience of practitioners (e.g. local, state and federal regulators, natural resource managers, individual land owners, loggers, foresters, residential and commercial developers, educators and conservation organisations). Researchers and stakeholders also participated in dozens of workshops *post-publication* to increase the understanding of the guidelines and to share this information with a broader range of stakeholders. Since their publication, the guidelines for forestry practices around vernal pools have been used as a model in other northeastern U.S. states, while BMPs for development around vernal pools have been used as a standard by the Army Corps of Engineers and U.S. Fish and Wildlife Service in New England (both of these federal agencies are involved in regulating wetlands).

The importance of adopting flexible strategies for linking knowledge-to-action

The use of voluntary BMPs was successful in conserving pool functions in the context of forestry operations, where the impact is potentially reversible (e.g. unlike pavement, trees regenerate and provide suitable post-breeding habitat). The forestry community readily embraced the BMPs, because voluntary stewardship was preferable to regulation. In contrast, the BMPs for development were viewed as an impediment to economic growth and were not accepted by stakeholders. Given this, the VPWG recommended a regulatory solution for conserving pool functions in human-dominated landscapes. The group presented the scientific foundation for the proposed protections to the natural resources committee of the Maine legislature, who voted unanimously to support a bill providing protections for an ecologically outstanding subset of vernal pools recognised as significant vernal pools (SVPs). This successful outcome occurred in part, because stakeholders were familiar with the resource through the 10 years of outreach and research efforts by the VPWG. The legislation (LD 1952) was passed in 2007 and still stands as the most comprehensive vernal pool regulation for pools in forested landscapes in North America.

The fact that it took nearly 10 years to reach consensus on a four-sentence definition of vernal pool (Table 2) and to pass a SVP regulation underscores the patience and stamina required to foster productive partnerships involving scientists and stakeholders. Clearly, the SVP regulation reflected a political compromise and does not provide the level of protection (often, over 245 m from the breeding pool) recommended by ecologists for maintaining long-term populations of pool-breeding amphibians (see Harper, Rittenhouse & Semlitsch, 2008; Rittenhouse & Semlitsch, 2007; Semlitsch, 2008). Without such compromise, however, progress would have been halted and the goal of devising a practical conservation strategy that at least *considers* the best-available-science would not have been realised. Although the scientists' recommendation for a 200- m zone of regulation for SVPs was not adopted, the compromise of 75 m around each SVP provided recognition by policy makers that the conservation of terrestrial and aquatic habitats must be linked.

Table 2 Consensus-based definition of vernal pools created by the Vernal Pool Working Group

''A vernal pool, also referred to as a seasonal forest pool, is a natural, temporary to semi-permanent body of water occurring in a shallow depression that typically fills during the spring or fall and may dry during the summer. Vernal pools have no permanent inlet or outlet and no viable populations of predatory fish. A vernal pool may provide the primary breeding habitat for wood frogs (Rana sylvatica), spotted salamanders (Ambystoma maculatum), blue-spotted salamanders (Ambystoma laterale) and fairy shrimp (Eubranchipus sp.), as well as valuable habitat for other plants and wildlife, including several rare, threatened and endangered species. A vernal pool intentionally created for the purposes of compensatory mitigation is included in this definition''.

The SVP regulation also provided the impetus for town involvement in natural resource management strategies for vernal pools at the local scale and provided even greater opportunities for addressing unique 'sociocultural contexts' that influence the management of natural resources on private lands. The University of Maine and Maine Audubon Society are currently working with 14 Maine towns on vernal pool mapping and conservation projects including research to address the economic benefits and costs of conservation on private lands. Although no one town will necessarily fill the gaps left by the state regulation, the involvement of local citizens and resource managers can potentially generate a wider appreciation for the spirit of the regulation and an increased sense of community responsibility for stewardship of these and other natural resources.

Collaborative strategies for linking knowledge with action: challenges and opportunities

The collaborative nature of the VPWG provided opportunities for different stakeholders to help define the problem, shape the research agenda and influence the decision-making process. Each of these activities is believed to strengthen the potential for linking knowledge with action (e.g. Cash *et al.*, 2003). But collaborative processes involving diverse groups of stakeholders are often complicated, time consuming and contentious (e.g. Sabatier *et al.*, 2000), which underscores the need for research on their effectiveness relative to conventional regulatory approaches. Although a growing body of work has sought to identify various factors that contribute to effective collaborative *processes* (e.g. level of participation), much less is known about the actual environmental, social and economic *outcomes* of collaboration (Sabatier *et al.*, 2000; Koontz & Thomas, 2006; Mandarano, 2008).

Research is currently underway as a part of the Sustainability Solutions Initiative to evaluate more rigorously the collaborative process used by the VPWG as well as its outcomes. This research, part of a Ph.D. project, makes use of an established partnership in which the University of Maine and Maine Audubon are working with 14 Maine towns on municipal-wide vernal pool mapping and conservation projects. Using a mixture of social science methodologies, this innovative, interdisciplinary project seeks to answer a variety of critical questions, including: (i) To what extent do collaborative planning efforts affect government policies concerning vernal pools?; (ii) Did the collaborative planning process help to overcome sociocultural conflict and foster a better understanding or perception of natural resource conservation?; (iii) Have individual and institutional choices been changed by the collaborative process?; (iv) Were new initiatives developed to link conservation to the economic well-being of the towns (i.e. to support sustainable communities)?; (v) Were barriers among the scientific community, practitioners and citizens identified and reduced or eliminated?; (vi) Do collaborative planning efforts have an effect on both the attitudes and behaviours of various stakeholders involved in conservation and development conflicts? and (vii) More generally, what are the factors contributing to or impeding the success of collaborative planning efforts?

Thus, a robust assessment of the success of the VPWG cannot be gauged by any specific legislation, but must be measured in terms of a range of tangible social and environmental outcomes (Mandarano, 2008). Moreover, it will be important to monitor the performance of VPWG on an on-going basis, not only to help maximise its own success, but also to help guide other collaborative efforts.

A clarion call for scientists

Many of the studies in this special issue provide compelling evidence of declines in the health of freshwater ecosystems at local to global scales. But what role(s) should ecological researchers play in response to such alarming trends? One option is to continue documenting patterns of ecological degradation, with the hope that society will respond to such evidence by implementing policies and practices that protect ecosystems and their biodiversity. To date, however, this approach has often failed to generate the level of action needed to halt or reverse these disturbing trends. As a consequence, scientists who focus on this role may find themselves relegated to documenting inexorable declines in ecosystem health and diagnosing the causes of ecological demise.

We believe that there is another, potentially more potent, role for ecologists. This role requires that they engage more directly in the complex processes by which society identifies and defines potential problems, deliberates about their causes and gauges the trade-offs of potential solutions. Evidence drawn from a variety of sources has begun to shed light on a suite of institutional mechanisms that can potentially facilitate efforts to link scientific knowledge with effective action. Nonetheless, much remains to be learned about the effectiveness of different mechanisms and their context dependence. Thus, the process of linking knowledge with action should be viewed as a form of social learning which can be enhanced by appropriately focused research. By actively participating in such novel and necessarily long-term research collaborations, we hope that ecologists can contribute more effectively to the production of knowledge and connection with actions that meet human needs while preserving the planet's life-support systems.

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Conflicts of interest

The authors have declared no conflicts of interest.

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