Improving management of small natural features on private lands by negotiating the science–policy boundary for Maine vernal pools

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Vernal pools are far more important for providing ecosystem services than one would predict based on their small size. However, prevailing resource-management strategies are not effectively conserving pools and other small natural features on private lands. Solutions are complicated by tensions between private property and societal rights, uncertainties over resource location and function, diverse stakeholders, and fragmented regulatory authority. The development and testing of new conservation approaches that link scientific knowledge, stakeholder decision-making, and conservation outcomes are important responses to this conservation dilemma. Drawing from a 15-y history of vernal pool conservation efforts in Maine, we describe the coevolution of pool conservation and research approaches, focusing on how research-based knowledge was produced and used in support of management decisions. As management shifted from reactive, top-down approaches to proactive and flexible approaches, research shifted from an ecology-focused program to an interdisciplinary program based on social–ecological systems. The most effective strategies for linking scientific knowledge with action changed as the decision-makers, knowledge needs, and context for vernal pool management advanced. Interactions among stakeholders increased the extent to which knowledge was coproduced and shifted the objective of stakeholder engagement from outreach to research collaboration and development of innovative conservation approaches. New conservation strategies were possible because of the flexible, solutions-oriented collaborations and trust between scientists and decision-makers (fostered over 15 y) and interdisciplinary, engaged research. Solutions to the dilemma of conserving small natural features on private lands, and analogous sustainability science challenges, will benefit from repeated negotiations of the science–policy boundary.

wood frog | community-based conservation | temporary pools | natural resource management | mesofilter

Many landscapes have small natural features that are far more important for providing ecosystem services and maintaining biodiversity than one would expect based on their size—e.g., coral heads in a bay dominated by sea grass beds or the ephemeral potholes that punctuate some prairies (1). Even individual organisms—such as large, old trees and the snags and logs they become—can fill a keystone ecological role (2). The importance of these features has long been recognized in some cases; for example, prairie potholes provide breeding habitat for >50% of all North American duck populations despite covering only a tiny portion of the area of their range (3). In other cases, such as vernal pools, recognition of their significant role is just emerging.

Vernal pools are small, ephemeral wetlands (usually fractions of a hectare) that typically fill in spring with snow melt and precipitation, or in fall with rising water tables, and are dry by summer's end. In glaciated northeastern and midwestern North America, vernal pools occur in shallow depressions in forest-dominated landscapes (4). Because they are largely free of fish, they provide an ideal breeding habitat for invertebrate and amphibian species susceptible to depredation by predators associated with permanent waters. Vernal pool systems include the pool and adjacent forests that provide shade and organic material for the pool and postbreeding habitat for pool-breeding amphibians that live the majority of their lives on the forest floor (5). Besides habitat for many aquatic and terrestrial species, vernal pools provide other ecosystem services, such as export of carbon and nutrients to adjacent forests (4, 6).

Although vernal pools are unique ecosystems that perform important functions at the landscape scale (7), they face significant management challenges. In the United States, vernal pools are regulated at the federal level and may or may not be regulated by state and local levels of government. This patchwork of regulatory strategies is not effectively reducing the vulnerability of pools to multiple stressors, including urbanization, intensive land-management activities, and environmental changes associated with climate change (4). Complicating management is the fact that most U.S. vernal pools occur on private land where public good values (e.g., biodiversity or ecosystems services) rarely accrue to a significant extent for private landowners. This private land setting also introduces an interesting mix of stakeholders, including multiple scales of government, diverse resource-management organizations, and heterogeneous landowner and development community interests. When faced with the prospect of vernal pool regulation, most landowners have little incentive to either inform regulators of the existence of pools on their land or to conserve them. Because pools are so

Significance

We address a key sustainability challenge: management of natural resources on private land. Managing small natural features, such as vernal pools, on private land presents unique problems but also unique opportunities to provide benefits to both nature and society. Our innovative approach to management and research described here uses vernal pools as a model system but exemplifies a broader framework for understanding social and ecosystem processes, interactions between them, and how these interactions may facilitate solutions. The challenges and opportunities encountered in navigating the science–policy boundary presented here are not unique to vernal pools: Our findings have wider conservation significance for natural resource management, especially for other small natural features on private lands (e.g., riparian zones, prairie potholes).

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small, filling is cheap, and landowners may find it within their financial self-interest to do so (8). Accordingly, vernal pools exhibit the classic spatial mismatch associated with small features that generate widespread benefits but require concentrated costs for their conservation, and thus they can ignite tensions over private property rights vs. societal rights to environmental protection (9). The small, ephemeral nature of vernal pools, the lack of public awareness of this resource, the uncertainties over vernal pool quality and location, and the fragmented regulatory authority at all governmental scales further complicate individual and institutional responses to calls for enhanced pool protection. However, the small size of these features also presents opportunities for flexible, innovative resource-management strategies on private lands in which developed uses and intensive land management coexist with designated natural resource conservation areas (10). The development and testing of new conservation approaches that link scientific knowledge, stakeholder decision-making, and on-the-ground conservation outcomes are important responses to this representative conservation dilemma (11, 12).

In this work, we recount a 15-y history of efforts to conserve vernal pools in Maine in order to examine how knowledge is produced and used relative to management of small natural features—in this case, vernal pools, on private land. This rich history provides an excellent opportunity to explore linkages among scientific knowledge, stakeholder decision-making, and conservation actions (13, 14). Our experiences also provide a unique opportunity to distill general guidance for boundary work by scientists in pursuit of solutions to pressing sustainability science problems (15), especially those related to small natural features and private land.

Vernal Pools: The Science–Policy Boundary

This historical summary emphasizes the following: (*i*) the coevolution of vernal pool management and research at the socially constructed boundary between scientists and decision-makers (broadly defined from policymakers to private landowners), and (*ii*) the role of multiple management units (e.g., federal, state, and local government), processes, and products (i.e., boundary objects) in successfully negotiating the science–policy boundary (14, 16). "Boundary object" is a term coined by the social sciences to describe tangible or intangible products, tools, or techniques that individuals or groups may use to process, interpret, or exchange information (e.g., maps, databases, scientific publications, or technical reports) (14, 17, 18). Conceptually, boundary objects maximize communication across scientific and decision-making communities to address tensions between divergent viewpoints (17). Boundary organizations, institutions that bridge the divide between scientists and managers (17, 19, 20), aid in the development and implementation of these different tools and processes (17, 20). Here, our purpose is to share lessons learned from our experience as academic scientists as we worked through five different phases of developing vernal pool conservation strategies (Figs. S1 and S2). This practical experience provides a useful foundation for considering the design and implementation of research and management approaches focused on the conservation of all small natural features on private lands.

Phase 1—Reactive Management Approach (1995–2007). Maine's vernal pool conservation effort began as a top-down, case-by-case, reactive approach based on an inconsistent patchwork of federal and state regulations (21). In 1995, vernal pools were identified as a resource of importance in state wetland regulations, but their protection was not implemented because the resource was not easily mapped (due to their small, ephemeral nature), as is required for a protected Significant Wildlife Habitat. Consequently, federal regulators urged Maine to improve its poor record in regulating small wetlands, including vernal pools. In response, Maine formed a collaborative Vernal Pool Working Group (VPWG) in 1999 with representatives from key federal and state agencies, environmental groups, environmental consultants, and an academic wetland ecologist (A.J.K.C.) (22, 23). The mandate of this boundary organization was to develop a state vernal pool conservation policy that would meet the mission of the regulatory agencies and be understood by the public.

Tasked with developing a vernal pool management policy, the VPWG realized that both they and the public knew little about this natural resource. There were no published research data on vernal pools in northern New England (24). The VPWG began with a multipronged strategy including the following steps: (*i*) a preliminary statewide inventory and ecological assessment of vernal pools; (*ii*) an evaluation of the feasibility of both voluntary and regulatory approaches to pool conservation; and (*iii*) public education and outreach. This strategy generated some important outcomes. The Maine Audubon Society and the University of Maine (UMaine; i.e., A.J.K.C.) collaborated on a citizen–science initiative, the Very Important Pool (VIP) program, which led to preliminary mapping and assessment of pools by trained citizen-scientists in select regions. From 1999 to 2004, the VIP program produced data on >400 vernal pools and introduced citizen-scientists and the wider public to vernal pool ecology and the importance of these small wetlands through dozens of workshops, newspaper and magazine articles, radio and television programs, and a manual, *The Maine Citizen's Guide to Locating and Documenting Vernal Pools* [Calhoun, 1999, 2003 (25)]. The collaborative initiative of the VPWG galvanized UMaine's vernal pool research program, which, in addition to citizen-focused activities, also responded to scientific gaps identified by the VPWG with ecological studies focused on understanding the pools as critical amphibian breeding habitat (e.g., refs. 26 and 27; see *SI Text* for a bibliography of UMaine vernal pool publications).

Phase 2—Experimenting with Voluntary Management (2000–2005). Many members of the VPWG believed that a voluntary approach to vernal pool protection—piggy-backing on the broad educational initiative—would be sufficient to conserve Maine's vernal pool resources and meet the needs of key stakeholders, including resource managers, the forestry community (both commercial and family woodlot owners), and the development community (developers, municipal planners, and real estate agents). Two lay manuals—one on best development practices for development around pools (28) and the other on habitat management guidelines for forestry (6)—were produced to provide more tools for voluntary stewardship of pool resources. A.J.K.C. and others hosted >50 workshops and public presentations for foresters, land trusts, schools, and various citizen groups. UMaine's vernal pool research team also initiated new studies focused on how forestry affects breeding pools and amphibian movements in adjacent forests (e.g., ref. 29 and *SI Text*) in collaboration with key forestry stakeholders. The voluntary approach achieved mixed success. The forestry community was quite receptive to the guidelines and continues to implement them, particularly state agencies (e.g., Maine Forest Service and Bureau of Public Lands), some private small woodlot owners, and many private commercial forestry companies. However, the impacts of development on pools and forested habitat adjacent to pools were not being addressed by a strictly voluntary approach (28).

Phase 3—Emergence of a Regulatory Approach (2001–2007). The shortcomings of a voluntary approach prompted the Army Corps of Engineers (ACOE), New England District, to include review of impacts to vernal pools of any size in its purview, which, in turn, led the VPWG to support a parallel regulatory approach to limit the impacts of development. The VPWG debated at length about regulatory tools and, in the end, decided that only a subset

of vernal pools should be regulated as Significant Wildlife Habitats under Maine's Natural Resources Protection Act (30).

With formal regulation on the horizon, agency staff expressed specific needs for scientific information to support a regulatory approach, including a formal definition of vernal pools, criteria to support prioritization of a subset of Significant Vernal Pools (SVPs) for conservation, and the basis for regulatory standards (most notably, zones of regulation around pools). The VPWG met multiple times per year for 10 y to develop, among other tasks, the definition of a vernal pool and of a SVP—a protracted process because of the group's broad constituency. Legislation was drafted with input from the VPWG and its stakeholders and was passed by the Maine Legislature in September 2007 after four legislative information sessions and hearings attended by A.J.K.C. Notably, the VPWG crafted definitions for vernal pool and SVP using data from the VIP citizen–science program and from UMaine ecological research. SVPs were identified as pools with exemplary breeding activity of amphibian indicator species (based on egg mass counts) or the presence of fairy shrimp. The regulatory zones around pools were informed by published recommendations for pool-breeding amphibians from the eastern United States. The final regulations reflected many political compromises in both the percentage of pools to be considered Significant and in the size of the management zones. For example, amphibians are known to spend most of their time at distances often three times larger than the zone currently regulated. Two Maine state agencies, the Department of Environmental Protection and the Department of Inland Fisheries and Wildlife, were tasked with regulatory oversight of the new law. Resultant tensions between ecologists and regulated communities, which questioned the nature (i.e., scientific foundations) and extent of the new regulations, motivated the transition to Phase 4.

Phase 4—Implementation and Maintenance of Vernal Pool Regulations (2007 to Present). Concerns that landowners might fill potential vernal pools to avoid regulatory restrictions emerged, and in both 2011 and 2013, real estate development groups introduced bills to the state legislature to overturn or weaken the regulations. During this stage, UMaine's vernal pool research program assumed a leadership role, filling the gap at the science–policy boundary following the discontinuation of the VPWG. In response to emergent management needs and a lack of public understanding, UMaine scientists held >30 workshops for various stakeholders (i.e., regulators and landowners) to explain the science behind the regulation. Fact sheets on the new regulation and vernal pool ecology were developed and posted on agency and UMaine websites. UMaine's vernal pool research program added the following three critical components: (*i*) a municipal-based citizen science program, the Vernal Pool Mapping and Assessment Program (VPMAP; 2006 to present) to provide the state and municipalities with a database of SVPs (see www.umaine.edu/vernalpools for program details); (*ii*) a social science dimension to better understand human dimensions of vernal pool conservation on private land (31, 32); and (*iii*) a study of the effects of urbanization on vernal pool amphibians and biogeochemical functions. Economics research quantified the impact of the current regulation on landowners in urbanizing landscapes and simulated ecological outcomes under that policy and potential alternatives (33). Key findings from this research informed the program's engagement strategies, including revisions to new outreach materials (34). UMaine scientists also initiated meetings with municipal planners and citizens to discuss challenges to pool conservation, especially perceived threats from increased regulation, and how they could be addressed through research or better communication.

Phase 5—Adaptive Management: Development of Local Alternatives to the Status Quo (2008 to Present). Two divergent responses to Maine's vernal pool legislation shaped this management stage. Some stakeholders focused on limitations of the state legislation (i.e., regulating less than a quarter of all pools and regulating an inadequate amount of key amphibian habitat around each pool), whereas others focused on perceived excesses (i.e., regulating too many pools and adjacent uplands and infringing on private property rights). Vernal pool regulations at both the federal and state levels became the subject of intense political scrutiny (e.g., many counter bills were crafted and introduced to the legislature) and were a target of attempted rollbacks with the goal of allowing increased development activity associated with vernal pools.

Amid efforts to repeal the law, UMaine's vernal pool research team and state and municipal officials discussed how to effectively conserve vernal pools given the current political and social context. This group, ultimately referred to as the Vernal Pool Streamlining Working Group (VPSWG), grew over 3 y from a small group of concerned individuals (including A.J.K.C. and one federal regulator, three state regulators, and two UMaine graduate students) into a formal entity with over 50 stakeholders focused on producing local alternatives to conserve vernal pools. Pilot projects (in year four of five) to test new regulatory approaches designed to develop a local, incentive-based conservation mechanism for small natural features (35, 36) are underway in two towns. The mechanism, a local in-lieu fee program, would allow all federal and state vernal pool regulations to be relaxed in designated growth zones in exchange for greatly enhanced protections in rural areas (see www.umaine.edu/vernalpools for details) funded through mitigation fees in the growth zones. The local in-lieu fee program, with land trusts as third-party holders, would be set up to oversee the conservation work. Developers are engaged by predictable regulation and less paperwork, rural landowners receive remuneration for increased conservation, and municipalities feel empowered by local control. This work is informed by ongoing UMaine interdisciplinary research (i.e., biophysical and socioeconomic sciences) on conserving pool-breeding amphibians in urbanizing landscapes (funded by a National Science Foundation Coupled Natural Human Systems grant. If successful, this new mechanism will appear in a Special Area Management Plan (SAMP) in federal (ACOE) regulations and will be made available as an alternative to federal and state regulations to states in the ACOE's New England region. This SAMP, developed for vernal pools, would provide a template for other such small natural features throughout the United States, including some discrete wetlands and stormwater features.

Discussion

Two overarching themes emerge from our experiences as academic scientists working at the boundary between research and decision-making communities. First, consistent with prior work (20, 37), the most effective strategies for linking scientific knowledge with action changed as the actors, knowledge needs, and context of vernal pool conservation evolved. New boundary organizations emerged, and products, tools, and processes were adapted to better align scientific knowledge production with decision-making priorities. Second, also consistent with prior work (38), repeated negotiations of the science–policy boundary permitted development of innovative management approaches. Drawing on our experiences and the 15-y history of vernal pool conservation efforts, we suggest three key guidelines for natural resource conservation of small natural features on private land.

Dynamic Conservation Dilemmas, Such as Those Posed by Small Natural Features, Require Flexible Research, Management, and Engagement Approaches. The coevolution of management and research is conspicuous in the history of vernal pool

conservation efforts. We observed vernal pool management approaches gradually change from reactive, rigid, and top-down to proactive, flexible, and hybrid top-down/bottom-up. Top-down regulatory approaches are often the impetus for voluntary approaches, and regulatory backlash was clearly a motivation for VPMAP as a tool to enhance regulatory compliance and reduce public fear and misunderstanding of the vernal pool regulations.

As management approaches changed, our research program shifted from a disciplinary, ecology-focused program to an interdisciplinary program that integrates social–ecological systems (SES) research. Understanding and responding to the concerns and information needs of the large, diverse group of stakeholders required testing multiple conservation approaches, developing processes to engage with this heterogeneous group, and spanning disciplinary boundaries. Foresters, developers, citizens, regulators, legislators, and municipal leaders have distinct knowledge needs and preferences for coproducing knowledge. Strategies for effectively aligning science and management varied with the intended uses of scientific knowledge and the different sources of knowledge that were drawn on (20). For example, disciplinary journal articles helped support the SVP criteria for the formal regulation, whereas the maps produced by the VPMAP citizen science program served as a catalyst for the local pilot projects. Similarly, early citizen–science programs aimed to raise public awareness, whereas later programs strived to generate key data for management decisions.

As local communities struggled to implement the state regulation, a growing emphasis on tailoring resource management to local conditions emerged, which led to tools and management strategies and organizations primarily focused on coproducing knowledge with local communities as major stakeholders. However, these local policy experiments required prior approval from, and participation by, federal and state partners. Notably, our UMaine vernal pool research team exhibited considerable flexibility and endurance by expanding the scope of research, partnering with additional stakeholders as priorities evolved, and ultimately assuming a convening role after the VPWG dissolved. In summary, the observed vernal pool conservation advances were made possible by dynamic links among managers, researchers, and other stakeholders. These relationships addressed key challenges associated with vernal pools and other small natural features, including tensions between private property rights and societal rights to environmental protection; uncertainties over resource location, quality, and function; conflicting and diverse stakeholders; and fragmented regulatory authority.

Trust, Collaboration, and Effective Leadership Are Vital for Management of Small Features on Private Lands. The evolution of this vernal pool conservation program underscores the challenges of resource management on private lands. Tensions over private property rights, resource and governance conflicts, and polarized politics are common. However, this history also reveals significant opportunities that can be fostered by trust and collaboration among scientists, regulators, managers, and landowners, and the effective leadership of key individuals. Boundary organizations, such as the VPWG, VPMAP, and VPSWG, assumed key roles in building relationships and performed important boundary-management functions through communication, translation, and mediation (14). Successful outcomes of the VPWG can be attributed to strong, personal relationships among researchers and town and federal and state agency decision-makers that developed during a decade of working together. UMaine assumed a strong leadership role to effectively span the scientific and management communities in order to encourage the exchange of ideas and knowledge between scientists and nonscientists. Consensus on the language of the new vernal pool legislation, "spinoff" partnerships such as VPMAP, and the VPSWG's launching of innovative policy experiments would not have been possible without these longstanding relationships and a core group of people willing to assume leading roles (22). The VPSWG's institutionalized process of knowledge-sharing also contributed to bipartisan support by legislators in defeat of proposed regulatory rollbacks in the Maine State Legislature in 2013. Similarly, VPMAP strengthened communication between scientists and municipal officials, mobilized town support for proactive planning, and improved understanding of vernal pools at the local level (32). Thoughtful facilitation and organization of VPSWG meetings by UMaine scientists and a record of successful collaboration among key stakeholders allowed for (*i*) new stakeholders (developers, legislators, and municipal leaders) to assume greater roles in management and research discussions and (*ii*) approval and active support of both federal and state partners. As these examples suggest, by nurturing lasting relationships around small feature management on private land, collaborative strategies can effectively straddle divides between communities of experts and decision-makers and lessen uncertainties about resources, regulations, and science (37).

Organizations That Foster Interdisciplinary and Engaged Research Are Critical to Management of Small Natural Resources on Private Lands. The dynamic context of vernal pool management highlighted the importance of interdisciplinary and engaged SES research to agile and enduring boundary work (39, 40). In response to management needs, our vernal pool research team grew to include ecological, social, and economics researchers. Furthermore, increased connections across these disciplines and with stakeholders enabled a more sophisticated understanding of SES linkages, more robust science–policy negotiation activities, and ultimately a more innovative conservation strategy. Two novel organizations allowed for these benefits to be realized by our team. First, the VPWG set up by the State of Maine established a unique forum for linking scientific knowledge to action, a safe space from which the interdisciplinary and engaged research program could emerge. Secondly, Maine's Sustainability Solutions Initiative, a National Science Foundation–Experimental Program to Stimulate Competitive Research-funded research project based at UMaine, provided critical resources to expand the research team and extend its impact. Without sustained investments interdisciplinary and engaged research projects are unlikely to thrive (38). Collaborative, interdisciplinary research demands more of researchers, managers, and stakeholders (37). By helping reduce barriers across disciplines and divides among experts and decision-making communities, organizations can help lower the costs of interdisciplinary and engaged research; foster and institutionalize new research agendas; and accelerate the identification of key opportunities in which scientific knowledge can improve management actions.

Way Forward

We conclude that solutions to sustainability science challenges will benefit from repeated negotiations of the science–policy boundary by researchers, managers, and other stakeholders. Flexible, solutions-oriented research and conservation approaches, trust and collaboration among scientists and decision-makers, and interdisciplinary, engaged research can create opportunities for the development of novel mechanisms for conservation. We believe the challenges and opportunities encountered in navigating the science–policy boundary summarized in this work are not unique to vernal pools, and thus our findings have wider management significance for natural resource management, especially for small natural features on private lands such as riparian zones and prairie potholes or for indirect conservation issues including stormwater management.

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