Special Issue: Overview

Land Stewardship and Freshwater Outcomes: An Overview of Practice and Results

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Editor: Eric Menges

Natural Areas Journal 39:6–21

ABSTRACT: This special issue of the *Natural Areas Journal* focuses on the stewardship of protected landscapes for the benefit of freshwater quality and quantity and for aquatic ecosystem integrity. Land stewardship, the responsible use and care of natural lands and ecological resources, can be done in ways that enhance, or at least avoid harming, connected aquatic ecosystems and the people that depend upon the renewable goods and services provided by fresh waters. There is a critical need for a compendium of current science on the effects of various land stewardship practices on freshwater ecosystems, to guide the planning and implementation of on-the-ground stewardship activities, identify knowledge gaps for research scientists, provide funders of land stewardship activities with knowledge that can be applied to the evaluation of grant proposals and project outcomes, and offer the scientific evidence underlying the most efficient and effective practices to decision makers involved in developing and amending conservation policy. Our objectives with this special issue are to further the process of compiling the relevant science and encourage those involved in conservation land management to automatically and routinely consider the effects of their practices on water quality and quantity.

The benefits of protected natural areas to freshwater quality and quantity and aquatic ecosystem integrity are indisputable, but how those protected lands are managed has a strong influence on the degree of benefit. Stewardship practices in riparian areas, floodplains, and other locations near surface waters have the greatest influence on freshwater resources. When done judiciously and based on current scientific understanding, they can reduce or eliminate excessive inputs of sediment, nutrients, pathogens, organic matter, and pollutants to fresh waters by minimizing disturbance to soils and to the soil-protecting and soil-building functions of vegetation. The challenges are not simply identifying the current best stewardship practices, but also include deciding among competing management goals and priorities; putting effective incentives in place (and amending or avoiding perverse incentives) for implementation of conservation practices; succeeding within a framework of social, political, and economic constraints; and acting effectively despite considerable uncertainty. This overview and the other papers in this special issue report recent advances in the environmental sciences, and also the science of human behavior, that will be pivotal for land stewards as they take into consideration the freshwater consequences of their actions.

Index terms: agricultural BMPs, aquatic ecosystems, beaver management, conservation decision-making, invasive earthworms, invasive plants, natural areas, outdoor recreation impacts, prescribed fire, stewardship, water quality, wildfire

INTRODUCTION

Humans damage freshwater ecosystems through activities that directly or indirectly alter their physical, chemical, and biological characteristics. Much of the literature on human-caused threats focuses on the ecological impacts associated with modified or engineered landscapes, including urban and agricultural lands (e.g., Malmqvist and Rundle 2002). The consequences of land development include altered hydrology resulting from changes in surface runoff, evaporation, water withdrawals, and consumptive uses; increased nutrient, sediment, and pollutant loads; increased water temperature; degraded habitat structure; and consequent impacts to biological communities including changes in abundance, dominance, and diversity (Malmqvist and Rundle 2002). Such impacts to water quantity and quality are of great concern, not only because they harm in-stream biota, but also because they degrade those ecosystem goods and services that support human well-being: provision of unpolluted drinking water for humans, including water that is suitable for processing by municipal facilities; ample water for crops, livestock, and industrial processing; and water that is clean and abundant for recreational uses (e.g., wading, fishing, and boating) and aesthetic enjoyment (Landers and Nahlik 2013).

There are many tools available for addressing water quality and quantity impacts. Some involve planning and legal instruments, including comprehensive land use planning; land protection and preservation, through fee simple acquisition or conservation easements; and policies and regulations that limit damages (e.g., by regulating pollutant discharges or consumptive withdrawals) and protect designated uses (e.g., water quality standards and antidegradation provisions). Others involve on-the-ground implementation, including stream restoration, stewardship of natural lands, and agricultural best management practices (BMPs). Decisions about conservation strategy, including identification of the appropriate policy, planning, and management tools, should be guided by clearly articulated goals and a solid understanding of the suitability and effectiveness of various management approaches.

The focus of this special issue of the *Natural Areas Journal* is on the management of protected landscapes for the benefit of water quality and quantity, as protected lands are major portions of watersheds in some areas and additional preservation efforts will increase the importance of such lands. Land stewardship, the responsible use and care of natural resources, is ultimately driven by a land ethic that derives from the connectedness of humans and nature (Leopold 1949); by extension, it can be assumed that land stewards act not only for the benefit of the ecosystems they manage directly, but also for the benefit of connected (downstream) ecosystems and the people that depend upon the goods and services provided by those ecosystems. Although land stewardship is broadly recognized as a potential means for addressing water quality and quantity impacts, the utility and benefits of the full suite of stewardship approaches are poorly catalogued; thus, there is a critical need for a review of current science on the effects of various land stewardship practices on freshwater ecosystems.

The papers in this issue review the current state of science on major topics within the theme of land stewardship from a water resource perspective, including the freshwater effects of nonnative invasive plants in riparian zones, wildfire and its deterrence using prescribed fire, agricultural best management practices, and ungulate populations elevated above ecological carrying capacity (i.e., the maximum density of animals that can be sustained without inducing trends in vegetation). They also explore the benefits to fresh waters of natural area and wilderness protection. The subjects of the special issue papers do not include all land stewardship activities that are known to have freshwater quality effects; for instance, managing land-based recreation, selective tree harvesting, and beaver management are not treated. Some of these additional topics are covered briefly later in this overview; they and others await comprehensive review in future issues of the *Natural Areas Journal* or other publications.

CHALLENGES OF MANAGING FOR WATER QUALITY AND QUANTITY VIA LAND STEWARDSHIP

Competing Management Goals and Priorities

The best land stewardship approach in a given situation often, if not always, involves tradeoffs among competing goals and priorities. For example, improving habitat for an endangered species may degrade conditions for other desired species (Marshall et al. 2016), or preserving an agricultural landscape may take precedence over other actions, even in a park or nature preserve, because of their economic, cultural, or historical value. With respect to water quality, recreational uses strongly favor access along stream corridors, such as trails and fishing access points, but access can harm riparian vegetation and promote erosion, sedimentation, and eutrophication (Olive and Marion 2009; Kidd et al. 2014; Marion and Wimpey 2016).

Recognizing and weighing such tradeoffs is essential in land stewardship planning, but the process is often hampered by gaps in information. Planners and practitioners may lack knowledge of which underlying conditions of a site are most important to measure and understand in order to make wise management decisions and evaluate their outcomes. This is particularly true in weighing the water quality and quantity effects of land stewardship, where no comprehensive treatment of that subject has been published until now. Furthermore, because the focus of land stewardship can be narrow (e.g., a land stewardship activity is advocated by stewards for a single purpose), tradeoffs may not be known or recognized without prompting by regulators or engaging a group of partners with diverse interests. Finally, we often lack normative standards for comparing disparate benefits and costs, such as riparian integrity versus recreational benefits; the clearest answers will come in alternatives analyses, such as the relative riparian impacts of various trail and stream access options. In this special issue we review and synthesize the existing research in an effort to provide land managers with knowledge needed to balance land stewardship priorities with freshwater quality and quantity objectives.

The Need to Motivate Implementation of Conservation Practices

Land stewardship practices are often cooperative and voluntary rather than compulsory, and many of the opportunities to address water quality and quantity concerns require implementation of conservation practices on privately owned lands. In addition, stewardship practices generally have different funding sources, involve different staff units within government and nongovernmental organizations, and require different expertise from land protection, all of which complicate the decision-making process to undertake stewardship activities. Achieving landowner adoption of proven practices that benefit adjacent streams and rivers can be challenging for a host of reasons: implementation may conflict with economically desirable uses of the land (e.g., by taking land out of crop production), be cost prohibitive, require specific expertise to implement or manage, or be misunderstood or negatively perceived by landowners for other reasons (e.g., cultural, historical). An effective, watershed-level strategy should include incentives that motivate landowner participation. Public recognition, the opportunity to play a role in protecting resources for future generations, and personal benefit (e.g., cost-sharing, offset payments, tax credits) may motivate landowners to adopt good stewardship practices (Vickerman 1998). Compensation that reflects the actual performance of implemented practices, rather than an estimate based on regional average benefits for those practices, may further encourage willing private landowners (Sweeney and Blaine 2016). Incentivizing landowners is complicated by the fact that the effects of incentives depend on their design, type (e.g., monetary or non-monetary), duration, and interaction with intrinsic and social motivations (Gneezy et al. 2011; Maki et al. 2016). Programs designed to stimulate land stewardship often include education, technical assistance, and cost-sharing elements. Unfortunately, many existing programs have strict eligibility requirements, are narrowly focused, and are excessively complicated, which can be discouraging to potential participants (Vickerman 1998). Furthermore, federal incentive programs, such as the Environmental Quality Incentives Program (EQIP) and the Forestland Enhancement Program (FLEP) administered by the Natural Resources Conservation Service (NRCS) and the US Forest Service, respectively, are often underfunded and underused. Governmental landowners face additional constraints, including whether elected officials agree to budget for stewardship.

The Constraints of Macro-Environmental and Strategic Context

All decisions about conservation, including land stewardship, occur within the context of the macro-environment, which includes social, political, and economic elements. We know that science-based conservation strategies are likely to yield the greatest benefits; yet even with this knowledge, an ideal, evidence-based conservation strategy may be difficult to achieve in practice (Margules and Pressey 2000). Macro-environmental forces influence all stages of conservation planning. Initial decisions about which ecosystem goods and services to conserve and how to conserve them may be partly informed by ethical and aesthetic motivations, which can narrow the field of publicly supported conservation efforts to those that are visually appealing or directly benefit society. Subsequent decisions about conservation strategy may be further constrained by available resources, including funding, available land, or willing landowners (Margules and Pressey 2000). Where governmental and nongovernmental organizations are involved, their capacity to pursue additional projects will also be a critical factor.

Because conservation dollars are limited, decision-makers should invest existing resources based on a finely tuned understanding of how the ecological benefits (i.e., ecosystem services such as flood reduction or provision of clean water), the economic costs associated with achieving desired ecological outcomes (e.g., land prices, incentives, implementation, and management costs), and interactions between the two, vary across the landscape (Naidoo and Ricketts 2006). Even though such strategic investment may result in an uneven distribution of resources for conservation, it is important that the distribution of funds is guided by needs identified at the largest practical scale (e.g., municipal, watershed, state, national) that is relevant to the targeted ecosystem service to ensure the greatest return on investment. Furthermore, decision-makers should implement projects, or collections of projects, that are sizeable enough to have a measurable conservation impact. Decision-makers also need to be aware of mismatches between the most appropriate management scale and the geographic scope of available organizations, collaboratives, or landowners.

It can also be challenging to work within a landscape where conservation priorities and activities have already been identified, especially when attempting to use new approaches or applying existing approaches in novel ways. For example, existing planning documents (e.g., Water Resources Plan for the Delaware River Basin or Philadelphia's Long Term Control Plan) and frameworks (e.g., NRCS National Water Quality Initiative) identify priority goals and assistance programs (e.g., NRCS's Regional Conservation Partnership Program) and help to concentrate effort—and funding—in key areas, but they are unlikely to include the full suite of possible water quality and quantity goals, and may focus on the application of a subset of conservation actions to the exclusion of all other suitable approaches. Prior successes, regional expertise, and the availability of practice-specific funding all can contribute to some approaches being favored over others without a reasoned comparison of costs and benefits. As a result, the pursuit of other water quality and quantity goals and the implementation of alternative, optimal approaches may be denied technical and financial support even if they are scientifically justifiable. Ideally, conservation priorities should be dynamic and reflect current needs and evolving scientific understanding rather than previously generated lists (Margules and Pressey 2000; Hermoso et al. 2017). When resource managers and stewards, including state agencies and nonprofit organizations, disregard broader needs and continue to favor approaches in support of narrowly focused missions, others operating in the same conservation space may become frustrated that their efforts are being hindered.

Even where the relevant management framework, funding and organizational capacity all match, stewardship poses significant complexities. For example, restoration activities can result in near-term water quality and ecological damages. These impacts can engender opposition to implementation, even though the long-term benefits may be clear. Two examples make the point. First, prescription fire may pose a small risk to water quality in a nearby stream in the short term while reducing high fuel loads and the risk of wildfire and its potentially catastrophic water quality impacts in the long term (Hahn et al. 2019, this issue). Second, the removal of invasive species can result in short-term soil exposure while replanted native species become established (Robertson and Coll 2019, this issue).

The Uncertainty of Working in a Multi-Threat Landscape

The interactions of human-caused threats with each other pose significant challenges to natural resource management (Craig et al. 2017). Threats that harm water quality and quantity include point and nonpoint sources of pollution, urban and agricultural land use, resource extraction, water withdrawals, and climate change; however, managers who rely on a toolbox of land stewardship practices often are positioned to address only a subset of these threats due to limitations on organizational mandates, funding, capacity, or expertise. Furthermore, because scientists and managers still have a relatively poor understanding of how threats interrelate, it may be unclear how land stewardship practices will perform in terms of water quality or quantity and whether they will be sustainable within the context of multiple, interacting, and ever-changing threats. Because of the uncertainties associated with working in a multi-threat landscape and the potential risks of management failure (e.g., loss of ecosystem goods and services, continued decline of ecological integrity), managers may be wary of implementing or promoting specific activities due to concerns that they could waste effort and funding (Hart and Calhoun 2010; Côté et al. 2016). To overcome these challenges, it is critical that resource managers identify and implement strategies that—based on the most credible evidence—are likely to be successful or, at a minimum, harmless, in spite of uncertainties about the nature of interactions between existing threats that directly or indirectly affect water quality and quantity. Managers must evaluate the potential benefits and risks to freshwater ecosystems of pursuing different land stewardship options, while avoiding unintended consequences, including improving water quality to the detriment of water quantity (or vice versa), constraining future conservation actions, or otherwise damaging the terrestrial or aquatic ecosystem (Craig et al. 2017). In addition, if managers can capably develop strategies that identify and capitalize on opportunities to achieve multiple benefits, they may eliminate the incentivization and implementation costs of redundant conservation actions.

THIS SPECIAL ISSUE: A COMPILATION, SYNTHESIS, SUMMARY, AND CRITIQUE OF THE PERTINENT RESEARCH

Synthesis of Findings

The benefits of protected natural areas to freshwater quality and quantity and aquatic ecosystem integrity are indisputable (Lynch et al. 2019, this issue; Meldrum and Huber 2019, this issue) but how those protected lands are managed has a strong influence on the degree of benefit. Stewardship practices in riparian areas, floodplains, and other locations near surface waters have the greatest influence on freshwater resources. When done judiciously and based on current scientific understanding, they can reduce or eliminate inputs of sediment, nutrients, pathogens, and pollutants to fresh waters by minimizing disturbance to soils and to the soil-protecting and soil-building functions of vegetation. The locally indigenous plant community, with intact native plant species diversity, density of cover, and vertical structure (well-stocked ground, shrub, subcanopy, and canopy layers) is the ideal vegetation on land in close proximity to surface waters. Certain of its functions (e.g., reducing the impact of raindrops, runoff, and floodwaters on soils; holding soils in place with multiple species' multilayered root systems; fostering a healthy soil microbial system that retains nutrients; and exporting leaves, branches, and trunks to aquatic ecosystems) cannot be equaled by vegetation compromised by:

- large-scale nonnative species invasion (Robertson and Coll 2019, this issue);
- white-tailed deer populations above ecological carrying capacity (Sweeney and Dow 2019, this issue);
- grazing and trampling by livestock (Kroll and Oakland 2019, this issue);
- high-intensity wildfire (Flint et al. 2019, this issue; Hahn et al. 2019, this issue);
- or overuse by outdoor recreationists (Rayburn et al. 2019, this issue).

Fortunately, enough is known about the impacts of these disturbances and the effectiveness of various practices in minimizing harm to aquatic ecosystems to inform improvements in stewardship methods (summarized in Table 1). In some cases, advances in knowledge and methods are quite recent and have not yet been widely circulated among the land stewardship community. For example, we know that high-severity wildfires cause widespread plant mortality followed by massive erosion during post-fire storms, resulting in sedimentation and other impairments to surface waters. Intuitively it may seem that prescribed fires should have similar, if less severe, impacts to freshwater ecosystems. However, long-term comparisons of watersheds with no fire and with prescribed fire (leaving riparian buffers unburned) have shown water quality to be either unaffected or temporarily enhanced immediately after prescribed fire, attributed to repeated prescribed fires leaving behind a mixture of slightly burned or partially charred material that minimizes water quality effects even with moderate post-fire erosion (Hahn et al. 2019, this issue). The papers in this special issue report this and other, similar instances of recent advances that could be game-changers for land stewards as they expand their thinking to consider the water consequences of their actions as a matter of course.

As mentioned earlier, not all pertinent topics are covered in the special issue papers. Additional land stewardship activities are known to have freshwater quality effects, such as beaver management; provision and management of land-based recreation; or selective tree harvesting to enhance habitat for species of high conservation need, contend with tree-killing insects or pathogen outbreaks, hasten the onset of old-growth forest conditions, or generate income (see Table 2 and Box 1).

Identifying and Addressing Knowledge Gaps

The special issue authors point out where there are still potentially consequential gaps in understanding that should be high priorities for further research (summarized in Table 3). For instance, there is a critical need for long-term and watershed-scale studies in areas of inquiry such as agricultural best management practices and nonnative invasive species, where nearly all studies to date have looked at freshwater effects over short periods of small-scale manipulations (Kroll and Oakland 2019; Robertson and Coll 2019). Although harm to water quality and aquatic communities have been found for some of the few nonnative invasive plant species that have been studied, the freshwater effects of most such species have yet to be investigated (Robertson and Coll 2019). Research to date has documented freshwater impacts of high-intensity wildfires and low-intensity prescribed fires (Flint et al. 2019; Hahn

Table 1. Summary of major findings from the papers in this issue on land stewardship effects on freshwater ecosystems, water quality, and water quantity, and applications of those findings to land stewardship practice and policy.

Reference	Topic	Summary of findings	Application to land stewardship practice/policy
Robertson and Coll 2019	Freshwater effects of invasive nonnative plant species in riparian zones	• Invasive nonnative plants tend to colonize densely and exclude indigenous species by: • usurping growing space, nutrients, sunlight • reducing ecosystem biodiversity • transforming ecosystem function • Where densely growing nonnative plants have different growth habits from diverse native vegetation or exude toxic chemicals, impacts can be readily apparent • Even if invading plants are relatively similar to the indigenous species they displace, differences in leaf decomposition rates or timing of leaf-out and leaf-drop may nevertheless cause cumulative, long-term impacts	• Targeting highest-risk nonnative invasive species can yield most-favorable performance/cost ratio, so long as steps are taken to assure that a site-appropriate native plant community is well established soon enough to resist recolonization by invasives • Achieving desired conditions depends on planting multiple species within each growth form (herbaceous perennials, shrubs, trees) of the indigenous plant community as soon as is feasible after invasive plants are removed, then continuing to monitor and spot-treat remnants or new outbreaks of highest-risk invasive species
Sweeney and Dow 2019	Freshwater effects of ungulate populations elevated above ecological carrying capacity	• Where white-tailed deer populations are elevated above ecological carrying capacity, conserving existing streamside forests and efficiently restoring previously destroyed forests are difficult to impossible in many areas of eastern North America • Result is more soil exposure and erosion, and increased invasive species dominance • Recreational hunting alone rarely is sufficient to reduce and maintain deer densities at levels that allow adequate survival of tree seedlings and shrubs for effective afforestation or sustained native tree and shrub-layer regeneration in riparian buffers and elsewhere • Sharpshooter culling over bait or tall, permanent fencing are effective but prohibitively costly in most situations • Tube tree shelters are ineffective in restoring a native forest shrub layer • New research shows low fencing increasing tree and shrub seedling survival and growth relative to unfenced areas at rates not significantly different from tall fencing, where fenced areas are small or when large areas are exclosed by two rows of low fencing 3 m (10 feet) apart	• Low fencing (1.2 m [4 feet]) is considerably less costly to build and maintain than tall fencing (1.8–3 m [6–10 feet]) and can be used effectively in piecemeal approaches to afforestation or forest restoration, e.g., applied nucleation (i.e., planting patches of trees as focal areas for recovery) • Low fencing can result in levels of survival and growth of trees and shrubs suitable to meet the success criteria for afforestation projects funded by the U.S. government and other sources
Flint et al. 2019; Hahn et al. 2019	Freshwater effects of wildfire and prescribed fire	New modeling tools allow natural resource managers to predict post-fire scenarios and compare wildfire to prescribed fire effects by forecasting how a range of post-fire weather and vegetation conditions may influence hydrology and water quality in specific watersheds	Parameterizing and running the models can optimize management choices, for example: • by evaluating how risk differs across the landscape and among sites • by prioritizing areas for fuel reduction
			Continued

Table 1. ***(Continued)***

Reference	Topic	Summary of findings	Application to land stewardship practice/policy

Hahn et al. 2019	Freshwater effects of prescribed fire	• Comparing watersheds with no fire and with prescribed fire over decades shows water quality as either unaffected or temporarily enhanced immediately after prescribed fire
		• Effect is attributed to repeated prescribed fires leaving behind slightly burned or partly charred material that minimizes water quality effects even with post-fire erosion
			• Risk of adverse water impacts due to prescribed fire is generally low
			• Needs to be evaluated on a case-by-case basis, considering:
			  • buffer width and composition
			  • slope
			  • soil conditions
			  • season of burning
			  • expected vegetation response

Hahn et al. 2019	Freshwater effects of prescribed fire	Long-term fire exclusion shifts forest species dynamics to more mesophytic, fire-intolerant species, which: • channel more water into evapotranspiration, resulting in less groundwater and surface water yield at the watershed scale • are increasingly displacing forests of xerophytic, fire-tolerant species (oaks, pines) in temperate eastern North America and destroying habitat for many native plant and wildlife species of greatest conservation need	Prescribed fire is an effective and efficient way to: • halt or reverse mesophication trend and its associated homogenization of ecosystems and decline of native species diversity • sustain higher groundwater and surface water yield at the watershed scale
Hahn et al. 2019	Freshwater effects of prescribed fire	Fire prescriptions that leave riparian buffer zones unburned typically have effects on surface fresh waters that are either negligible, slightly adverse but short-lived, or slightly beneficial	Leaving riparian buffer zones unburned can minimize or prevent freshwater impacts so long as buffer width is tailored to local conditions that influence soil erodibility, including: • slope • soil type • ground-layer vegetation • infestation by forest-floor-altering nonnative invasive earthworms
Kroll and Oakland 2019	Freshwater effects of agricultural best management practices	There is extreme variability in the results of studies documenting agricultural BMP impacts on fresh waters, accounted for in part by strong effects of site-specific and neighborhood-specific factors, for example: • location in the watershed • proximity to a stream • upstream activities • potential for improvement • extent and types of BMPs employed on neighboring properties	Monitoring is most productively done in a regional context, with collaboration among agencies to: • apply consistent metrics • perform long-term studies • analyze and interpret results at watershed scales
			Continued

Table 1. ***(Continued)***

Reference	Topic	Summary of findings	Application to land stewardship practice/policy
Kroll and Oakland 2019	Freshwater effects of agricultural best management practices	A combination of BMPs nearly always achieves better freshwater outcomes than a single type	• Livestock exclusion and riparian forest planting are the simplest, most effective BMP combination • Can be implemented where whole-farm nutrient management plan is considered impractical • Livestock grazing can be rotated to allow recovery periods where space for riparian buffers is limited
Kroll and Oakland 2019	Freshwater effects of agricultural best management practices	• BMPs require maintenance to continue providing the expected level of efficiency • Maintenance is essential for preventing breaches that could allow concentrated flow through buffers	• Riparian buffers must be maintained to ensure trees survive past seedling and sapling stages • More trees may be needed over time • Invasive species must be monitored and managed • Cover crops must be planted and maintained regularly for continued effectiveness
Rayburn et al. 2019	Freshwater effects of land-based recreation	Surface water contamination from dog off-leash areas highlights vulnerability of streams and other surface water on public lands faced with increasing recreation pressure	Land management agencies and organizations should be thoughtful when considering whether a particular amenity is appropriate, especially if it caters to a narrow visitor category relative to that served by agency's or organization's mission
Meldrum and Huber 2019	Economic benefits to fresh waters from wilderness protection	• Significant volumes of water originate in wilderness in the U.S. • Wilderness areas include many watersheds of high importance for drinking water supplies and other water-based ecosystem services • Analysis of data from wilderness areas in disparate ecoregions nationwide, using modeling methods that include nonmarket valuation techniques, enable economists to realistically estimate value associated with allocation or management of a given area of land as wilderness and compare with value provided by existing (or likely) non-wilderness land uses and management regimes	• Further refinement and application of such analytic methods will be key to prioritizing designation of new wilderness areas and fostering buy-in by stakeholders and policymakers • Rigorous estimation of the benefits of wilderness areas on water resources needs to rely on focused case studies by interdisciplinary research teams who can connect specific impacts of wilderness protection status on natural systems to the associated ecosystem service benefits
Lynch et al. 2019	Benefits of natural area stewardship for protecting drinking water reservoirs	Drinking water reservoirs generally: • include a corridor of protected land around shorelines • provide a nexus with water-quality-based funding and political support as sources of drinking water • provide opportunities for partnership and constituency building as places beloved by shoreline residents, hunters, anglers, boaters, and other water-based recreationists • are adjacent to lands that support natural communities and species of conservation concern.	Large drinking water reservoirs provide opportunities for conservation projects and major land stewardship campaigns with efficient costs relative to water quality and quantity benefits.

Table 2. Some additional areas pertinent to land stewardship from a water resource perspective not covered in this special issue.

Topic	References	Summary of findings and research needs	Application to land stewardship practice/policy
Freshwater effects of land-based recreation	Pickering et al. 2010; Godtman Kling et al. 2017; Price et al. 2018	Major determinants of recreational impacts on water are: • proximity of trails, picnic areas, campgrounds, and access points to surface waters • types and amounts of use • siting, slope, and contouring • composition of surfaces • immediate surroundings	• Trails and other facilities for outdoor recreation are best kept at a distance from surface waters with buffers of sufficient width and surface characteristics to intercept sediment-, nutrient-, and pathogen-bearing runoff • Where such a natural buffer is not feasible, artificial barriers to soil disturbance and runoff from known problem spots are needed • Where users create problem spots despite best design and management practices (e.g., by creating unauthorized paths along streambanks), practices aimed at behavioral modification can help (e.g., brush piles, log or fence barriers, special plantings, signage, educational practices, constituency building)
Freshwater effects of land-based recreation	Pickering et al. 2010; Godtman Kling et al. 2017	Little research exists on water quality impacts of: • horseback riding • off-road biking • ATV use (permitted or illicit)	Demonstration of magnitudes of horseback riding and off-road biking impacts on water quality would provide clear-cut evidence to back up possibly controversial restrictions on these recreational activities and their enforcement
Freshwater effects of land-based recreation	Pickering et al. 2010	Most research on hiking impacts on water quality focuses on easily observable soil and vegetation change; there is little research on indirect and cumulative effects, for example spread of: • invasive nonnative plant species • plant pathogens (e.g., the soil-borne water molds *Phytophthora cinnamomi* Rands and *P. ramorum* Werres, De Cock & Man in't Veld, which cause root rot and dieback in many native plant species) • aquatic animal pathogens (e.g., the fungal chytrid pathogens *Batrachochytrium dendrobatidis* Longcore, Pessier & D.K. Nichols and *B. salamandrivorans* Martel, Blooi, Bossuyt & Pasmans, which cause chytridiomycosis, a disease of amphibians) • human pathogens (from feces)	Documenting severity of various indirect and cumulative impacts of hiking on water quality and aquatic ecosystem integrity will feed into public education, development of means of modifying behavior, and innovation of physical safeguards to reduce seed and pathogen dispersal by hikers
Freshwater effects of land-based recreation	Hendrix and Bohlen 2002; Callaham et al. 2006; Keller et al. 2007; Costello and Lamberti 2008, 2009; Nuzzo et al. 2009	Research shows significant freshwater impacts of nonnative invasive earthworms introduced into natural areas as discarded fishing bait, particularly members of the genera *Amynthas* (family Megascolecidae) and *Lumbricus* (family Lumbricidae): • direct effects (eutrophication from increased soil nitrogen mineralization, disappearance of soil-shielding litter layers)	• Further behavioral research is needed on best ways to overcome resistance by a large proportion of anglers to idea that dumping excess bait on the ground can be harmful and should be avoided • Methods of reaching, educating (à la Smoky Bear), and reshaping the behavior of anglers who use earthworms for bait need to be devised and tested
			Continued

Table 2. (*Continued*)

Topic	References	Summary of findings and research needs	Application to land stewardship practice/policy
		• indirect effects (proliferation of invasive nonnative plant species, which can adversely affect food web in adjacent aquatic ecosystems and cause earthworm populations to increase through positive feedback) Behavioral research documents resistance by large proportion of anglers to idea that dumping excess bait on the ground can possibly be a harmful practice	

Freshwater effects of land-based recreation		• Lack of research on soil erodibility and sedimentation impacts of nonnative invasive earthworms
		• Anecdotal observations suggest impacts may be profound, for example where *Amynthas* worms are abundant:
		  • leaf litter is quickly consumed, leaving soil bare and exposed to weather and runoff
		  • soil is loosened by borrowing, feeding, and deposition of massive quantities of fine-particulate soils on the surface as castings (worm excrement)
			Documenting severity of impacts of nonnative invasive earthworms on water quality and aquatic ecosystem integrity will provide greater incentive for efforts to foster behavioral change by anglers and policy change to prohibit commercial availability of the most harmful species

Freshwater effects of land-based recreation	Hendrix and Bohlen 2002; Madritch and Lindroth 2009; Ikeda et al. 2015	• Very little research exists on reducing invasive nonnative earthworm impacts on soils; in two studies, removing nonnative invasive shrubs and prescribed fire reduced earthworm density moderately
		• Infestations and their impacts on natural areas so far are essentially irreversible
		• Further research is needed on practical means of large-scale invasive earthworm management, for example:
		  • planting soil-acidifying species—oaks, pines, members of the heath family (Ericaceae)
		  • testing the feasibility, target-specificity, and risks of potential biocontrols for most-damaging species
			• Research on invasive earthworm management methods could give land stewards tools to contain the spread of most-harmful species and begin reversing terrestrial and aquatic degradation
			• New infestations could be reduced by:
			  • establishing buffer zones of unsuitable habitat to impede migration
			  • enacting enforceable regulations to prohibit import and sale of nonnative earthworms
			  • enlisting help of conservation and outreach groups (e.g., Great Lakes Worm Watch, greatlakeswormwatch.org) to raise public awareness of the magnitude of problems resulting from dumping bait

Freshwater effects of beaver management	Callahan 2005; Boyles and Savitzky 2008; Hood et al. 2018; Goldfarb 2018	Beavers' roles in water-related processes include: • groundwater recharge • sediment removal • flood mitigation • prolonging high stream baseflows • provision of habitat for many native animals, plants, and other organisms • boosting habitat heterogeneity and increasing native biodiversity at a landscape scale	Preventing beaver damage to property without removal and a perpetual cycle of recolonization and repeated damage can be far more cost-effective and beneficial to freshwater quality, using recent, proven advances in design and construction of flow devices to stop culvert blockage and maintain acceptable beaver pond levels

Continued

et al. 2019), but the effects of fires in the mid-range of intensity, which are increasingly being employed to reduce fuel loads and for other purposes, are poorly known (Hahn et al. 2019).

Addressing knowledge gaps through rigorous, comprehensive scientific studies is desirable; however, adaptive management (also known as adaptive resource management, adaptive environmental management, or adaptive ecosystem management) has the potential to increase knowledge directly relevant to resource management and reduce uncertainty associated with decision-making, all at much lower cost. It does this by testing promising alternatives for achieving management objectives using the principles of scientific experimental design and data analysis, but in the course of everyday management activity (Allen and Stankey 2009). In brief, adaptive management is a recursive process of "learning by doing": carrying out a set of actions, quantitatively monitoring the results, reconsidering management decisions and methodologies in light of those results, and adjusting the next round of implementation accordingly. Specific, measurable objectives are developed based on the available knowledge about a natural area and its ecosystem, comparison with high-quality reference sites or conditions, and brainstorming by qualified scientists and practitioners recruited to bring their experience and best judgment to bear (Eckert 2009). Desired conditions are described by target ranges of a carefully selected set of measurable indicators, and then compared with existing conditions to serve as the basis for strategies to narrow the gap between the two.

Adaptive management is becoming the "industry standard" for managers of natural areas, including federal, state, and local natural resource agencies and organizations such as land trusts, arboretums, institutions of higher learning, and others who wish to conduct a truly science-based (i.e., evidence-based) natural area stewardship program. Rayburn and colleagues (2019) make a crucial point that basing management decisions on rigorously measured evidence is not always popular with all segments of the public or all administrators:

Table 2. (*Continued*)

Topic	References	Summary of findings and research needs	Application to land stewardship practice/policy
Freshwater effects of beaver management	MacRae and Edwards 1994; Lokteff et al. 2013; Smith and Mather 2013; Kroes and Bason 2015; Weber et al. 2017	Speculative beliefs without basis in evidence contribute to default beaver management approach of killing or translocation; research shows, for example: • beavers do not heat up creeks by felling shade trees and exposing surface waters to sunlight • beaver dams can actually dampen daily heat spikes in summer, likely because of hyporheic exchange, forcing surface water into groundwater where it cools before reemerging downstream • beaver dams are not a barrier to fish movement • beaver dams can sustain high levels of fish diversity by increasing habitat heterogeneity and enhancing downstream fish habitat by trapping sediment	Paradigm shift away from speculative claims of beaver detriments to appreciation of beavers' proven contributions to water quality and aquatic ecosystem integrity could lead to increased and more widespread extraction of benefits from beavers' low-cost, high-return ecosystem services

BOX 1. WATER EFFECTS OF BEAVER MANAGEMENT

The American beaver (*Castor canadensis* [Kuhl 1820]) is an ecosystem engineer and keystone species. Research has documented beavers' substantial role in water-related processes, including:

- groundwater recharge;
- sediment removal;
- flood mitigation;
- prolonging elevated baseflows;
- provision of habitat for palustrine and aquatic organisms, including economically important species; and
- boosting habitat heterogeneity, thereby increasing native biodiversity at landscape and regional scales (Goldfarb 2018).

For most of the past roughly 100 years, beaver management has consisted mainly of killing by recreational trappers and nuisance wildlife removers (Goldfarb 2018). Beaver dam-building can cause property damage, but the lethal approach to beaver management stems in large part from long-held misconceptions about the effects of beaver dams. A meta-analysis of 108 published studies found the majority of claims for beaver benefits were supported by data while claims for beaver detriments tended to be speculative (Kemp et al. 2012).

Fear that beavers heat up creeks by felling shade trees and exposing surface waters to sunlight does not comport with the data (MacRae and Edwards 1994). In fact, there is evidence that beaver dams can actually dampen daily heat spikes in summer, likely because of hyporheic exchange, forcing surface water into groundwater where it cools before reemerging downstream (Weber et al. 2017). Fears that beaver dams are a barrier to fish movement are also unsupported by studies designed specifically to test that hypothesis (Lokteff et al. 2013). Beaver dams have been found to sustain high levels of fish diversity by increasing habitat heterogeneity (Smith and Mather 2013) and to enhance downstream fish habitat by trapping sediment (Kroes and Bason 2015). As a fringe benefit, beaver ponds make excellent firebreaks; they are generally much wider than constructed firebreaks and reliably feature expanses of standing water. Such natural firebreaks limit the spread of wildfires and make prescribed fire less costly and laborious, thereby minimizing the negative impacts of wildfire on water quality and quantity.

Beaver removal is often followed by beaver recolonization, in a continuing cycle, often involving costly damage to roads, other structures, or cropland before each successive removal. Recent advances in artificially regulating beaver pond water levels instead of repeatedly killing or evicting a succession of beaver families have proven successful. After many decades of failed attempts to artificially regulate beaver pond water levels, foiled by the beavers' instinctive determination to block up any and all leakages, recent progress has been made based on the principle of "deceive and exclude" (Simon 2006). Flow devices with designs and situation-specific options honed over years of experimentation consist, in simplest terms, of a submerged pipe (rigid or flexible) flowing into a culvert with the ends enclosed in metal fences or cages. They can be set to permanently maintain the desired (by humans) maximum pond water level. The beavers try to find the leak and may put some effort into stopping it, but if the flow device is properly designed they eventually give up and live with the water level they have been assigned (Simon 2006).

Increasing success over time of improved designs has been well documented (Boyles and Savitzky 2008; Hood et al. 2018). In a study in Massachusetts (Callahan 2005), 227 flow devices installed to protect culverts had a 97% success rate and for 135 flow devices installed to maintain acceptably low water level in beaver ponds the success rate was 87%. The costs of installation and maintenance over 10 years were $260–$370 per year (in 2018 dollars, adjusted for inflation) and amounted to $18 per 0.4 ha (1 acre) of beaver-created wetlands saved by letting beavers stay instead of removing them. Compare these costs with the project costs per 0.4 ha (1 acre) of roughly 1,000 wetland restoration/mitigation projects in the southeastern United States, pegged by a 1994 study (adjusted to 2018 dollars) at $30,500–$132,000 (average $64,900) (Baca et al. 1994). To these figures should be added the time-lag costs, that is, the loss of value in wetland ecological services between the times of wetland destruction and full restoration of wetland function. A study of mitigation wetlands, eight in Ohio and eight in Colorado, found the number of years required to achieve full functional equivalency for both floristics and soils was 8–50 years (median 33 years) in Ohio and 10–16 years (median 13 years) in Colorado; estimated restoration lag costs per 0.4 ha (1 acre) were $5,045–$72,636 (average $24,265) in Ohio and $32,618–$45,950 (average $39,944) in Colorado (all values adjusted to 2018 dollars) (Gutrich and Hitzhusen 2004).

Clearly, allowing beavers to colonize where the habitat is ecologically appropriate and socioeconomically feasible, or translocating nuisance beavers to such places, is worth thoroughgoing consideration.

Table 3. Summary of high-priority research needs identified in papers in this special issue to better understand land stewardship effects on freshwater ecosystems, water quality, and water quantity in order to improve land stewardship practices and policies.

References	Topic	Gap in current scientific knowledge	Land stewardship practice/policy significance
Robertson and Coll 2019	Freshwater effects of invasive nonnative plant species in riparian zones	Morphological, physiological, and biochemical differences between native and invasive nonnative plant species that affect fresh waters and aquatic ecosystems are poorly understood	Deeper understanding of mechanisms of nonnative plant impacts on freshwater aquatic ecosystems and water quality and quantity will equip land stewards to better predict likelihood and severity of newly invasive species' impacts and target high-risk offenders in early stage of invasion
Robertson and Coll 2019	Freshwater effects of invasive nonnative plant species in riparian zones	• Impacts on water of the majority of nonnative invasive riparian plant species in mesic temperate North America still have not been investigated (effects of only two have been investigated in multiple studies) • Impact studies are needed of other species identified as likely to have significant impacts by their abundance and morphological, physiological, and biochemical characteristics	Prioritization of species to target with invasives management would be far more effective if all nonnative invasive species that are prolific in riparian zones were ranked by the magnitude of their impacts on fresh waters
Robertson and Coll 2019	Freshwater effects of invasive nonnative plant species in riparian zones	• Longer-term studies are needed of freshwater ecosystem effects of removing invasive plants from floodplains (nearly all published studies to date report data from one growing season or one year) • Aquatic ecosystem effects of invasives removal are unlikely to be measurable until native plant species dominance is restored and aquatic communities have time to rebound	Studies of riparian invasives removal across a variety of sites over multiple growing seasons will enable better prioritization of species and landscapes for invasives management and evaluation of performance of riparian invasives removal
Robertson and Coll 2019	Freshwater effects of invasive nonnative plant species in riparian zones	• Invasives management rarely eradicates offending species from a site, thus research is needed to document by how much densities of nonnative invasive plants must be reduced in invaded riparian zones to yield significant improvement in water quality and aquatic ecosystem function • To date, methodology most likely to produce credible results (i.e., highly controlled, paired watershed experiments) has not been applied	Reliable research results demonstrating improvements in aquatic ecosystem functioning when nonindigenous species are removed and replaced by natives would help justify costs of invasive species removal and restoration of native plant cover
			Continued

Table 3. (*Continued*)

References	Topic	Gap in current scientific knowledge	Land stewardship practice/policy significance
Hahn et al. 2019	Freshwater effects of wildfire and prescribed fire	• Studies are needed of fire dynamics across a variety of watersheds in moist-temperate eastern North America • Trend of increasing use of intermediate-intensity prescribed fires makes it ever more critical to improve ability to measure fire intensity and severity and predict fire effects in the field accurately and at a fine spatial scale	• Using new methods and models that consider heat release in conductive, convective, and radiative phases will better parse subtleties of fire dynamics (e.g., levels of intensity and severity relative to vegetation types and terrain features) and how they influence post-fire effects on groundwater and surface water • Conduct of additional studies across diverse sets of local conditions will hone predictive models based on combinations of key site factors • Refinement of models will enable improved prescriptions designed to produce specific short- and long-term fire effects while minimizing adverse impacts and risk of escape
Kroll and Oakland 2019	Freshwater effects of agricultural best management practices	Need further studies on agricultural BMPs: • focused on responses of riparian vegetation and geomorphology • with increased representation of organisms other than salmonids in fish monitoring • avoiding use of circumstantial (case-study-based) data to reach conclusions • avoiding the assumption of transferability of results from small projects to whole watersheds	Improving and standardizing research methods and approaches and undertaking whole-watershed research should lead to further significant advances in BMPs and protection of water quality and aquatic ecosystem integrity
Kroll and Oakland 2019	Freshwater effects of agricultural best management practices	• Lack of long-term, large-scale studies in any given region results in large uncertainties in using models and their estimates • Diatom and macroinvertebrate indices, chemistry, habitat, and geomorphology give different temporal- and spatial-scale responses, and therefore each has an important contribution to make in understanding effects of BMPs • Fish communities have not shown consistent responses in the short or medium term; they can be long-term, large-scale indicators • Recovery of macroinvertebrates, diatoms, and chemistry may be observed if efforts are concentrated geographically, based on watershed boundaries, but single projects are not expected to show measurable, in-stream community recovery	Evidence-based guidelines for effective monitoring include: • Aggregate multiple farms in a watershed for planning and implementing BMPs and monitoring performance • Measure key indicators before BMP implementation to understand the baseline and whether improvements are feasible • Perform surveys after implementation often enough to document responses (physiochemical and biotic community change) to BMPs • Use multiple indicators and choose those that are most likely to respond to agricultural management actions • Report datasets to appropriate regional database(s) to contribute to resolving uncertainties and improving study design

"Land managers must be willing to make difficult and often controversial decisions when empirical data make it clear that a change in management is needed to protect surface water quality" and other highly valued resources and ecosystem components.

Given that adaptive management is an approach straddling the line between scientific inquiry and operational stewardship, a frequent complication is that the results are generally not reported in the peer-reviewed literature. Rather, the results may remain within organization files, seen as relevant to the specific projects, but not documented and published in generally accessible publications. Consideration should be given to how the results of these efforts can be compiled and evaluated for broader benefit.

PRACTICE AND IMPLEMENTATION

This issue is intended as the first installment of a planned "guidance system," eventually to include an online interactive decision-making tool, a series of user-friendly handbook-style pieces available online and in paper form, and a distribution strategy to maximize information exposure to, and adoption by, those involved directly or peripherally in land stewardship. This set of resources is already under construction, targeting users in the Delaware River watershed (parts of Delaware, New Jersey, New York, and Pennsylvania) and applicable to most of east-central North America. The hope is that it will serve as a model for expansion to other regions.

Federal, state, and local governments, conservation land trusts, arboretums, scientific and educational institutions, and certain private and corporate entities manage large tracts of dedicated open space, each with a specific set of purposes. Governments also regulate development within or affecting the riparian areas, floodplains, and wetlands of our freshwater systems. Fresh waters run through these lands, ranging from nearly pristine to badly damaged. In all cases, decisions must be made regarding the most appropriate and cost-effective methods of protecting or restoring freshwater resources that are or could be impaired by ecosystem changes or development. A major problem for all, including regulated entities, is that scientific evaluation of every specific case would be too costly. Therefore, land managers, land regulators, and developers' consultants must use existing science for clues regarding how to manage the lands.

The result, common in ecosystem and land management, is that complete answers are unavailable, and therefore approximations must be used. These approximations are always subject to question. Can resources spent on land management reasonably be expected to achieve the desired results? If not, decision-makers will be less likely to approve the expenditures, as funds may be better spent elsewhere. Is the resulting regulatory response reasonable, or is it seen as an arbitrary application of inapplicable science? The less clear the science application, the less likely that public decision-makers, from legislatures to the courts, will support the regulatory agency. Given that trust of government has eroded, these questions matter.

The detailed science is understood by a very small percentage of the general public, public decision-makers, and even land managers and consultants. One problem is a lack of synthesis, a concern that this special journal issue attempts to address. Resource managers often lack time to research what is known and access to research databases, and so compilations are critical. Guidance documents based on the syntheses are also needed, prepared by top experts. Change does not happen quickly, and so patient effort by experts is required over years to encourage adoption of good practices. The experts, in turn, must recognize that management occurs through the use of approximations that achieve what economist and political scientist Herbert Simon called "satisficing," a mashup of satisfactory and sufficing (Simon 1956). For managers, deep detail gets in the way of time-conscious decision-making. In other words, specific scientific knowledge must be adapted to general management needs (despite identified variability or uncertainties), providing approaches that can fit many situations, or it is ignored. This special edition of the *Natural Areas Journal* is a first, important step in addressing these issues.

ACKNOWLEDGMENTS

We would like to thank the William Penn Foundation for providing the support necessary to convene the panel of scientists and conservation practitioners whose discussions laid the groundwork for this paper and special issue. We are pleased to have the opportunity to further knowledge in support of one of the philanthropic organization's focus areas: watershed protection. We also extend our gratitude to our fellow panel members for sharing their time and thoughtful contributions: John Cecil, Terry Cooke, Emile DeVito, Richard Evans, Stefanie Kroll, Greg Podniesinski, David Robertson, Will Ryan, and Bern Sweeney.

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