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A Framework for Establishing Restoration Goals for Contaminated Ecosystems

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EDITOR'S NOTE:

This article represents 1 of 6 articles in the special series “Restoration of Impaired Ecosystems: An Ounce of Prevention or a Pound of Cure?” The articles result from a Technical Workshop organized by SETAC and the Society for Ecological Restoration, held June 2014 in Jackson, Wyoming, that focused on advancing the practice of restoring ecosystems that have been contaminated or impaired from industrial activities.

ABSTRACT

As natural resources become increasingly limited, the value of restoring contaminated sites, both terrestrial and aquatic, becomes increasingly apparent. Traditionally, goals for remediation have been set before any consideration of goals for ecological restoration. The goals for remediation have focused on removing or limiting contamination whereas restoration goals have targeted the ultimate end use. Here, we present a framework for developing a comprehensive set of achievable goals for ecological restoration of contaminated sites to be used in concert with determining goals for remediation. This framework was developed during a Society of Environmental Toxicology and Chemistry (SETAC) and Society of Ecological Restoration (SER) cosponsored workshop that brought together experts from multiple countries. Although most members were from North America, this framework is designed for use internationally. We discuss the integration of establishing goals for both contaminant remediation and overall restoration, and the need to include both the restoration of ecological and socio-cultural-economic value in the context of contaminated sites. Although recognizing that in some countries there may be regulatory issues associated with contaminants and clean up, landscape setting and social drivers can inform the restoration goals. We provide a decision tree support tool to guide the establishment of restoration goals for contaminated ecosystems. The overall intent of this decision tree is to provide a framework for goal setting and to identify outcomes achievable given the contamination present at a site. *Integr Environ Assess Manag* 2016;12:264–272. © 2015 The Authors. *Integrated Environmental Assessment and Management* published by Wiley Periodicals, Inc. on behalf of Society of Environmental Toxicology & Chemistry (SETAC)

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INTRODUCTION

Contamination from legacy pollution as well as continued spills and accidental releases is an issue threatening the health of terrestrial and aquatic ecosystems throughout the world. The process for addressing these contaminated ecosystems varies globally, and may include voluntary, mission or liability-driven, incentive-based, and/or regulatory approaches to remediation, mitigation, reclamation, rehabilitation, and restoration. This article is 1 of a series of 6 developed at a workshop held in June 2014, the overall goal of which was to provide a forum for ecotoxicologists and restoration ecologists to collaborate and define the best scientific practices available for preventative restoration to limit contamination and for restoration of impaired ecosystems where toxicants have been released (Farag et al. this issue). This panel of ecotoxicologists and restoration ecologists, that included academics, government agency and industry representatives, as well nongovernmental organizations working in land restoration, was challenged to explore more ways to involve restoration thinking into contaminated land-water assessment and planning for an international audience. In the United States the Comprehensive Environmental Response and Liability Act (CERCLA) and the Oil Pollution Act (OPA) provide legal authority for resource managers to assess a

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contaminated site and sue for dollar damages to restore that site. Although these procedures can be used as an example, they are US-specific and perceived limits in the legal process can sometimes hamper the ability of parties to work together freely. There are also initiatives, for example in the European Union (EU), focused on developing strategies for the rehabilitation or regeneration of brownfields that are typically urban or industrial sites (NICOLE 2013). These efforts are taking a multistakeholder holistic approach to brownfield rehabilitation.

Ecological restoration can be defined as "the process of assisting the recovery of an ecosystem that has been degraded, damaged or destroyed" (SER 2004). In this article, restoration is defined broadly to encompass not only ecological aspects of restoration, but socio-cultural-economic aspects that together lend sustainability to the endeavor of ecosystem recovery (note that key terms are defined in Farag et al. [this issue]). Although integration of remediation and restoration is standard practice for some entities, the participants in the workshop identified a gap in the consistent use of an integrated approach globally. Integration of restoration goals early in the remediation process can lead to more cost-effective and efficient resolutions and in many cases more complete restoration of ecosystem functions and services. Socio-cultural-economic aspects can drive a stratified approach to restoration goal setting where, rather than a restoration to full historical baseline, the goal is to manage a revised ecosystem with accepted functional values. Participants realized that resolution of these different outcomes early in the process could lead to reduced conflict between remediation and restoration managers.

An integrated approach

When contamination is identified, the first step often is to address the remediation of the site through removal, treatment or other measures that reduce or eliminate the contamination. In many cases, restoration planning for a site does not occur until after contamination removal or mitigation, which may limit the opportunities to fully restore a site (Pape et al. 2015). Regulatory processes that prioritize addressing the threats of contamination prior to an analysis of how the restored site will function in the future foster an approach in which risk assessors and restoration ecologists work sequentially and often independently. Determining there has been a release of contaminants, conducting a risk assessment (e.g., ecological risk assessment) based on a site conceptual model and species specific effects, defining actions to reduce that threat, and implementing those actions are the purview of risk assessors and toxicologists. Planning and conducting ecological restoration fall to the restoration ecologists. When these activities are done in sequence, approaches used in the remediation step may delay or preclude future restoration opportunities (Whicker et al. 2004; Fukuyama et al. 2014). Integrating remediation and restoration from the outset via collective goal setting has been shown to result in successful outcomes for restoration of contaminated lands and waters. A detailed example of this approach from Alcoa's restoration of bauxite mining sites in Australia, in which restoration planning begins with cultural resource surveys that precede the first excavation, can be found in Galatowitsch (2012) (see pages 447–454); essentially, contamination is minimized or eliminated by restoration planning before the first mine is developed. Another example is the Richardson's Flat Superfund Site, where United Park City Mines agreed to restore wetland areas during the ongoing remedial efforts (USEPA 2014). In this article, we set forth a framework to facilitate this integrated approach.

SETTING GOALS

Recognition of the critical value of goal-setting as a foundation for successful ecological restoration has been discussed at length (Burger 2008; Matthews and Endress 2008; Hallett et al. 2013; Balaguer et al. 2014; Weinstein et al. 2014). Ehrenfeld (2000), in particular, emphasized the need to clearly identify guidelines for goal determination as well as to develop an understanding of limitations of what can realistically be accomplished. She recognized the need for flexibility, as opposed to strict adherence to a potentially unobtainable historic reference condition. Such notions are especially relevant in the context of contaminated sites, where developing goals that simultaneously evaluate steps to achieve remediation and restoration of a site benefit from the different perspectives of risk assessors, remediation specialists, ecotoxicologists and restoration ecologists (Burger 2008).

Attributes of an ecologically restored ecosystem developed by the Society for Ecological Restoration (SER 2004; modified in Table 1) are the generally accepted standard among restoration practitioners, agencies, and academics (Hallett et al. 2013); we have adopted those attributes here, with slight modification. These attributes constitute well-established endpoints; it is the process of arriving at appropriate goals (that may incorporate these attributes), within the constraints imposed by contamination that is the focus of this article. As a framework to guide the establishment of restoration goals for contaminated sites, we provide a decision tree support tool (Figure 1). This tool is intended to help guide a multidisciplinary team through the restoration goal-setting process. The series of decision points and identification of possible inputs to the decisions can help the team compile useful information from a combination of data, documents, models and technical expertise. The process is expected to identify site-specific issues and data gaps. In general, this type of decision support tool improves efficiency, expedites problem solving, facilitates interpersonal communication, promotes learning, reveals new approaches, and generates evidence in support of decisions. This evidence can play an important role in the transparency, acceptance, and defensibility of the final restoration decisions. This tool is not intended to prescribe specific remediation or restoration goals, but rather to function at a higher level to guide processes that are common to the majority of contaminated sites, regardless of the type of contaminants present. The focus is not only on clean up goals or criteria, but also on the vision for the site once remediation has been completed and the site is restored to a productive ecological state. Although our primary focus is on ecological systems, we acknowledge alternative end states that necessarily elevate socio-cultural-economic outcomes over ecological, as well as brownfields (defined as formerly developed sites where continued use is compromised by real or perceived contamination (Oliver et al. 2007) where the end use is likely redevelopment).

STEP ONE: ASSEMBLE THE TEAM

Contaminant remediation projects typically have a core team of individuals who are responsible for designing, implementing, managing and monitoring the remediation. The term "core team" is used in this article to refer to the team

Table 1. Attributes for restoration targets

Target	Minimum attributes
Historical: sites where it is possible to target the full suite of SER attributes and the ecosystem service flows associated with them. They retain historical continuity and their current state lies within their known or assumed historic range of variation.	Reference ecosystem, characteristic assemblages
	Indigenous species, some exceptions
	Functional groups present or available
	Physical environment appropriate
	Ecosystem functions normally for successional stage
	Landscape integration, biotic, and abiotic interactions
	Potential threats eliminated
	Resilience and integrity
	Self-sustaining
	Provide ecosystem services
	Commitment to long-term management
Hybrid: systems have moved outside the historical range of variation, often because of the arrival of non-native species that interact and form assemblages not previously present; thus, they constitute a mixture of historical and novel elements. These systems could be returned to their historical state and trajectory with appropriate intervention, but the intervention may be technologically or economically impractical. These systems might offer an opportunity to use species that can assist in long-term contaminant removal or sequestration, provided a n attractive nuisance is not created.	Functional groups present or available
	Physical environment appropriate
	Landscape integration, biotic, and abiotic interactions
	Potential threats eliminated
	Resilience and integrity
	Self-sustaining
	Provide ecosystem services
	Commitment to long-term management
Novel: systems have moved so far away from their historical range of variation, through on-site and off-site biotic, abiotic and functional changes, including prior contamination, that they retain very little of their historic characteristics. They are likely to be resistant to attempts to return them to their historical state and trajectory.	Physical environment appropriate
	Landscape integration, biotic, and abiotic interactions
	Potential threats eliminated
	Resilience and integrity
	Self-sustaining
	Provide ecosystem services
	Commitment to long-term management
Threat removal: contamination and/or its remediation render the site ecologically unrestorable.	Safe and nonpolluting
	Stable
	Commitment for long-term management
	Provide ecosystem services where possible

Three primary restoration targets have been identified in the left column, as well as a nonrestoration, threat-removal target (see Figure 1). In the right column are the SER (2004) attributes that consitute the restoration goals, given the target.

that has the legal and/or regulatory responsibilities to develop plans for the remediation and restoration of a site. The composition of the core team may vary based on regulatory statutes in a country, types of impacts from contamination, and the identification of entities responsible for the management and release of the contaminant or contaminants. For contaminated ecosystems, it would be advantageous if the core team had at least 1 member with broad visions of how the remediated site might evolve into a restored ecosystem. This member need not possess technical restoration knowledge, only the ability to envision remediating the contaminated area as part of recovering a larger landscape. The core team can then rely on a broader technical team with at least 1 member with specific working knowledge of the contaminant or contaminants of concern, and a member with working restoration ecology knowledge for technical guidance.

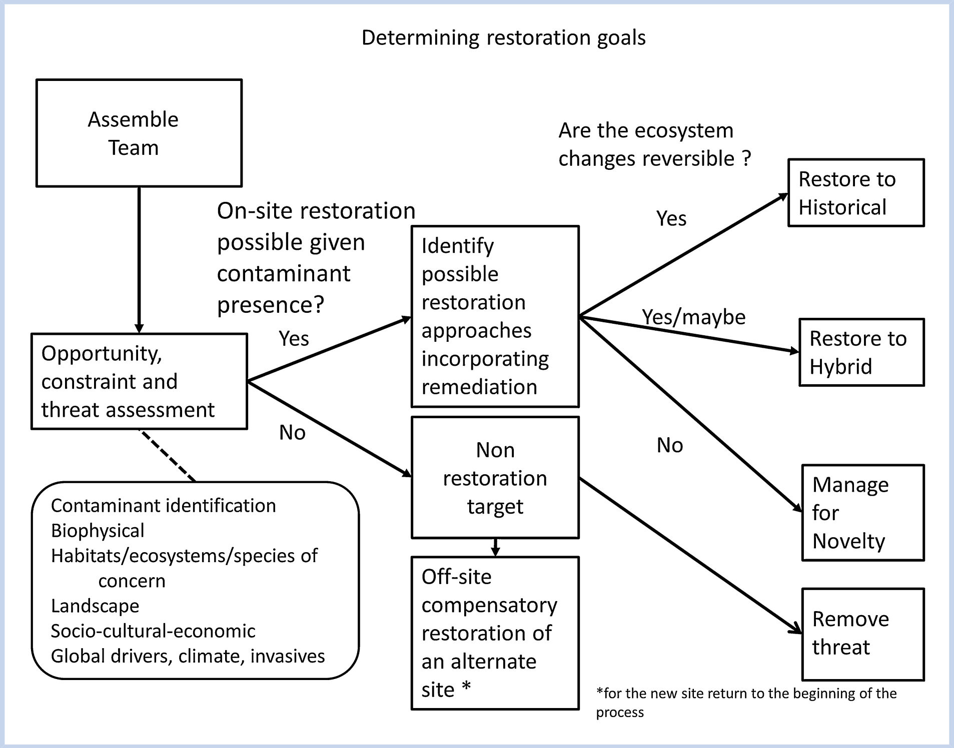

Figure 1. Decision tree for determining restoration goals for contaminated sites based on Hobbs et al. (2014). Rectangles represent actions and the lozenge in the first column represents inputs to the Opportunity, Constraint and Threat Assessment. Arrows indicate decisions with respect to the questions posed above them.

We recommend assembling a team comprising a broad spectrum of technical advisors and stakeholders who can work with the core team to concurrently plan for contaminant remediation, ecological restoration, and any socio-cultural-economic needs for restoration at the onset of the project. This approach will enable the core team to make well-informed decisions that can seamlessly move the site along the entire contaminated-to-restored site continuum (Farag et al. this issue). Technical advisors may include representatives from public and private sector land management agencies, nongovernmental organizations, academia, consultants, and responsible parties who can inform and conduct risk assessments given the contaminants present, identify appropriate restoration targets and goals, assess the feasibility of remedial and restoration strategies in light of these restoration targets, and develop long-term management plans for the site (ASTM 2010). The team would benefit from members who have the expertise to assess socio-cultural-economic issues that impact the decision-making process and the goals for the site. Groups, institutions or individuals who are directly impacted by the restoration and remedial actions (i.e., stakeholders) thus will have a voice. Articulating the interest, concerns and expectations of stakeholders early in the planning process can help the core team design a project that has the necessary community support for long-term sustainability.

The US Department of Interior, the National Oceanic and Atmospheric Administration (NOAA), the Environmental Protection Agency, and other Federal and State Trustees, as well as responsible parties in cooperative assessments, have recognized that assembling teams that focus on restoration early in the process typically results in more effective and practical restoration of natural resources (NOAA 2005). Kapustka et al. (this issue) also provide examples of where simultaneous consideration of risk, remediation and restoration has been successfully used both in the United States and internationally.

Although the approach to remediation and/or restoration in the United States often stems from federal regulatory processes, including CERCLA, OPA, and Natural Resource Damage Assessment and Restoration (NRDAR), the integrated goal setting process proposed here fits a variety of restoration and remediation approaches. Examples include addressing legacy mining impacts while expanding new mine production (Stevens et al. 2013), brownfields assessments and cleanups in urban areas that may re-establish watershed drainages, restoration of wetlands for better storm water controls (Township of Woodbridge 2011), nongovernmental organization (NGO) efforts to restore Great Lakes wetlands (The Nature Conservancy 2015), and projects developed in the European Union (e.g., CLARINET [Contaminated Lands Rehabilitation Network for Environmental Technologies]).

Within this framework, the core team provides structure for assembling the advisory group, gathering information, and incorporating it into the decision-making process that fits the needs of the project and that allows advisors to contribute at an appropriate level. Information-gathering sessions at the beginning of the process can help to identify key advisors and stakeholders. Technical advisors and stakeholders who have a long-term role in the life of the project (South River Science Team 2014) may be especially valuable members of the project team. There may also be a less formal role for key individuals who can be consulted for advice as needed. Another option is to establish an advisory board that periodically reviews progress toward meeting the ultimate goals of the project. A communication plan will keep stakeholders well informed and engaged in the project (e.g., the Hudson River Public Participation Plan and associated Web site) (NOAA 1998).

Building consensus among the core team, technical advisors and stakeholders can be a challenge. Opening the process to a wide range of stakeholders may create contentious situations between participants with competing visions or expectations (Davies et al. 2013). In this case, engaging a "trusted intermediary" can help facilitate the process (Morris et al. 2014) and maintaining records that document decisions made over the course of the project will help avoid controversy.

Additional considerations in implementing this approach can include

- Special role of indigenous peoples (e.g., the Indigenous Peoples' Restoration Network, a working group of the Society for Ecological Restoration International) (http://www.ser.org/iprn/iprn-home/welcome);
- Identification and the review of existing resource management, land use and/or watershed plans and determining if the owners of these plans should be included on the team or be a resource;
- Legal restrictions on the core team in making decisions; and
- Financial constraints.

STEP TWO: OPPORTUNITY, CONSTRAINT AND THREAT ASSESSMENT

Once the core team has assembled the larger, diverse project team, the next step is to conduct a comprehensive scoping exercise to identify opportunities and constraints and to conduct a threat assessment (Figure 1). Information gathered from technical advisors and stakeholders can inform a review of natural resource management, land use and watershed plans that will foster an understanding of the role of the contaminated site within the larger natural and built landscape. This will provide context for the risk assessment and may influence the questions the risk assessment addresses (Kapustka et al. this issue). Social constraints that need to be considered include cultural (e.g., traditional use), political (e.g., incompatible zoning), and legal (e.g., ownership), as well as factors that affect project readiness or implementation (e.g., cost, presence of utilities). This process will help the core team define the potential range of feasible remediation and restoration targets and goals, as well as identify constraints due to infrastructure and the contaminants present.

Inputs to the opportunity, constraint and threat assessment

The opportunity, constraint, and threat assessment will be informed by a variety of site attributes (lozenge connected by dotted line, first column in Figure 1). Although we cannot anticipate every circumstance, this discussion highlights those inputs pertinent to the vast majority of assessments.

Contaminants. Contamination of lands and water resources is unique relative to restoration of other sites because the potential release of the contaminant may cause deleterious human health and ecological effects. A thorough evaluation of the contaminants present at a site and how they might interact with the future restoration is a key aspect of the initial scoping process (Kapustka et al. this issue). Ideally, the evaluation will not just address containment or removal of the contaminants present, but also how these containment or remediation procedures may interact with the suite of possible future restoration goals. Including restoration ecologists in this evaluation, before remediation decisions are made, could result in outcomes that reduce the costs of remediation. For example, extensive contamination of the soil profile may require removal of the contaminated soil in the remediation phase and removal of the soil profile may impose limitations on the possibility of ecological restoration. Methods that allow contaminated soil to remain in place, with remediation accomplished using phytoremediation (Megharaj et al. 2011), or allowing the creation of wetlands using a "wet cap" (NOAA 2009) for example, offer new options for both remediation and restoration to occur simultaneously. Likewise, groundwater may recover in situ using a targeted pump and treatment protocol (Thornton et al. 2014). Though these techniques have limited applications, they may allow the realization of restoration goals that would have been unattainable previously. On the other hand, restoration plans may interact with contaminant containment procedures. For example, restoration on top of a contained site may mobilize contaminants and create a new threat to human or ecological health. The Salt Bay Restoration Project is working to restore tidal marsh and other wetland areas. However, this work may inadvertently be mobilizing methylmercury from the contaminated San Francisco Bay Estuary (Schwarzbach et al. 2005) that is not sufficiently rendered inert. In general, the type of contaminants present, the rates of breakdown, their solubility and movement, among other traits, and the potential ecological receptors, will influence the restoration potential (hence, the goals) of a site (Peinado et al. 2015). The ability of remediation methods to address these contaminant traits coupled with a clear vision of the suite of acceptable restoration outcomes constitute the raw materials necessary to create sustainably restored sites that resist unexpected contaminant release or exposure.

Biophysical. The biophysical setting, which includes geological, ecological, and climatological conditions (SER 2005), will influence the range of opportunities, constraints, and threats that are manifest at a site. Typically, restoration plans explicitly consider the biophysical setting to determine restoration potential and goals (SER 2005). When developing goals for a contaminated site, the effect of biophysical conditions on stability and movement of the contaminant in the eventual restored ecosystem is also a concern. Future climate scenarios, potential invasive species, and other land use changes in the landscape can interact with and impact restoration goals for the site. In addition, remediation activities to manage the contaminants may influence biophysical conditions that could then limit restoration potential (Peinado et al. 2015). For example, if complete removal of the topsoil of a site is needed to remove contaminants, the lack of topsoil will influence the potential and options for restoration (Klimkowska et al. 2010).

Questions of scale—species to landscapes. A challenge for restoring contaminated sites is to clearly understand and articulate the interactions between the contaminated site and the landscape, especially with respect to movement of contaminants off the site and use of the site by species (potential ecological receptors) that may be damaged by contaminants that remain after cleanup. Species of concern, which may include species with particular legislative mandates for preservation of both the species and its supporting habitat (e.g., in the United States, Threatened and Endangered Species

Act), will strongly influence restoration planning. Within the landscape context, then, it is critical that these issues be identified early in the process. Questions to address with respect to contaminants include: 1) how completely can the contaminant be removed or sequestered on the site, 2) what are the pathways by which contaminants may leave the site and how will they impact the surrounding landscape, 3) what are the sensitivities of organisms that will use or inhabit the site to any remaining contamination, and 4) are existing or potential food chains likely to amplify the contaminant in higher order predators (Rolfhus et al. 2015)? Traits of individual species and their role in the food and interaction webs of the restored site are key pieces of information: a plant that sequesters contaminants may further remediation goals, but if that plant is also a resource for organisms further up the food chain, toxicity may negate its positive remediation value and in fact may create an attractive nuisance.

In addition to issues related primarily to contaminants, it is equally important to understand how restoration alternatives for the site would contribute to broader conservation goals in the region. As Hermoso et al. (2012) pointed out with respect to freshwater rehabilitation, planning should occur at a landscape scale, even if implementation only occurs at smaller areas within that landscape. Rare habitats or ecosystems, even if they do not support designated species of concern, may require early and detailed planning if they are to be reinstated following contamination. Might the site provide "stepping-stone" habitat for migrating organisms? Or key habitat for a species of concern? Could it provide needed or desired ecosystem services? Regional conservation or natural resource management plans can be very useful for this step. Answers to these questions will guide the team goals toward an appreciation of the role the restored site might play, both positive and negative, within the larger landscape.

Socio-cultural-economic resources. A site's socio-cultural-economic resources include beliefs, customs, practices and behavior related to historical, archaeological, cultural, or natural resources that contribute to social or economic well-being. Evaluation from an ecosystem services perspective could include provisioning services, which refers to "[p]roducts obtained from ecosystems" (e.g., food, raw materials, energy), and cultural services, which are the "[n]onmaterial benefits people obtain from ecosystems through spiritual enrichment, cognitive development, reflection, recreation, and aesthetic experiences" (Millennium Ecosystem Assessment 2005). Provisioning services and cultural uses like recreation tend to be well-understood and readily valued (see Kapustka et al. this issue). Cultural resources often have spiritual, religious, or other special significance to indigenous peoples, which can pose unique challenges: reference conditions and the magnitude of impacts can be difficult to identify and quantify because the use of impacted natural resources may include some spiritual or religious practices that are not public; valuation can be challenging because cultural resources may be described by elements that are not easily captured in some measurable way; and restoration may be difficult because some cultural resources, once affected, may be irreplaceable.

Restoration of socio-cultural-economic resources has the potential to conflict with ecological goals. For example, restoration plans that include preservation of a non-native fish due to its importance to sport-fisheries and tourism would further economic goals at the expense of ecological goals. Depending on the nature of stakeholder interaction and the level of scientific and economic uncertainty, the team may want to embark on a formal decision making process. Structured decision making approaches can be used to help formally identify the political, economic, social, technical, legal, and environmental factors involved in setting restoration goals. Criteria can be set to help organize the team's understanding of the competing issues and their relative importance. See, for example, Srdjevic et al. (2012) for a case study on a Serbian water project, and Schädler et al. (2011) for a brownfield revitalization application in Germany. In this framework, the socio-cultural-economic restoration goals may amount to a threshold condition leading to a hybrid target (e.g., a nonnative fish in an otherwise diverse riparian system), or even an irreversible threshold leading to a novel target (e.g., including infrastructure to access the fishery).

Global drivers. Potential impacts of global drivers and their implications for long-term sustainability are factors in successful restoration. A first step for evaluation is to assemble and prioritize a list of global drivers likely to impact the site. For example, as effects of climate change become more apparent, an understanding of model projections should inform restoration goals (Galatowitsch et al. 2009). With respect to contaminated sites, knowledge of potential interactions between contaminants on the site and anticipated climate change could avert long-term problems (Manciocco et al. 2014), especially as land-use changes occur in the surrounding landscape (Cooper et al. 2013). Likewise, contaminants or their remediation may interact with a site's susceptibility to invasion by nonnative species. Knowledge of likely invaders can help managers plan for early detection and long-term management (Hulme 2012). Impacts of global drivers are inherently unpredictable. However, methods exist, such as scenario planning (Peterson et al. 2003), that can help stakeholders visualize and anticipate alternative futures for a site and help optimize remediation and restoration planning.

Synthesis: determining achievable attributes

The final step in the process of site planning, and the outcome of the Opportunity, Constraint and Threat Assessment, is to determine which attributes are ultimately achievable through consideration of contaminant mitigation and restoration approaches. As indicated above, the SER has developed a primer which lists 9 attributes of a restored system (SER 2004); to these we have added "provide ecosystem services" (Millennium Ecosystem Assessment 2005), and "commitment to long-term management" (Table 1). We consider these attributes to be the aspirational goals for restoration of a contaminated site. Although 10 of the 11 have previously been defined elsewhere, commitment to long-term management has not, yet it is key to sustainability and maintenance of the restored site and it is included in all potential targets of restoration (historic, hybrid, novel, and threat removal).

The attainment of a reference condition is the goal most commonly reported in published descriptions of ecological restorations (Hallett et al. 2013). Subsumed in the idea of reference condition is typically an assemblage of appropriate, usually native, species that provides structure and facilitates ecosystem function. In this article we use the term "historical conditions" to capture this target, a term more completely examined by Higgs et al. (2014). Also inherent in reference condition is the "range of natural variability" (Swetnam et al. 1999), which is becoming increasingly important as a changing climate adjusts our expectations of what may be possible at a restoration site. Even the most basic ecological restorations that involve no contaminants can take a century or more to reestablish some ecosystem functions (e.g., nutrient cycling [McLauchlan 2006]); restorations that involve reconfiguring the abiotic as well as biotic components can be expected to take much longer. Thus, capturing a range of related conditions within a site's reference condition allows one to define benchmarks of progress that can be evaluated and monitored as the restoration proceeds. Although it may not be feasible for hybrid and novel ecosystems to attain all of the 9 attributes of a restored site, they generally should achieve some (Table 1) and should provide ecosystem services.

To establish site specific restoration goals, determination of actions to reverse changes, i.e., to cross abiotic and/or biotic barriers, to achieve the target endpoint and/or endpoints is needed (Hobbs and Harris 2001; Parks Canada 2008). This step allows assessment of whether it is feasible to cross thresholds, and is aimed at determining the potential target states—historical, hybrid, or novel ecosystems (Figure 1, third column, and defined in Table 1)—or whether to consider other uses aimed principally at eliminating threat and achieving other end use goals.

Historical targets may be tenable in many cases, but in others this may be a difficult, impossible or impractical target due to a number of factors (including the contaminant itself) acting to create an irreversible threshold (Suding and Hobbs 2009). Here, irreversibility is the key attribute, and the one that leads to targets that differ from the historical condition. Higgs et al. (2014) suggest an approach in which history is used as a guide to decide between multiple restoration trajectories, with an emphasis on process and pragmatic goals that reflect ecosystem structure, function, and services rather than historical fidelity. Ehrenfeld (2000) urged realism in expectations of restorations, and acknowledgment that a reconstructed system will necessarily differ from the presumed predisturbance state. The presumption in this article is that the preferred target is an historical state, followed by hybrid, then novel systems (Figure 1, third column, defined in Table 1), but individual circumstances may lead to different targets. Hybrid and novel ecosystems may be diverse, functional, and valuable components of the landscape and the global ecosystem, provided they achieve the attributes in Table 1, and they may be the only available option for the persistence of certain species and services (Ehrenfeld 2000; Hobbs et al. 2009) given contaminants or other constraints present at some sites. Although it is optimal to select a restoration goal that maximizes net benefits (i.e., total benefits minus total costs in present value), it can be difficult to quantify all of the ecological benefits (Rohr et al. this issue). At a minimum, given a specific restoration goal, and all else being equal, the least-costly option to meet that goal would likely be selected.

There may be instances where ecological restoration of a contaminated site is not possible due to the nature of the contamination, lack of technology or prohibitive costs (Figure 1, second column). This may occur when contaminants are difficult to dispose of, such as high-level radioactive wastes, or where the spatial extent of the contaminants makes removal cost prohibitive. In some cases restoration of a highly contaminated site may create an attractive nuisance, where restoration would make the contaminants more readily available than if the site were capped or contained in place. For example, restoration of a wetland in California led to an increase in the bioavailability of Se, which produced an ecological disaster for wetland birds (Garone 1999). It is possible that in these cases, containing the contaminant and eliminating or at least reducing the potential movement of contamination from the site may be the best available option and restoration of the site to a previous ecosystem may create more environmental hazards than benefits. This would be termed a "nonrestoration target," but the site may have the potential to still provide some services. For example, a capped site could be used for solar generation (Gulde et al. 2011) or could provide recreational activities. Nonrestoration targets may also include off-site restoration or other mitigations to compensate for a site that cannot be restored. Madsen et al. (2010, 2011) summarize a variety of nonrestoration approaches, including "biodiversity offsets, mitigation banking, conservation banking, habitat credit trading, fish habitat compensation, BioBanking, complementary remediation, conservation certificates, and many more." When contaminated site strategies are necessarily very long-term (e.g., 50–100 or more years) because of the nature of the contamination and/or reliance on natural recovery, decision-makers may also consider the replacement value from offsite-restoration (e.g., compensatory restoration in the United States, biodiversity offsetting in Canada, Habitats Directive to compensate for adverse impacts on Natura 2000 sites in the EU). For further guidance on selection of appropriate off-site locations we recommend either using the decision tree presented in Figure 1 or see guidance in Hull et al. (this issue).

CONCLUSIONS

Sustainability of restoration

Throughout this discussion, we repeatedly return to 3 critical aspects of restoration: 1) ecological, 2) economic, and 3) socio-cultural. These are adapted from the 3 "pillars" of sustainability (Pope et al. 2004), which are necessary to achieve restoration goals in the long-term. These pillars are a synergistic concept of ecosystem restoration maintenance where the multi-faceted system is not allowed to degrade. As highlighted by Gann and Lamb (2006), a "[b]alance exists between ecological processes and human activities such that human activities reinforce ecological health and vice versa. The people who are dependent [*sic*] on the ecosystem have a key role in setting priorities and in project implementation." They are the stewards who will help ensure the sustainability of restoration. The core team needs to strategically evaluate the ecological, economic, and socio-cultural effects from the outset of the process, and build consensus across the suite of options given this broad context. That is, a successful restoration will be ecologically sustainable (e.g., given a changing a climate) and, as relevant, will enable people to satisfy their basic needs and enjoy a better quality of life, without compromising the quality of life of future generations (UK Government 2005). Neglect of any of the 3 puts the entire enterprise at risk (e.g., as conceptualized for invasive species management by Larson et al. [2011]). Globally, there are a number of initiatives, most notably in the European Union (EU) focused on risk based or sustainable remediation and rehabilitation. These are primarily focused on remediation of industrial or urban sites rather than ecosystem restoration (e.g., Network for Industrially Contaminated Land in Europe [NICOLE]), Common Forum, and Tailored Improvement of Brownfield Regeneration in Europe (TIMBRE), but do emphasize incorporation of the pillars of sustainability.

The importance of the iterative process

The decision tree is not a one-time activity, but rather an iterative process with a number of feedback loops. The tree can provide useful guidance on goal-setting for both reactive (e.g., regulatory) and proactive (e.g., permitted) restorations. When working through the Opportunity, Constraint and Threat Assessment, the team membership may be adjusted to obtain a comprehensive mix of decision makers, multidisciplinary experts, and affected stakeholders. Team participation may continue to evolve throughout the restoration goal-setting process. Both reactive and proactive goal setting have a range of uncertainties associated with contaminants that may require rethinking possible restoration approaches. The proactive process is further complicated by the need to be predictive about the future starting conditions of the site. More iteration may be needed to determine how to best achieve the common goal of return to reference. If the decision process leads to a nonrestoration target, it may be necessary to revisit the Opportunity, Constraint and Threat Assessment to help guide goal setting for threat removal and potential off-site compensatory restoration. Notably, monitoring helps ensure that the restoration targets are revisited over time to ascertain whether the attributes have been achieved (Hooper et al. this issue). Depending on the level of restoration success, the targets and associated attributes may need to be adjusted through adaptive management (but see Howe and Martinez-Garza 2014). Finally, changes in preferences, budget and/or technology can lead decision-makers to again ask, “Are ecosystem changes reversible?” Future conditions may make different targets and attributes more desirable and feasible.

Finally, it is important to note that this process ideally begins before a site is exploited and contamination is introduced (Koch 2007). A thorough understanding of the ecological and socio-cultural-economic implications of exploitation of the site will ultimately help avoid or limit the need for costly restoration actions on sites highly valued by stakeholders.

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