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# Transforming Ecosystems: When, Where, and How to Restore Contaminated Sites

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## EDITOR'S NOTE:

This paper 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

Chemical contamination has impaired ecosystems, reducing biodiversity and the provisioning of functions and services. This has spurred a movement to restore contaminated ecosystems and develop and implement national and international regulations that require it. Nevertheless, ecological restoration remains a young and rapidly growing discipline and its intersection with toxicology is even more nascent and underdeveloped. Consequently, we provide guidance to scientists and practitioners on when, where, and how to restore contaminated ecosystems. Although restoration has many benefits, it also can be expensive, and in many cases systems can recover without human intervention. Hence, the first question we address is: "When should we restore contaminated ecosystems?" Second, we provide suggestions on what to restore—biodiversity, functions, services, all 3, or something else—and where to restore given expected changes to habitats driven by global climate change. Finally, we provide guidance on how to restore contaminated ecosystems. To do this, we analyze critical aspects of the literature dealing with the ecology of restoring contaminated ecosystems. Additionally, we review approaches for translating the science of restoration to on-the-ground actions, which includes discussions of market incentives and the finances of restoration, stakeholder outreach and governance models for ecosystem restoration, and working with contractors to implement restoration plans. By explicitly considering the mechanisms and strategies that maximize the success of the restoration of contaminated sites, we hope that our synthesis serves to increase and improve collaborations between restoration ecologists and ecotoxicologists and set a roadmap for the restoration of contaminated ecosystems. *Integr Environ Assess Manag* 2016;12:273–283. © 2015 The Authors. *Integrated Environmental Assessment and Management* published by Wiley Periodicals, Inc. on behalf of SETAC

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## INTRODUCTION

Chemical contaminants are pervasive and diverse (Gilliom et al. 2007; Loos et al. 2009; ORD 2011). In the United States and European Union (EU), there are more than 80 000 chemicals registered for use (ORD 2011) and in the United States, pesticides or their degradates were detected in each of over 1000 streams analyzed for contaminants (Gilliom et al. 2007). Additionally, in the United States, there are over 1300 "Superfund" Sites (http://www.epa.gov/superfund/sites/npl/status.htm) and 287 active Natural Resource Damage Assessment and Restoration (NRDAR) cases (NRDAR 2015) where contaminant cleanup and restoration are being implemented. Chemical contaminants, including metals, pesticides, nutrients, PCBs, and PAHs, have reduced biodiversity in many ecosystems (Clements et al. 2000; McMahon et al. 2012; Beketov et al. 2013). These biodiversity losses often result in reduced environmental health, ecosystem functions, and ecosystem services (Carpenter et al. 1998; Carlisle and Clements 2003; McMahon et al. 2012; Halstead et al. 2014), the latter of which are ecosystem functions that provide benefits to humans (Dobson et al. 2006; Cardinale et al. 2012).

Restoration is the process of returning a disturbed site to a more-or-less natural condition, and thus the field of restoration ecology provides a suite of tools for accelerating the recovery of

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ecosystems damaged by contaminants. As a result, ecological restoration is a critical complement to conservation efforts in maintaining services provided by natural capital and thus improving human livelihoods (Dobson et al. 1997; Hobbs and Harris 2001). Indeed, meta-analyses suggest that ecological restoration regularly increases the provisioning of biodiversity and ecosystem services (Dodds et al. 2008; Benayas et al. 2009), and ecosystem service valuations suggest that the economic benefits of restoration can outweigh the costs (Bullock et al. 2011). Consequently, ecological restoration has increasingly taken a prominent role in global environmental policy (Bullock et al. 2011). For instance, by 2020, the international Convention on Biological Diversity (http://www.cbd.int/decision/cop/?id512268) aims for the restoration of ecosystems that provide essential services, and, by this same target, the EU aims to restore ecosystems "so far as feasible" to cease biodiversity loss and degradation of ecosystem services (http://www.eu-un.europa.eu/articles/en/article_9571_en.htm).

Unlike many other stressors that can degrade ecosystems (e.g., invasive species, climate change, habitat loss), there are national and international laws regulating environmental contamination which hold responsible parties liable for restoration of polluted sites (Rohr, Johnson et al. 2013). The International Convention for the Prevention of Pollution from Ships, known as Marpol, holds polluters responsible for the release of hazardous substances into international waters (Rohr, Johnson et al. 2013). In the United States, one program for holding responsible parties liable for cleanup and restoration is known as NRDAR, and the EU has a similar process that is described in an environmental liability directive (Rohr, Johnson et al. 2013). These regulations provide funds for environmental restoration associated with point-source pollution. For nonpoint-source pollution, tax dollars of many countries support restoration. For instance, in the United States and Canada, more than 1 billion tax-payer dollars have supported cleanup and restoration of the Great Lakes (Allan et al. 2013) and in the state of California, 1.5 billion dollars has recently been allocated for "multibenefit ecosystem and watershed protection and restoration projects" (Water Quality, Supply, and Infrastructure Improvement Act of 2014 [Assembly Bill No. 1471]).

Despite existing regulatory instruments and the unique opportunities that funding for contaminant cleanup offers to the field of restoration ecology, restoration ecology remains a young but rapidly growing discipline, and its intersection with toxicology is even more nascent and underdeveloped. Consequently, there has been little scientific guidance on which endpoints should be targeted for restoration in contaminated ecosystems or when, where, and how to restore ecosystems degraded by contaminants. These are the focal topics of this review and synthesis. Importantly, when providing guidance on how to restore contaminated ecosystems, we merge insights based on ecological and economic theory with insights obtained from on-the-ground restoration activities in an effort to make this review useful to practitioners and regulators.

## WHEN TO RESTORE?

The initiation of a restoration activity may be determined by political support and funding or a regulatory driver, by a recent environmental event, or even recent public awareness of an older environmental disaster. In other instances, it is practical to restore marginally contaminated areas to increase the value of a property. The timing of restoration actions not only depends on the environmental and ecological site conditions (e.g., is the contamination or perturbation still present), but also on the available funding and political will to engage in a potentially expensive long-term restoration process. It may be prudent for responsible parties to wait until litigation plays out or until certain agreements are in place before restoration begins. Private land-owners may want to wait until the market of an enhanced property allows for them to recuperate the cost of restoration. Regardless of the pragmatic issues, there are several broad considerations that should be included in a site restoration plan.

### *The passive–to-active restoration continuum*

At one end of the spectrum, restoration can occur passively, where the sources or releases of the contamination are eliminated and then the system is allowed to recover via natural processes. Unlike remediation, which is often synonymous with cleanup or contaminant removal, passive restoration entails monitoring to ensure that the system is returned to some previous "healthy" condition. At the other end of the continuum, restoration can occur actively, where humans intervene to accelerate the recovery (Benayas et al. 2009; Rohr, Johnson et al. 2013) (Figure 1). Ultimately, determining whether active or passive restoration is more cost-effective requires knowing something about the degree of damage caused by the contaminant, the intrinsic rate of natural ecosystem recovery, which can be influenced by disturbances and sources of propagules (organismal dispersers) in the surrounding landscape, the landscape context in which the site is positioned, and restoration goals, funds, and costs (Dobson et al. 1997; Holl and Aide 2011). For example, a forest restoration project in Latin America revealed that passive restoration was more cost-effective than active restoration because of the high costs of planting trees (Birch et al. 2010), and a meta-analysis of 240 aquatic systems revealed that most recovered naturally from disturbances in approximately 10 y, again suggesting that passive restoration might be more cost-effective (Jones and Schmitz 2009). Similarly, a report by the US National Academy of Sciences on the effectiveness of dredging at Superfund sites concluded that monitored natural recovery is often more effective than active removal and disposal of contaminated dredging materials (NRC 2007). If natural recovery rates are unknown, it might be worth estimating site-specific, unassisted recovery rates for a few years before intervening (Holl and Aide 2011). In some cases, active restoration can even cause more harm than good. For instance, mechanically planting trees can damage naturally resprouting vegetation (Holl and Aide 2011) and dredging sediments can resuspend contaminants making them more bioavailable (Knott et al. 2009). However, even if passive restoration is more cost-effective, active restoration might be required by law or could be necessary to meet specific restoration goals, such as creating habitat for threatened species or to maximize a particular ecosystem service.

Passive restoration is often referred synonymously with monitored natural recovery (MNR). After the contaminant source is stopped, MNR entails relying on natural physical, chemical, and biological processes to isolate, destroy, or reduce the bioavailability or toxicity of contaminants (Fuchsman et al. 2014). Unlike cleanup and active restoration, there is no construction phase, but MNR does include a site

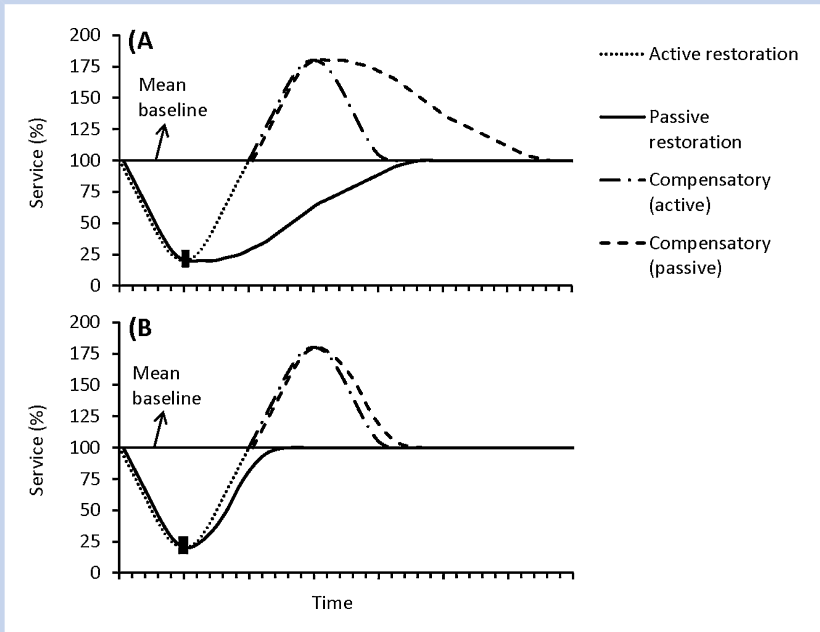


**Figure 1.** Scenarios (for countries without required compensatory restoration) where active or human-assisted restoration is **(A)** and is not **(B)** more cost effective than passive restoration, where the contaminant or its adverse effects are removed or mitigated (black rectangle) but the system is monitored until it recovers naturally to the mean baseline condition. Also shown is compensatory restoration for the active and passive restoration scenarios. Compensatory restoration, which is only required in some countries, requires the polluter to compensate the public for the time and magnitude of the lost services caused by the contaminant release. Note how the compensatory restoration is a mirror image (relative to the baseline) of the active and passive restoration but later in time. Compensatory restoration can begin at any time after the damage has begun (i.e., before or after the active or passive restoration is complete) and often entails improving the services offered by natural resources at ecosystems near the contaminated site (off-site restoration).

investigation, development of a conceptual site model, and long-term monitoring. If monitoring indicates that recovery is not proceeding as predicted, site managers may enhance the MNR by combining it with other remedies such as capping or removing contaminated sediments or soils. MNR or enhanced MNR has been used extensively for metal-, PAH-, and PCB-contaminated sediments because dredging can increase contaminant bioavailability; consequently, MNR is a US Environmental Protection Agency (USEPA)-recognized remedial alternative to cleanup and active restoration (Fuchsman et al. 2014).

Whether passive restoration is more cost-effective than active restoration will partly depend on whether the restoration is occurring in a country that requires compensatory restoration. Compensatory restoration, which is mandated in the United States, requires the polluter to compensate the public for the time and magnitude of the lost services caused by the contaminant release during the time period before the on-site restoration is completed (Figure 1). Passive restoration and MNR are more costly where compensatory restoration is required because these processes tend to be slower than active restoration and thus the compensatory restoration costs for passive restoration and MNR are typically larger than for active restoration (Figure 1). In summary, although active restoration can often be cost-effective (Benayas et al. 2009; Bullock et al. 2011) (Figure 1A), in some cases it might not be (Figure 1B) and thus it would be judicious to evaluate whether active restoration is necessary before implementing an active restoration plan (Holl and Aide 2011).

### *When to begin restoration?*

If it is determined that restoration will be implemented, then ecological restoration ideally should be considered up front and incorporated into the remediation plan for several reasons (Kapustka et al. this issue). Practitioners can define the extent of cleanup and restoration to minimize disturbances. This ensures that sensitive areas and key features are protected during the remediation process, which, in turn, can increase the rate of recovery. Identification and protection of sensitive site attributes can aid in the siting of equipment staging areas, egress routes, and stock piling of removed contaminants. This can further serve to minimize damage and thus speed recovery. By considering ecological restoration up front, equipment and labor already present on site might be used in an efficient and cost-effective manner toward both remediation and restoration activities. Perhaps the strongest reason for considering restoration up front is that it might influence the type of remediation strategy that is used and how it is ultimately carried out.

## WHAT TO RESTORE? DEFINING BASELINE AND IDENTIFYING ENDPOINTS

### *Defining baseline conditions within the context of natural variability*

Because the ultimate goal of ecological restoration at contaminated sites is often to return structure and function of a system to predisturbance conditions, baseline conditions should be determined before initiating restoration activities. Consequently, identification of reference sites or reference conditions has received considerable attention in the ecotoxicological literature and is a critical component of ecological restoration. A variety of approaches have been used to select reference conditions, including the use of historical and paleoecological data, quantitative models, best professional judgment and regional reference sites (Hughes 1995; Rohr et al. 2009). A significant challenge associated with identifying reference sites is to understand their natural spatial and temporal variability, which are often scale-dependent and interactive (White and Walker 1997). Furthermore, the trajectory of baseline conditions will influence the rate at which recovery is observed. If conditions are already degraded or on a downward trajectory relative to the baseline, for example as a result of climate change or other persistent disturbances, perceived recovery will occur sooner than in a system with more constant baseline conditions (Rohr, Johnson et al. 2013) (Figure 2).

The likelihood of achieving reference or baseline conditions and thus the ultimate success of restoration activities at contaminated sites will greatly depend on the definitions of these terms. For example, returning contaminated ecosystems to their historical, predevelopment conditions may be impossible for some sites. The legacy of contaminant exposure might permanently shift communities to an alternative stable state, making it impossible to restore baseline conditions (see below).

Two general approaches reflecting either temporal or spatial variability have been used to identify reference conditions at contaminated sites: use of historical (e.g., precontamination) conditions or identifying similar sites outside the area of contamination for comparison ("reference"). Regardless of whether baseline is defined by historical characteristics or best available conditions, it is widely recognized that a single reference site is usually insufficient to characterize natural spatiotemporal variability (Ruiz-Jaen and Aide 2005), although we also recognize that in some instances a single reference site might be all that is available. Selecting multiple reference sites that reflect the range of natural variation within a region highlights the fact that ecological restoration of contaminated sites is rarely focused on a specific numerical value but rather sets goals within a realistic range of values.

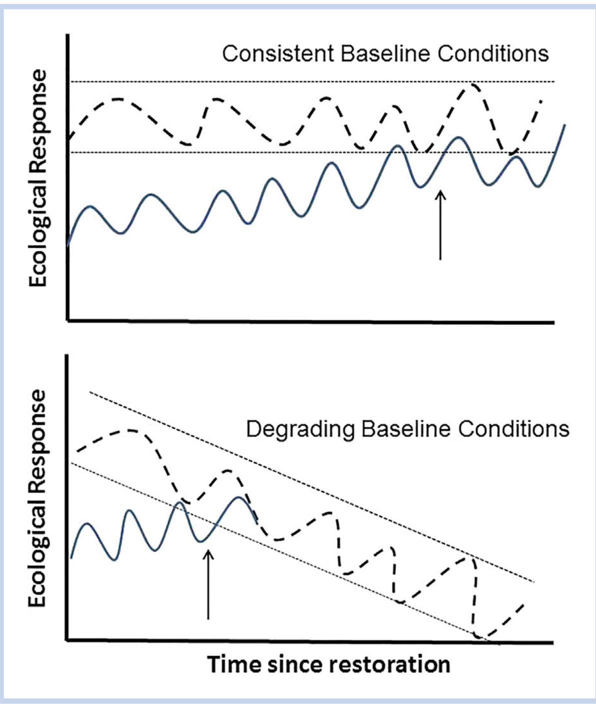


**Figure 2.** The influence of baseline conditions on rates of recovery in contaminated ecosystems. The figure shows situations where baseline conditions ($\pm$SD) are consistent (upper panel) and degrading (lower panel) over time. Arrows show the point where there is no statistical difference between restored and baseline conditions. Perceived recovery occurs much more rapidly in the lower panel because of degrading baseline conditions.

Also, reference sites must be selected carefully so that they capture the desired conditions. For example, in a 12-state survey of streams and rivers in the Western US, physical and chemical disturbance measures and biotic indices did not significantly differ between "handpicked" reference sites provided by resource agencies and those selected by a probability-based design (Whittier et al. 2007). Hence, it is important that reference sites do indeed represent least-disturbed conditions if that is their goal (see White and Walker [1997] for guidelines on reference site selection). Regardless of the approach to selecting a reference condition, where possible, a before-after-control-impact (BACI) experimental design to restoration (Green 1979) is ideal because it captures both temporal and spatial variation among the reference and contaminated sites. Advantages and disadvantages of these different experimental designs for monitoring restoration effectiveness are described in Hooper et al. (this issue).

### *Restoration endpoints*

Restoration goals and objectives are fundamental components of any successful ecological restoration (Wagner et al. this issue). Although most would agree that measures such as genetic diversity, community structure and function, and the services provided by ecosystems are critical aspects of natural systems (Pereira et al. 2013), there is a lack of consensus among practitioners regarding which specific features should be restored and the default is often to only restore vegetative cover. Unfortunately, the field of environmental toxicology provides incomplete guidance on this topic because ecological risk assessment has focused primarily on endpoints at individual and populations levels, such as LC50, low-effect, or no-effect values on individuals, despite evidence that these endpoints often provide incomplete information regarding how communities and ecosystems will respond in nature (Rohr, Kerby et al. 2006; Clements and Rohr 2009). Similarly, despite theoretical and empirical evidence of relationships between species diversity and ecosystem function (Cardinale et al. 2012; McMahon et al. 2012), this relationship is far from universal and in some cases, preservation of biodiversity or ecosystem functions can even be in conflict (Bullock et al. 2011).

Recognizing that compiling simple inventories of species does not adequately assess biodiversity loss, Periera et al. (2013) presented the following list of essential biodiversity variables (EBV) that should be considered in monitoring programs: 1) genetic composition of selected populations, 2) individual fitness, 3) population abundance of species, 4) species traits, 5) evolutionary diversity, 6) community structure and composition, 7) ecosystem function, 8) resistance and resilience, and 9) ecosystem services. Although it is unlikely that all restoration programs would include all of these variables, the first 8 variables highlight the fundamental characteristics of ecosystems that may need to be restored and maintained to provide necessary ecosystem services. Although Periera et al. (2013) define these 9 variables as "essential," we realize that these variables represent a candidate list of restoration endpoints.

Some of the proposed EBVs will be familiar to ecotoxicologists and ecological risk assessors. For instance, there is a long history of ecotoxicologists quantifying the effects of contaminants on individual traits and fitness (Rohr et al. 2003; Rohr and Palmer 2005; McMahon et al. 2011; Jennings et al. 2012), and more recently they have begun to more thoroughly quantify effects on population dynamics (Forbes and Calow 2002; Rohr, Sager et al. 2006), species interactions (Rohr et al. 2008; McMahon et al. 2013), community composition, and even ecosystem functions and services (Rohr and McCoy 2010b; McMahon et al. 2012; Halstead et al. 2014). However, other EBVs have received relatively little attention in the toxicological literature, but may offer important insights to restoring contaminated sites. For instance, functional or species traits (e.g., particular guilds of herbivores or consumers), an alternative measure of biodiversity with tight links to the delivery and stability of ecosystem functions and services (Petchey and Gaston 2006; Cadotte et al. 2011), is an underappreciated restoration target for contaminated ecosystems. Similarly, with anthropogenic factors becoming increasingly more common and problematic, ecosystem resistance, the ability of a community to maintain equilibrium conditions following exposure to a contaminant, and resilience, the ability of a community to return to predisturbance conditions after a contaminant is removed, are important but uncommon restoration endpoints (Clements and Rohr 2009).

When restoring contaminated ecosystems, it is also important to recognize that it may not be possible or desirable to restore a system to its original, historical conditions (Hobbs et al. 2009). Contaminants can reduce ecosystem resistance and resilience pushing ecosystems across irreversible thresholds (Clements and Rohr 2009). Thresholds are defined as abrupt, nonlinear changes in structure or function of communities that result in alternative stable states of ecosystems. Depending on the type, duration, extent and level of the stressor, these alternative states might remain stable long after stressors are removed, resulting in a novel (mostly novel elements and that cannot be restored to historical conditions) or hybrid ecosystem (partly novel elements with the potential to be restored to historical conditions) (Wagner et al. this issue) with characteristics very different from the original system (Folke et al. 2004; Scheffer et al. 2009). These regime shifts have been reported in lakes, coral reefs, pelagic and desert communities (Bellwood et al. 2004; Scheffer et al. 2009), examples that demonstrate the importance of preventing concentrations of contaminants and other stressors from exceeding critical thresholds and the challenges of restoring these communities after they transition to an alternative stable state. In extreme cases where regime shifts have occurred, the only alternative might be to restore ecosystem functions with novel communities (Hobbs et al. 2009). There could also be situations where a habitat being restored is so rare, unique, or limited that there are not many alternative locations to restore that ecosystem, and thus novel communities might be the best option to support specific restoration goals (e.g., certain ecosystem services).

It is important for restoration planners to understand the costs and benefits of different restoration endpoints. For example, even if the original biodiversity at a contaminated site recovers, the process of selecting for contaminant-tolerant individuals can result in communities that are more susceptible to other stressors. Experiments conducted with benthic communities collected from metal-contaminated streams showed that these organisms were more susceptible to predation, acidification, and UV-B radiation (Clements 1999; Courtney and Clements 2000; Kashian et al. 2007). Similar patterns were revealed in a long-term assessment of metal-contaminated streams in the wild, despite recovery of community composition (Clements et al. 2010). Contaminant-tolerant individuals might even pose threats to higher trophic levels if contaminants become concentrated in prey tissues and as a result become a toxic food source for predators. Additionally, sometimes it might be best to restore a novel or hybrid community because it offers more services, is more resilient, or is more likely to thrive sustainably under future climatic conditions (Choi 2007; Hobbs et al. 2009; Rohr, Johnson et al. 2013). However, if the restoration targets are ecosystem functions, services, resistance, or resilience, practitioners must keep in mind that threatened, endangered, or rare species might be lost. Likewise, if the target of restoration is species richness, then important ecosystem functions and services might be lost. Where possible, we encourage a combination of structural (biodiversity) and functional endpoints to enhance the likelihood that both rare species and services are restored.

## WHERE TO RESTORE?

On-site restoration is often more desirable than offsite restoration (i.e., improving ecosystem services somewhere other than the location of the contamination). On-site restoration allows for the cost-effective combination of remediation and restoration efforts and ultimately comes closest to meeting the definition of restoration, "to assist the recovery of an ecosystem that has been degraded, damaged, or destroyed" set by the Society for Ecological Restoration (SER 2004). However, there are instances where "off-site restoration" (sometimes referred to as mitigation) might be desirable or even required. First, off-site restoration might be required in scenarios where the contamination cannot be removed without causing extensive damage, when disposal options for the contaminated waste do not exist, or where soil that has the requisite conditions to support native biota has been eliminated. Second, off-site restoration might be necessary in countries where compensatory restoration is mandated (Figure 1). Compensatory restoration is an effort to replace those interim losses of services between when a contaminant is released and when restoration is complete and thus often entails improving the services offered by natural resources at ecosystems away from the contaminated site (Figure 1). Finally, off-site restoration might be desirable if local conditions are expected to change adversely for local biodiversity. For instance, it might be best to re-establish some communities poleward in anticipation of climate change (Choi 2007). However, in some cases, climate change can enhance toxicity of contaminants (Moe et al. 2013), which might encourage off-site restoration, but global warming can also reduce exposure to contaminants (Rohr et al. 2011) potentially discouraging off-site restoration. Hence, uncertainties regarding the effects and magnitude of climate change, in addition to ethical issues associated with the local human population not being compensated for damages to their natural capital, can make off-site restoration in anticipation of climate change challenging (Choi 2007; Rohr, Johnson et al. 2013).

## HOW TO RESTORE: THE ECOLOGICAL THEORY

There are several ecological theories and disciplines that can inform and guide the restoration of contaminated sites, thus improving the cost-effectiveness and success of restoration programs. Although it is beyond the scope of this article to thoroughly cover all of these ecological contributions, we do provide a brief overview of these advances and encourage readers to explore the cited and associated literature if more information is desired.

Many active restoration projects of contaminated sites restore biodiversity by translocating (moving from elsewhere) or reintroducing (taking a local stock, replicating it in "captivity," and introducing at the same general location where it was found) wildlife. There is a rich history of attempted translocations and reintroductions that have provided guidance on how to successfully restore biodiversity using these approaches. Most of these successful tactics are summarized by the Association of Zoos and Aquariums Guidelines for Reintroduction of Animals (https://www.aza.org/reintroduction/), and we encourage restoration practitioners to consult these guidelines before using these tools to restore animal and plant diversity.

Like translocations and reintroductions, ecosystem engineers, or organisms that can create, significantly modify, maintain, or destroy a habitat (Jones et al. 1994), can be important tools for restoration (Byers et al. 2006). Perhaps the most well-known examples are those involving phytoremediation, or the use of plants to remove and concentrate contaminants from soil, sediments, or water. Phytoremediation has been used to clean up sites contaminated with metals and certain organic compounds, facilitating natural recovery (Meagher 2000). Although the plant communities associated with phytoremediation might represent novel or hybrid communities and thus an undesirable restoration endpoint (Hobbs et al. 2009), in many cases, the historical community can be restored after these plants are harvested. Like phytoremediation, microbial remediation, or the use of microbes to accelerate contaminant breakdown, has also proven to be a valuable use of ecosystem engineers for restoration purposes (Dobson et al. 1997; Kang 2014).

Ecosystem engineers that do not concentrate or break down contaminants have also been useful to restoration efforts. Oysters, which create reefs that provide habitat for other organisms (Gutierrez et al. 2003), have been introduced at several locations as natural barriers to storm surges and the contaminants and nutrients that these surges can bring to fragile coastlines (Coen et al. 2007). Lakes that have become eutrophic from P contamination have been restored by removing zooplanktivorous fish (that increases zooplankton that feed on suspended algae) and adding phytoplanktivorous fish, each of which helped to prevent algal blooms that can cause anoxia and subsequent declines of biodiversity (Scheffer et al. 1993).

In addition to facilitating restoration, ecosystem engineers can also be impediments to restoration. For example, in many cases contaminant cleanup might not be possible and thus contaminated sites are capped with soil or sediment to isolate and contain the chemical, minimizing exposure of the contaminant to biodiversity. If these caps do not include geotextile or armored barriers, many burrowing organisms can bring the contaminants to the surface where other organisms can be exposed. For example, ghost shrimp (*Sergio trilobata* and *Lepidophthalmus louisianensis*) burrowing has been shown to move buried metals to the sediment surface in Tampa Bay, Florida (Klerks et al. 2007). Burrowing species in general could increase the bioavailability of buried contaminants. Similarly, trees with deep penetrating roots can mobilize buried metals into the leaf litter (Mertens et al. 2007). Consequently, it is important to carefully consider the role that species play in altering exposure to chemical contaminants during the restoration process.

Theories on how communities assemble and change have been the objects of ecological research for over a hundred years (Connell and Slatyer 1977; Pickett et al. 1987), and these theories have relevance for the restoration of contaminated ecosystems (Palmer et al. 1997; Young et al. 2005; Funk et al. 2008). Community assembly theory is predicated on the fact that the composition of communities is influenced by 3 primary drivers or filters: 1) the dispersal limitations of species that form the possible or regional pool of species that could occur at a site, 2) abiotic conditions including site history, and 3) biotic interactions (Pickett et al. 1987; Funk et al. 2008). The key insight obtained from community assembly theory is that there are several factors that can be manipulated to attain desired community compositions and associated ecosystem functions. Restoration ecologists manipulate some of these factors, such as propagule pressure by introducing species and abiotic variables by removing contaminants, but seem to less frequently manipulate local biota, such as predators, competitors, or ecosystem engineers, to attain desired outcomes. Given the commonality of priority effects, the notion that the species that gets to a location first can out-compete another preventing its establishment, ensuring that desired species arrive before undesired species is important (Young et al. 2005). A more inclusive toolbox that holistically considers alterations to propagule pressure, abiotic conditions, and biota could improve restoration success, especially when challenged with restoring systems facing pollution in addition to other stressors, such as climate change and invasive species (Rohr et al. 2004; McMahon et al. 2013; Moe et al. 2013; Rohr and Palmer 2013; Rohr, Raffel et al. 2013).

Finally, there has been a recent and strong push to understand the assembly of ecological communities through an appreciation of the functional traits of species (McGill et al. 2006), and this trait-based approach to ecology has also been useful to restoration (Martinez-Garza et al. 2005; Funk et al. 2008; Martinez-Garza et al. 2013). For example, in cases where animals are being bred in captivity, there might be value in artificially selecting for tolerance of contaminants of concern or other stressors, such as pathogens, before reintroductions occur (Venesky et al. 2012). Across 25 restoration studies, herbaceous flowering plants with good colonization and competitive abilities both established and persisted when introduced (Pywell et al. 2003), and in a separate restoration study, 9 of 12 functional traits were predictive of growth rate or survival measures across all 24 plant species (Martinez-Garza et al. 2013). These results indicate that the traits of plants are often predictive of restoration success. Lastly, maximizing trait diversity or matching traits to potential invaders can reduce the invasibility of local sites, which is critically important because many restoration efforts have failed because of invasive species (Pokorny et al. 2005; Funk et al. 2008). However, an important caveat regarding invasive species is that not all are necessarily problematic when cleaning up or restoring a contaminated site. For instance, in North American salt marshes, the invasive reed *Phragmites australis* reduces methylation and transport of buried Hg relative to the native grass *Spartina alterniflora*, and thus the invasive plant actually makes Hg less bioavailable (Windham et al. 2003).

## HOW TO RESTORE: THE ECONOMIC THEORY

Economic theories relevant to restoration are critical because they facilitate providing the funds to translate the ecological theories on how to restore to on-the-ground practices. Even though there are systems to hold polluters financially responsible for restoring contaminated sites (Rohr, Johnson et al. 2013), most restoration projects are very small, fail to consider the landscape or watershed contexts that address connectivity among sites, and rarely have funds for monitoring, which is critical to determining restoration success (Bernhardt et al. 2007; Lake et al. 2007; Rohr et al. 2007; Rohr, Johnson et al. 2013). Additionally, economic valuations of future ecosystem services are considerably discounted, often exponentially declining into the future, which undervalues these services to posterity (Bullock et al. 2011; Rohr, Johnson et al. 2013). Hence, even where solid planning is in place, financial needs for restoration often far exceed available resources.

Payment for Ecosystem Services (PES) represents an alternative funding strategy that has potential to facilitate restoration (Bullock et al. 2011). PES strategies are designed to compensate parties for actions that maintain or increase the provision of ecosystem functions and these credits can be purchased, sold, or traded. There are several successful PES programs that could serve as models for restoration, such as in-lieu fee programs and wetland mitigation banking in the United States, the Grain to Green Project that is paying farmers to convert steeply sloping cropland to forest and pasture in China, and REDD1—Reducing Emissions from Deforestation and Forest Degradation—internationally (Bullock et al. 2011). The advantages of these programs is that they can produce more funds for restoration than present approaches and offer greater flexibility so that credits can be combined to pursue larger-scale restoration projects that occur rarely now. These larger scale restorations could also result in considerable administrative cost savings, assuming that transaction costs associated with dealing with regulatory issues and negotiating and executing contracts for the payments of services are kept low (Bullock et al. 2011).

There are, however, some hurdles that must be overcome for PES programs to be successful. First, models that encourage prospective restoration or restoration before any injury (Stahl et al. 2008) have been criticized as providing a license to pollute. Second, restored ecosystems rarely match the services of the same ecosystems before damage and future services are regularly discounted (Benayas et al. 2009). Hence, if services are not accurately valued, the level of services provided as an offset may not match the true losses, resulting in an accumulating ecosystem service debt (Palmer and Filoso 2009). Third, the long-term sustainability of PES programs is a concern because there is little disincentive to allowing the ecosystem to degrade after payments cease (Bullock et al. 2011). Nevertheless, if these obstacles can be surmounted and local and regional institutional frameworks can manage the complexities of PES programs, then these strategies could enhance restoration science.

## HOW TO RESTORE: TRANSLATING THEORY TO PRACTICE

There are 5 major stages of restoration projects: Planning, Design, Construction, Operations and Maintenance, and Adaptive Management and Monitoring (Figure 3). Adaptive management is a systematic approach for deliberately learning from management actions to improve subsequent management practices (Holling 1978). Adaptive management and monitoring preferably occur throughout the entire restoration project (Figure 3) and ideal restoration occurs when goals and objectives are realistically set, funding is adequate, stakeholders are thoroughly involved, and the costs and benefits of the selected restoration are carefully considered (Figure 4).

### *Planning*

Outside of the scientific issues involved with planning restoration (see text above), one of the most important pragmatic activities in the planning stage is the development of the interdisciplinary team to develop and implement the restoration plan. Depending on project details, each team should consider having an ecologist, project manager, plan formulator, construction manager, and a budget analyst, and may also consider including outreach specialists, permitting specialists, economists, biologists, cultural resource (archeologists), hydrologists, civil, mechanical, and geotechnical engineers, mathematical modelers, and surveyors depending on the type and scope of the project. Specifically for contaminated ecosystems these teams would include both ecotoxicologists and restoration ecologists to offer biological insights into the planning, design, and implementation process. With participants from these 2 disciplines, restoration activities will incorporate the unique aspects of the contaminated site into the overall restoration plan. It is key to understand all the stakeholders, their goals, objectives, and prioritization during the planning phase. The project manager,

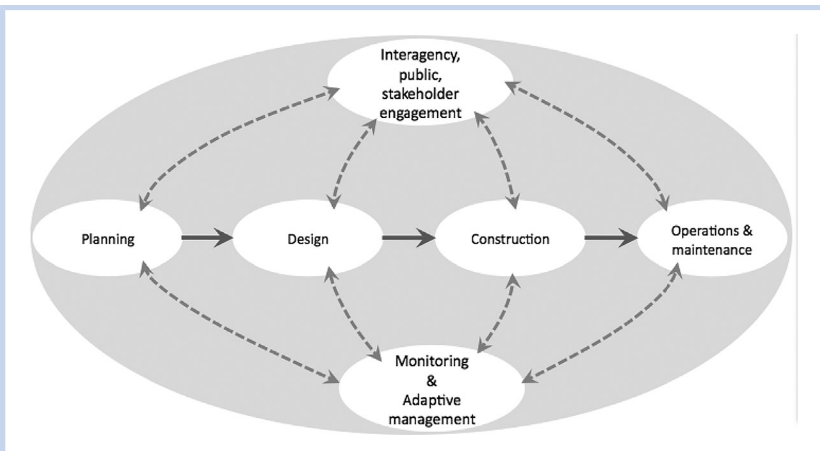


**Figure 3.** The stages of a restoration project, emphasizing that adaptive management and monitoring and communication with stakeholders should occur throughout a restoration project.

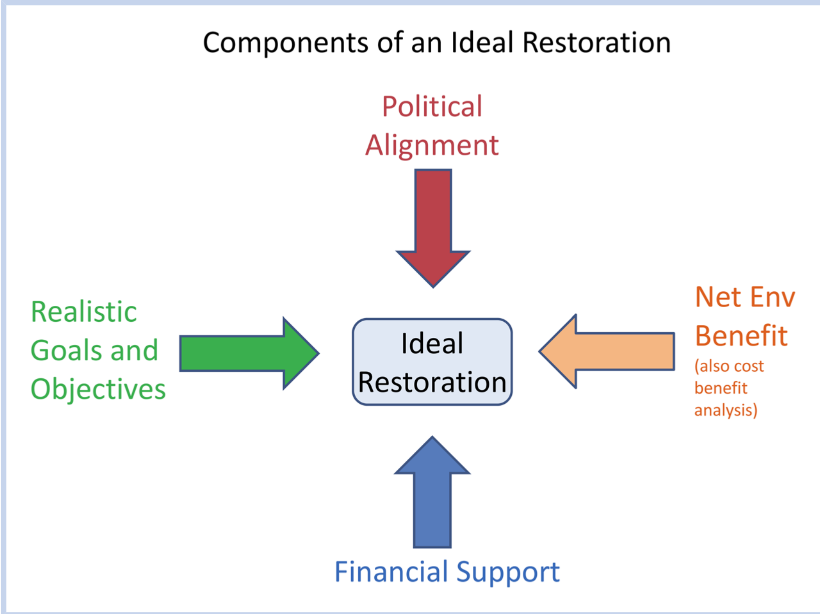


**Figure 4.** Components of ideal restoration. Ideal restoration occurs when goals and objectives are realistically set, funding is adequate, stakeholders are thoroughly involved, and the costs and benefits of the selected restoration are carefully considered.

with core team input, leads the preparation of a Project Management Plan (PMP), which details the scope, budget, and schedule for the restoration. The PMP is a "living" document that is often adjusted during the project life-cycle as progress is monitored and re-evaluated. The PMP may be replaced by a Project Agreement or Grant Agreement based on funding source and size of the restoration project. The project team also develops a Public Involvement Plan (PIP) that identifies relevant stakeholders and develops the methodology for public communication and involvement throughout the project. Good PMPs and PIPs should have clearly described processes for conflict resolution and should have protocols in place to avoid conflicts of interest that can compromise restoring biodiversity and ecosystem functions and services (Rohr and McCoy 2010a). One example of implemented PMP and PIPs is the restoration of the San Joaquin River Restoration Program (http://www.restoresjr.net/wp-content/uploads/General_Outreach/Program_Updates/2007/SJRRP_October_Update_Final_2007.pdf). This restoration effort focuses on returning adequate water flow for salmon communities, but contaminant influences from San Francisco Bay were recognized and prompted monitoring efforts.

Once the PMP is approved, the project team conducts a detailed site characterization. This entails compiling and reviewing existing and prior studies relating to contaminants, hydrological, ecological, and sediment characteristics of the study area, characterizing the damage to the site, and defining ecological and physical site parameters critical for project design and that could be affected by restoration, such as hydrology, soil characteristics, topography, bathymetry, species composition, and ecosystem functions and services. The final step in this process is developing a site map that highlights key features.

Once the site is characterized, goals, objectives, and performance measures ought to be developed and agreed upon. Clearly stating these provides the project team with the guidelines necessary to implement the project successfully. The selection of the restoration scenario should be coordinated with the project team and stakeholders (Wagner et al. this issue). Once the restoration scenario or plan is selected, the project team prepares a preliminary 1) design, 2) cost estimate, and 3) construction schedule, and describes postconstruction maintenance and the adaptive management and monitoring plan to determine effectiveness.

### *Design*

During the design phase, the preliminary design is fully developed, vetted, and described in a "Design Documentation Report" or "Basis of Design Report" that contains the technical basis for the plans and specifications and serves as a summary of the final design. A detailed discussion of restoration materials (their potential sources and suitability), procedures, and candidate disposal sites are generally identified. Technical review opportunities and incorporation of detailed engineering and permit requirements occur throughout this process. An example of such a report was constructed for the Lincoln Park/Milwaukee River site, which had contaminated sediments (http://dnr.wi.gov/topic/greatlakes/documents/LincolnPark-BasisofDesignReport.pdf). Equipment and production rates are identified during this design phase, which will serve as the basis for a more detailed and reliable cost estimate. Plans and specifications should contain all the necessary information required to bid on the restoration and/or construction plan. Independent reviews of the plans and specifications should be made for bidability (plans and specifications contain sufficient details for bidders to estimate accurate cost of project), constructability, and operability. Reviews of the plan provided by biologists and ecologists could preempt further destruction of habitat (e.g., related to nesting behavior of critical bird species) and costs associated with other unforeseen issues of this type.

### *Construction*

Upfront partnering among the contractor, engineer, and end-user is essential to ensure that common goals and objectives are clearly defined and that continual focus remains on potential contaminant releases. Contractors need to have a working knowledge of contaminant interactions at the site in question. Building trust, open communication and a defined issue resolution process eliminates surprises and minimizes formal disputes with contractors. The keys to successful construction projects are clearly defined construction methodologies and approaches that include detailed work tasks and resource requirements. In addition, experienced personnel in construction management, inspection, and oversight are essential to ensuring a quality product is delivered on time and within budget. Changes from the original plans may be especially important in contaminated ecosystems if remedial efforts fail or if a new source of contamination is discovered. If something needs to be changed from the original plans and specifications, a claim is submitted to the project team manager who oversees a modification. Operation and maintenance manuals and as-built drawings are required when the project is "transferred" to the end user. The as-built drawings may need to document the previous locations of contaminated hot spots for the end user, something that design engineering support can provide. Additional design engineering support for contaminated ecosystems might be required during the construction phase to provide support for contaminant-related contract claims and modifications and develop operation and maintenance manuals and as-built drawings.

### *Operations and maintenance*

Operation, maintenance, repair, replacement, and rehabilitation (OMRR&R) of a completed project is accomplished during this phase which lasts for the remainder of the project. Depending on the project elements, specific requirements for OMRR&R are defined. For example if the restoration project includes pump stations, there are detailed expectations from the manufacturer that are required to be implemented to keep the pump station operational for the life of the project. Initial restoration establishment criteria (i.e., percent of planted species survival and/or required stem count of individual species) would be implemented during OMRR&R stage. Finally, monitoring and repair of sediment caps used to isolate and sequester contaminants left in place would also be subject to OMRR&R.

### *Adaptive management and monitoring*

Adaptive management is embracing the need for continuous evaluation of the project and adjustments to the restoration plan to improve the prospects of restoration success. We encourage adaptive management and monitoring throughout the entire restoration project and afterward to ensure long-term success of the project (Figure 3). Details on developing and implementing adaptive management and monitoring plans are provided by Hooper et al. (this issue) in this issue.

## CONCLUSIONS

Here, we merged insights from ecological and economic theory and on-the-ground restoration activities to provide guidance on what endpoints should be targeted for restoration in contaminated ecosystems and when, where, and how to restore ecosystems degraded by contaminants. Specific to contaminants, we encourage considering equipment selection and the sequence of restoration-related activities to avoid disturbance or redistribution of contaminants, how remediation of contamination might assist restoration rather than damage habitat, and whether it might be better to leave contaminants in place rather than risk irreversible destruction of a functioning albeit impaired system. Additionally, although restoration to a natural ecosystem is often preferred, in some cases hybrid ecosystems might actually reduce contaminant mobility and bioavailability. More broadly, we encourage 1) practitioners to consider restoration as early as possible (i.e., before injury or before remediation), 2) restoration of both structural and functional endpoints, 3) consideration of broader landscape and seascape contexts, and 4) new ideas and approaches that can overcome the scientific and financial limitations of restoration. Most importantly, we urge more reciprocal transfer of knowledge among theorist and practitioners and academics, industry, government, tribal organizations, NGOs, and the public to improve the science of restoration.

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