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Environmental management: Integrating ecological evaluation, remediation, restoration, natural resource damage assessment and long-term stewardship on contaminated lands

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Abstract

Ecological evaluation is essential for remediation, restoration, and Natural Resource Damage Assessment (NRDA), and forms the basis for many management practices. These include determining status and trends of biological, physical, or chemical/radiological conditions, conducting environmental impact assessments, performing remedial actions should remediation fail, managing ecosystems and wildlife, and assessing the efficacy of remediation, restoration, and long-term stewardship. The objective of this paper is to explore the meanings of these assessments, examine the relationships among them, and suggest methods of integration that will move environmental management forward. While remediation, restoration, and NRDA, among others, are often conducted separately, it is important to integrate them for contaminated land where the risks to ecoreceptors (including humans) can be high, and the potential damage to functioning ecosystems great. Ecological evaluations can range from inventories of local plants and animals, determinations of reproductive success of particular species, levels of contaminants in organisms, kinds and levels of effects, and environmental impact assessments, to very formal ecological risk assessments for a chemical or other stressor. Such evaluations can range from the individual species to populations, communities, ecosystems or the landscape scale. Ecological evaluations serve as the basis for making decisions about the levels and kinds of remediation, the levels and kinds of restoration possible, and the degree and kinds of natural resource injuries that have occurred because of contamination. Many different disciplines are involved in ecological evaluation, including biologists, conservationists, foresters, restoration ecologists, ecological engineers, economists, hydrologist, and geologists. Since ecological evaluation forms the basis for so many different types of environmental management, it seems reasonable to integrate management options to achieve economies of time, energy, and costs. Integration and iteration among these disciplines is possible only with continued interactions among practitioners, regulators, policy-makers, Native American Tribes, and the general public.

Keywords

Contamination; Ecological evaluations; Restoration; Natural resource damage assessment (NRDA); Buffers; Ecological protection; Environmental management; Remediation; Restoration; Sustainability; Stewardship

1. Introduction

Increasingly the public and public policy-makers are interested in maintaining and managing healthy ecosystems, both in their own right and as they contribute to the health and well-being of people. Intact, functioning ecosystems provide the goods and services that healthy human populations require; not only clean air and water, food and fiber, medicines, other products, and protection from storms and inclement weather, but also recreational opportunities, aesthetic pleasures, cultural and religious experiences, and existence values (Harris, 2000; Harris and Harper, 2000; Zender et al., 2004; Bridgen, 2005; Stumpff, 2006; Burger et al., in press; Harper and Harris, 2008).

Maintaining healthy ecosystems requires information derived from evaluating natural resources within a community and ecosystem context, herein defined as ecological evaluation. Maintaining healthy ecosystems is easier for uncontaminated ecosystems than for those that have been exposed to undue physical disruption and high levels of environmental pollution. That is, contaminated sites often have both physical and biological disruptions, as well as contamination. Cleanup and restoration of contaminated sites is one of the most pressing environmental problems of this century (Lubbert and Chu, 2001; Crowley and Ahearne, 2002; Burger, 2007a), and one of the first steps in this process is evaluating ecological resources (receptors, including humans), ecosystem structure and function, and contamination levels and effects. Evaluating ecological resources provides the baseline for environmental management and long-term stewardship, particularly for contaminated systems that require remediation and restoration, and that might undergo Natural Resource Damage Assessments (NRDA, Deis and French, 1998; Sharples et al., 1993; Burger et al., 2003, 2007a). Yet these terms mean different things within and among disciplines, making it difficult to move forward with effective environmental management.

Ecosystem evaluation, and improving and managing ecosystems, are long-standing concerns of ecology, and now attract a broader audience. Although the terms and methods may have changed over the years, the goals have not (Cairns, 1980, 1994; NRC, 1986; Bartell et al., 1992; Cairns and Niederlehner, 1992, 1996; Cairns et al., 1992; Barnhouse, 1991, 1994; Suter, 2001; Burger, 1997a, b, 2002a,b, 2007a; Burger et al., 2007a). At a time when global changes include global warming and climate destabilization, sea level rise, development and destruction of habitats and major biomes, increasing human populations, and concentrations of people along coasts (Burger, 2001), it is particularly critical to evaluate and integrate the different processes that involve natural resource protection and management. The changing and complex global environment requires the integration of diverse environmental management disciplines and techniques. The problems we face require involvement, integration, and iteration. What is needed is involvement of a wide range of disciplines and

stakeholders, integration of ideas and approaches, and repeated iterations of approaches and solutions to our environmental problems.

The objectives of this paper are to examine the meaning of ecological evaluation, environmental and ecological management, remediation, restoration, NRDA, and long-term stewardship, to explore the relationships among them, and to suggest methods of integration and iteration that will move overall environmental management forward in the 21st century. It makes the point that environmental management should be proactive, rather than reactive; different phases of environmental management should be iterative, comprehensive, systematic, and inclusive of different disciplines, approaches, and processes. In this paper I use ecological evaluation in its broadest sense, from qualitative descriptions of the environment to formal risk assessments (see sections below). Although ecological evaluations are often conducted to understand why and how organisms behave, survive and reproduce, or to understand the structure and function of ecosystems, they are also conducted to meet very specific needs, such as determining the levels and types of remediation or restoration required, for environmental impact assessments, for formal risk assessments, or for NRDAs. This paper largely focuses on contamination (both chemical and radiological), and uses examples from the Department of Energy (DOE), the agency with the largest cleanup/remediation and restoration task in the United States (DOE, 1995; Crowley and Ahearne, 2002), although other agencies and the private sector have large cleanup challenges as well (Oughton et al., 2004; Burger et al., 2004a). The Department of Defense also has some contaminated lands with valuable natural and cultural resources that require environmental restoration (Sharples et al., 1993; Boice, 2001).

The DOE has some 5000 facilities located at 16 major sites and more than 100 smaller sites, in 34 states (Crowley and Ahearne, 2002). Some of these sites have a legacy of chemical and nuclear material from the production of nuclear weapons (DOE, 2000). In 1989, DOE created an Office of Environmental Management (EM) to deal with the cleanup of their facilities, which was largely driven by compliance with federal and state tri-party agreements, DOE orders, the Comprehensive Environmental Response Compensation and Liability Act (CERCLA), the Resource Conservation and Recovery Act (RCRA), other federal statutes, and the Nuclear Regulatory Commission (Daisey, 1998; DOE, 1994a,b, 2000; Burger, 2007b). The stewardship program of the DOE, initiated in 1994 (DOE Order 430.1), mandates the integration of ecological, economic, social and cultural factors into future land use decisions (Malone, 1998; DOE, 2001). Stewardship is particularly critical on DOE lands because of their unique habitats and valuable ecological resources (DOE, 1994a,b, 1996d; Brown, 1998; Dale and Parr, 1998; Burger and Gochfeld, 2001a,b; Burger et al., 2003, 2004b,c, 2007a,b, 2008; Whicker et al., 2004). Approximately 79% of DOE land area has been undisturbed for over 50 years because it served as buffer zones around the top-secret nuclear production facilities (DOE, 2001). These buffer lands now offer some of the finest and least disturbed plant and animal habitats in the United States (Brown, 1998; Dale and Parr, 1998; Burger et al., 2003).

2. Ecological evaluation

2.1. Goals of ecological evaluation

One of the goals of ecological evaluations is to assess ecosystem health, usually using indicators of status and trends (Peakall, 1992; Carignan and Villard, 2001; Burger, 2002, 2006). A healthy ecosystem can be defined as one with appropriate structure and functions that can continue to provide ecological goods and services (Leitao and Ahern, 2002). An ecosystem should have functioning food webs, nutrient cycling, and energy flow, appropriate biodiversity, predator–prey relationships and overall complexity, among other characteristics, and should be sustainable (Odum, 1957; Payne, 1966; Sheehan, 1984; Wilson, 1986; Hunsaker et al., 1990). To be truly sustainable, an ecosystem should have its own feedback loops and resiliency (able to recover from natural disasters or perturbations), without requiring net inputs (or exports) from outside the system (Cury et al., 2005). The definition of sustainability approved by the United Nations Food and Agriculture (FAO) Council in 1988 is that sustainability is the handling and conservation of natural resources, and the orientation of technological and institutional change so as to ensure the continuous satisfaction of human needs for present and future generations (Cena, 1999). A more accepted definition of sustainability is meeting the needs of the present without compromising the ability of future generations to meet their own needs (UN, 1987). Ideally, the use or extractions from the ecosystem should not compromise the biological structure and functioning of the system, or it is not sustainable on a long-term basis (Cabezas et al., 2005). Many agricultural systems, for example, are not sustainable because they require the addition of nutrients (fertilizers), pesticides, and in many cases, even water.

Ecological evaluations form the basis for many different environmental management processes, including determining status and trends of biological, physical, or chemical/radiological conditions, conducting environmental impact assessments, selecting remediation and restoration options, performing remedial actions should remediation fail, managing ecosystems and associated wildlife, and assessing the efficacy of long-term stewardship (Fig. 1). For example, ecological information essential for most environmental assessments of contaminated sites can be evaluated in the form of a checklist for managers (Burger et al., 2004b; Carletta et al., 2004; Greenberg et al., 2004). In this paper I consider humans as one ecological receptor, albeit one we are particularly interested in. Risk assessment is one type of ecological assessment for estimating the probability and severity of adverse effects, and it forms the basis for evaluating trends in risk over time. Ecological and human health risk assessments depend upon the information gathered in ecological evaluations.

2.2. Approaches to ecological evaluation

There are many different ways of conducting ecological evaluations, both in terms of approaches and the levels of biological organization examined (individual, species, populations, community, ecosystem, landscape). Landscape considerations often allow for interactions between other levels of organizations (Forman and Godron, 1986; Bennett, 2003). Both the type of evaluation (from qualitative to quantitative), and the range of biological organization (species to ecosystem) considered depend upon the problem or issue

being addressed (NRC, 1986; Ferenc and Foran, 2000). Ecological evaluations can range from inventories of local plants and animals, determinations of reproductive success of particular species of concern, levels of contaminants in organisms, types and levels of effects, and environmental impact assessments, to very formal ecological risk assessments for a chemical or other stressor (Beyer et al., 1996; Burger and Gochfeld, 1997; Suter et al., 2000, 2005; Gunderson and Pritchard, 2002; DOE, 1999, 2005; NRC, 2007a). Regardless of the complexity or rigorousness of the evaluation, all of them start with descriptions of species presence, abundance, interactions, ecological structure or processes, contaminant levels, and possible adverse effects. To be most effective, information on trends over space and time provide the necessary background for ecological risk assessment, management, and natural resource damage assessment.

Most ecological evaluations have an extensive problem formulation phase that often involves input from a range of stakeholders (PCCRARM, 1997; NRC, 1993; Suter et al., 2000; Burger et al., 2005, 2007b; Reagan, 2005). That is, an issue or problem needs to be defined before the evaluation can be designed, and the end use of the study should be clearly outlined. Without a clear definition of the problem, data collection will not be appropriate to answer the question. Problem formulation includes lists of potential receptors, sensitive habitats, pathways, media, endpoints, and chemicals of concern. For ecological evaluations, the problem formulation phase is the most critical because of the hundreds and even thousands of species within any ecosystem, the overall complexity and the great spatial and temporal scales. For example, single-celled organisms may live for minutes or hours, while some plants and animals live for hundreds of years; some plants reproduce asexually while others reproduce sexually, some organisms live only on land or water, while others have part of their life cycle in each (e.g. frogs). The variations are endless, and refinement or problem formulation is essential.

The problem formulation phase is particularly important for contaminated sites, such as those of the DOE, where the ecological information gathered will lead to decisions about future land use, level and types of remediation, and kind and levels of restoration, and can provide information to design long-term stewardship plans. Also, remediation and restoration can be used to augment and protect unique and rare species or habitats that already exist on contaminated sites. The DOE, with sites in 34 states (Crowley and Ahearne, 2002), has the opportunity to remediate and restore native habitats in states that have lost much of these unique habitats. For example, Brookhaven National Laboratory has a large part of the rare pine barrens ecosystem for Long Island (New York). Some of the land at the Idaho National Engineering and Environmental Laboratory represents the only pristine shrub-steppe habitat in the region, and the Savannah River Site in South Carolina has some of the only remaining Carolina Bays in the region (DOE, 1996a,b, 2002). The Hanford Site in Washington has the only free-flowing stretch of the Columbia River, an important spawning region for Chinook salmon, and its Arid Lands Ecology Reserve encompasses most of the remaining natural desert steppe habitat in the state (Geist, 1995; DOE, 1996c; Burger et al., 2006a).

Regardless of the stimulus for an ecological evaluation, all involve inventories of the status of species, populations, communities or ecosystems, as well as changes and trends in species

and ecosystem health and abnormalities, and such inventories or evaluations often involve indicators and monitoring (Suter, 1990, 1993, 1997; Suter et al., 2003). Indicators may be most useful if they provide information about both human and ecological health (DiGuillio and Monosson, 1996; Stahl et al., 2000; Burger and Gochfeld, 2001a, b, 2004). For example, contaminant levels determined for fish from the DOE's Savannah River in South Carolina were used to assess the potential risk to the fish themselves, their prey, and the consumers of those fish (Burger et al., 2001a,b). Understanding the levels in predatory fish provides information on whether the levels in their prey fish were high. Thus, the same data can be used to evaluate a range of ecological endpoints, including human health risk. In this case, mercury from the site resulted in sufficiently high levels of mercury in predatory fish to pose a risk to consumers, particularly African-American subsistence fishers (Burger et al., 2001b).

2.3. Indicators and monitoring

Two important processes of ecological evaluations are selecting indicators and developing monitoring plans. In both cases, the objectives need to be clearly defined (another aspect of problem formulation). Monitoring plans should be designed to take into account the value, vulnerability, susceptibility, and resiliency of the ecosystem, as well as sustainability (Harwell and Kelly, 1990; Burger, 1997a, 2002a, 2006; Burger and Gochfeld, 2001a,b; Leitao and Ahern, 2002; Cury et al., 2005; Vos et al., 2000). Monitoring is essential to assess changes in the environment, to provide early warning of potential problems, to assess efficacy of remedies, and to assess possible future adverse effects on humans and the environment. While it is more difficult to design biomonitoring plans for large, ecologically-complex sites, such as those of the DOE, it is both possible and essential (see VanHorn et al., 2004 for Idaho National Laboratory).

Bioindicators can be at any level of biological organization, from metabolic biomarkers to ecosystem metrics. In practical terms, bioindicators usually involve aspects of individual species (e.g. contaminant levels, health status, population numbers) or ecosystem metrics (e.g. primary productivity, nitrogen cycling, species diversity, Burger, 2006). Such plans will work best if they are holistic, rather than piecemeal, and if they are based on site-specific data (Burger, 1999), as was designed for the DOE's Amchitka Island (Burger, 2007c) and Idaho National Laboratory (VanHorn et al., 2004).

Usually a suite of bioindicators is assembled to form a biomonitoring plan, which is executed at some regular interval. For example, a biomonitoring plan to assure that the subsistence foods, commercial foods, food chain and ecoreceptors were free (and continue to be free) from radionuclides in the marine environment around Amchitka Island was designed only after completion of extensive sampling and analysis of biota, meetings and collaborations with the Aleuts (the resident Native Americans), and interviews with stakeholders (DOE, Department of the Interior, State of Alaska, environmental groups; Burger et al., 2005, 2006b,c, 2007b,c,d). Inclusion of stakeholders is extremely important to assure appropriate selection of meaningful bioindicators that the public will accept, have faith in, and ultimately support.

Bioindicators are particularly useful for contaminated lands because they can be used as indicators of both exposure and effects of chemicals or radionuclides, and can be used to evaluate both ecosystem damage and recovery following remediation and restoration. Given the very large remediation and restoration task on DOE lands, Department of Defense lands, and other lands contaminated by governmental agencies, private industry and agriculture, developing bioindicators that can be used over large regions also becomes important to allow comparisons among sites and habitats. Assessing recovery and functioning after remediation and restoration is important to advancing understanding of how to restore damaged ecosystems, what works best for particular habitats, and what methods can be applied in other regions.

2.4. Range of ecological evaluations: qualitative to ecological risk assessment

Ecological evaluations can be quite formal, such as ecological risk assessment (ERA), or less formal, and are often directed at contaminated systems (Beyer et al., 1996; Suter et al., 2000). Evaluations can be retrospective, forward-looking, or focused on present conditions only (Bartell et al., 1992; NRC, 1993; Suter, 1993, 2001; Suter et al., 2005). Less formal approaches are often used where sufficient data are not available for each of the required steps of ERA, the problem being examined does not require a formal process, or a more complex series of problems need to be integrated (e.g. mercury and radionuclide contamination, physical disruption, and human disturbance).

The lack of consistency among evaluation or assessment methods led to confusion not only on the part of managers and decision-makers, but also for the public. This created a need for a formal risk assessment paradigm that could be applied uniformly, regardless of the nature of the stressor or the target organisms. Evaluating the effect of chemicals on humans and ecological receptors became critical because of the need to evaluate the effects of new chemicals, and the potential for harm from chemicals already in the environment.

In 1983, the National Research Council (NRC, 1983) formalized the human health risk assessment paradigm (HRA) to include four parts: hazard identification, dose–response assessment, exposure assessment, and risk characterization. Hazard identification is defining the agent (or condition) that has the potential to cause harm (Rasmussen and Whetten, 1997). Dose–response usually involves laboratory tests with animals that indicate how the response varies with the exposed dose. Exposure assessment is determining the pathways (source, fate and transport) and routes (of uptake) of exposure, both to humans themselves, and to target organs; it is identifying the pathway from source to receptor. Risk characterization is integrating the hazards, dose–response curves, and exposure data to describe or characterize the risk to given receptors (for HRA=humans).

Relatively quickly, the NRC's formal risk assessment paradigm for humans was modified and adapted for ecological risk assessment (NRC, 1986, 1993; Burger, 1997b; Suter, 2001; Sorensen et al., 2004). Thereafter, the NRC risk assessment paradigm was modified to fit the needs of individual agencies, such as the U.S. Environmental Protection Agency (EPA, Norton et al., 1992). While the process varies among agencies, the overall steps are similar: problem definition or formulation, hazard identification, assessment of potential effects (and dose–response curves where possible), exposure assessment, and risk characterization

(melding exposure with assessment of effects, Figs. 2,3). Regardless of whether formal (ERA) or less formal ecological evaluations are performed, the process is designed to provide information that can be used for making decisions about managing refuges, restoring endangered species, planning forest harvesting, controlling water levels, remediation (level and extent of cleanup required, as well as its timing), restoration (re-establishing functioning ecosystems), NRDA, and establishing public policies.

3. Environmental and ecological management

Environmental, and ecological management are well-known disciplines with a wide range of paradigms, approaches, and techniques. For purposes of this paper, environmental management deals with the physical and biological components of the Earth's systems, while ecological management is largely interested in the biological components and with the physical components only as they impact the biota. Environmental and ecological management both require baseline information, and temporal and spatial patterns to evaluate the current status of environmental health and well-being (Ehrenfeld and Toth, 1997; Hobbs and Harris, 2001; Leitao and Ahern, 2002; Burger et al., 2003, 2004b; Baird, 2005). Ecological evaluation forms the basis for all forms of environmental and ecological management, including assessment of species abnormalities and reproductive success, population levels and distribution, community and ecosystem structure and dynamics, and landscape changes, among others. With this information, managers can protect, manage, and enhance species and ecosystems, determine remediation levels and types, determine restoration types and restore specific ecosystems, conduct NRDAs, and design long-term stewardship plans (see following sections) (Fig. 4).

4. Remediation and restoration

4.1. Remediation

The task for ecological or environmental evaluators is to assess the health and well-being of ecosystems and their component species (including humans). The task for remediation and restoration scientists is to correct any problems associated with chemical and radiological exposure (remediation; Wilson and Clarke, 1993; Lehr et al., 2002) and all types of stressors, including the aftermath of remediation (restoration; Cairns, 1980, 1994; Prach, 2004). Stressors can include biological, chemical/radiological, and physical. Physical stressors include physical disruptions such as clear-cutting, road building, tree-falls (from natural or anthropogenic causes), floods, erosion, and other weather-related events. Biological stressors include invasive species, emerging infectious diseases, and natural processes such as predation and competition. There are a range of actions aimed at reducing the risk of injury to ecosystems, ecological receptors, and humans, which include remediation, restoration, and blocking the exposure pathways (either physically or through education and advisories; Fig. 5, after Burger, 2007a).

Unfortunately, different disciplines use the terms remediation and restoration to mean different things, and it is necessary to define them clearly in any discussion. In its simplest sense, remediation means to remove or contain a chemical hazard, by removing it, stabilizing it, or inactivating the chemicals/radionuclides in the environment to meet some

pre-determined human health risk standards or guidelines, which differ depending upon the pollutant and jurisdiction (e.g. WHO, 1976; US FDA, 2001, 2004, 2005a,b). Restoration refers to rebuilding or creating a preferred or target ecosystem (Egan and Howell, 2001; Prach, 2004). Sites can be remediated without restoration, and left paved or capped. And sites can be left alone to recover on their own (called natural attenuation), or they can be restored.

For particularly sensitive ecoreceptors, such as endangered or threatened species, ecological risk screening levels could be used to establish cleanup standards, but more often, human health risk screening levels are used. In many cases, however, the false assumption is made that cleaning up contamination or radionuclides to protect human health will protect all ecological receptors. The evidence, however, suggests that for some chemicals, humans are not the most sensitive species. The reasons for greater sensitivity of ecoreceptors include: animals or plants can be exposed in ways humans are not (e.g. worms and other invertebrates consume large quantities of soil, birds fly at altitudes that expose them to airborne contaminants), they experience higher levels of exposure (e.g. aquatic organisms can experience 100% exposure from water), and some ecoreceptors are more sensitive than humans (Suter et al., 2000).

Anthropogenic disruptions, whether physical (road building, clear-cutting) or chemical/radiological, result in a spectrum of damages. An ecosystem can be degraded such that there can be no recover, it can undergo natural recovery on its own (natural attenuation), it can recover after some physical remediation, or it can recover after physical remediation and biological restoration (Fig. 6). Environmental managers often assume that natural attenuation will eventually restore remediated sites to a functioning ecosystem through the inherent resiliency of plants and animals, and they continue to monitor these sites. However, ecosystems that are heavily impacted by chemicals and radionuclides, along with associated physical disruptions, seldom approach natural systems unless aided by restoration.

4.2. Recovery and restoration

Two processes of ecosystem functioning predispose ecosystems to recover: succession and resiliency (Gunderson and Pritchard, 2002). Ecosystems normally undergo a regular series of changes called succession (e.g. an old field in the northeast will eventually succeed to a forest). If left undisturbed, an ecosystem will undergo natural succession that is typical and sustainable for that latitude, altitude, and climatic regime (Odum, 1957). Succession, however, is not a one-way process, since natural events (fires, floods, storms) result in disruptions that start the process again. Thus, when a stressor (either natural or anthropogenic) results in setting back (or degrading) an ecosystem to a less complex state, it can undergo success to reach a climax community.

Resiliency is the ability of an ecosystem to recover from a perturbation, such as a severe windstorm, cyclone, hurricane, tornado, or fire. Ecosystems that are regularly exposed to these perturbations have evolved mechanisms to recovery, and often relatively quickly. There are many examples: 1) some pine species have serotinous cones, which only open when heated by a fire, and the trees have the ability to sprout from the trunk if not burned too severely, 2) when a wind storm blows down trees in a forest creating a gap, it provides

an opportunity for new seedlings to sprout and quickly grow, 3) dune plants can quickly colonize new sand dunes created by severe hurricanes or storm tides and 4) some animals devastated by disease, predation or bad weather, can reproduce quickly, restoring their populations (e.g. mice, some birds; Odum, 1957; Wilkinson, 2006), to name a few.

Some plants and animals seem to have evolved mechanisms to handle contaminants, but these are situations where contaminants have been present in the ecosystem for long periods. For example, mercury and cadmium are found naturally in seawater (Fowler, 1990), and seabirds can tolerate higher levels of methylmercury in their internal tissues than can other birds (Monteiro and Furness, 1995; Kim et al., 1996). Most plants and animals, however, did not evolve with anthropogenic contaminants, and do not have mechanisms that evolved to respond to contaminants. However, there are examples of plants or animals that have evolved a tolerance to contaminants, but they do not thrive with these contaminants, but have merely accommodated to their presence. For example, some fish living in contaminated sites survive better in these sites than do naïve fish transplanted from clean sites to the contaminated sites (e.g. methylmercury, Khan and Weis, 1987; Weis et al., 2003).

Two situations may make it more difficult for species and ecosystems to recover: multiple stressors and radioactive wastes (Ferenc and Foran, 2000; Murray, 1994). In the former case, the stressors can be additive or synergistic, and in the latter case, some of the radioactive materials are extremely damaging (cancerous). The devastation following the Chernobyl nuclear accident in Russia has resulted in ecosystem damage that has not recovered. (Kryshev, 1995; Sundbom et al., 2003; Bell and Shaw, 2005). Similarly, some species have not recovered their previous population levels following the massive oil spill in Prince William Sound in 1989 (Carls et al., 2004; Taylor and Reimer, 2008).

Recovery from severe environmental contamination may not be possible without remediation to remove the contaminants, followed by restoration to provide adequate physical and biotic conditions for recovery to occur. For example, in some strip-mining regions, the area mined is very large, and the topsoil (with associated seed bank) has been removed or disturbed. Thus, recolonization by plants and animals will be slow because natural ecosystem are so far away that there is no dispersal of seeds into the strip mine region. Similarly, sometimes the environment is so harsh that without help, native species cannot become reestablished. For example, on Amchitka Island in the Aleutians, natural vegetation has not become established on the top of large soil piles because of the harsh windy environment and poor soil quality. Restoration efforts by the DOE failed because they planted non-native grasses that could not survive in that harsh environment (high winds and short-growing season), which also precluded the invasion of the nearby native species. Wherever soil is removed, without restoration, recovery is either delayed or does not occur. In such cases, restoration is essential.

Restoration is the active process of rebuilding ecosystems to a preferred habitat or series of habitats (Bradshaw, 1984; Jordan et al., 1987; Baldwin et al., 1993; Temperton et al., 2004). I make the distinction between physical restoration and biological restoration, although some managers believe that remediation should include physical restoration. They are not

always the same, however. Remediation can involve the physical removal of soil, but does not necessarily involve adding clean topsoil or restoring the appropriate gradient or soil type to achieve healthy ecosystems. Particularly, capping in place is not conducive to eco-recovery. For example, oil-contaminated soil might be removed from the banks of a saltwater creek, but unless the appropriate gradient is established along that creek, salt marsh vegetation will not invade or survive. Similarly, contaminated soil can be removed from a forest, but the depth and shape of the resultant “pond” will affect the ecosystem that becomes established. If a vernal pond (wet at some times of the winter/spring, dry in the summer) is desired because the managers wish to restore functioning amphibian communities, then the appropriate slope and depth of the pond must be established; and merely removing soil will not ensure an appropriate water depth to create a vernal pond. For example, on the DOE’s Savannah River Site in South Carolina, attention was devoted to creating ponds that were shallow enough to result in a dry-down in the summer, which encouraged breeding by amphibians. Dry-down is essential because permanent ponds provide habitat for fish, which eat the eggs and tadpoles of amphibians (Biebighauser, 2003).

While restoration involves mainly biological principles, the decision to restore an ecosystem is a societal one; selecting the habitat or ecosystem for restoration is a decision for the public, although it is influenced by biological constraints. For example, you cannot build a rainforest in a desert climate, nor can you build tundra in temperate regions. Restoration both decreases recovery time for damaged ecosystems, and encourages a particular kind of ecosystem. Restoration includes several steps that require the knowledge and experience of biologists, such as 1) examination of the local landscape to determine possible ecosystem types, 2) examination of the relative occurrence of different habitat types within the local landscape, 3) selection of a habitat or ecosystem type for restoration, 4) selection of topographic features (lakes, ponds, streams, hills), 5) inventories of local plants and animals appropriate for reintroduction or encouragement, 6) designing the pattern of habitat types, 7) planning and selection of seeds, propagules, plant plugs, or shrubs and trees, 8) consideration of, and introduction of animals (e.g. insect pollinators) if necessary, and finally 9) scheduling of restoration activities to mimic natural succession (e.g. pollinators cannot be introduced if there are no flowers to serve as nectar sources). Many of these phases should also include involvement and collaboration of a range of interested and affected stakeholders. One-way communication is not sufficient; stakeholders should be collaborators wherever possible (Burger et al., 2007b). Further, both restoration and remediation require evaluation of their successes or failures (Ruiz-Jaen and Aide, 2005).

5. Integration of remediation and restoration

While restoration can be part of remediation, and indeed can often be more cost-effective when accomplished in conjunction with remediation, the two are not usually integrated. The reason that restoration costs can be reduced when integrated with remediation is that the equipment needed for soil removal can be used to grade slopes, create ponds or lakes, or channel rivers and streams to achieve a desired ecological topography. Seeding of native plants can occur more easily when soil is first laid down, rather than after it has become compacted. Integration of remediation and restoration may not occur because different

agencies are responsible for each phase, or different regulators oversee the process. However, with consultation and collaboration among the responsible parties, regulators, natural resource trustees, public policy-makers, and the public, remediation and restoration can occur together to result in creation of desired, functioning ecosystems.

For example, at the DOE's contaminated Fernald site in Ohio, the state and federal regulators, and other stakeholders, worked with DOE to agree on a desired final end state, and collaborated to integrate cleanup with restoration such that they created fields, woods and wetlands that represented the undisturbed habitat for that region before it had been farmed (Bixby, 1995; Carnes et al., 1998; Bidwell and Sarno, 2003). Such collaborations can occur to the mutual benefit of all parties, while restoring functioning ecosystems suitable for conservation and outdoor recreation. Further, these collaborations and integration of remediation and restoration at Fernald resulted in decreased time, energy, and costs. When restoration follows after remediation, the process takes more time. Thus, integration of the restoration into remediation creates economies at each stage. Ecological evaluation should therefore be incorporated into remedial investigations under CERCLA and other environmental laws.

In the case of contaminated sites, restoration may not occur until the responsible party is encouraged to do so by legal action or by the threat of legal action. Responsible parties may not choose to restore degraded or destroyed habitats until a NRDA has demonstrated actual injuries. The response on the part of responsible parties is partly understandable since it takes time to perform remediation and restoration, and by the time restoration is complete, the legal parties to any agreement may have changed, or their interests may have changed. That is, an agency such as DOE may restore a habitat to the wishes of the appropriate state and federal agencies only to discover that personnel have changed and the new parties do not approve of the restoration or wish a different settlement.

Finally, agreement on an end state is critical. For instance, under CERCLA, the default cleanup criterion is for residential as the future land use. This may require extensive soil removal, which makes restoration difficult, whereas agreement on an "ecosystem" standard may facilitate the remediation and restoration process, reduce costs, and enhance ultimate ecological value. Such ecosystems could then be used for preservation and conservation of natural resources and recreation.

6. Natural resource damage assessment

NRDA is used to determine whether there have been injuries to natural resources and to calculate the costs necessary to restore or replace those resources (DOE, 1991, 1993a, 1997). Under CERCLA (section 101.16), natural resources are defined as "land, fish, wildlife, biota, air, water, groundwater, drinking water supplies, and other such resources". An injury to a natural resource is a measurable adverse change in the chemical or physical quality or viability of that resource, and damages are assessed on the basis of loss or reduction in quantity and quality of natural resource services due to releases after 1980 (DOE, 1993b; Trimmer and Smith, 1995). Natural resource trustees, including state (e.g. environmental departments) and federal agencies (US Fish & Wildlife Service) and Native American

Tribes, are responsible for assessing injuries to natural resources. Interestingly, by law, DOE is also a natural resource trustee for their lands, which sometimes places them in apparent conflict because of their role as a responsible party.

NRDA involves several steps: 1) determining if there have been injuries to natural resources caused by a chemical or radiological release, 2) assigning a monetary value necessary to either restore or replace those resources, 3) calculating the costs of lost services or values, and 4) collecting those monies or overseeing restoration or replacement (DOE, 1993a, 1997; Burger et al., 2007e,f). Determining whether there are injuries that can be compensated requires ecological evaluation (Bilyard et al., 1993), in conjunction with performance assessments of remediation and restoration to determine if the resources have been restored (Malone, 1990).

Assessing resource damage involves ecological evaluation, which is a complex task that includes examining ecological resources with respect to species, habitats and ecosystem functioning, and at several levels of biological complexity (Barnthouse et al., 1995; Barnthouse and Stahl, 2002). Many NRDA's have also been conducted under the Oil Pollution Act (OPA) of 1990 (Austin, 1994; Burlington, 1999; Burlington, 2002), and the Clean Water Act (Sheehy and Vik, 2003). The federal government has uniform rules and procedures for assessing economic losses and injuries developed by the U.S. Department of the Interior for CERCLA, and the U.S. Department of Commerce for OPA (Deis and French, 1998; Ofiara, 2002). At present, no NRDA's have been conducted for Department of Energy sites. However, a demonstration project was performed at the DOE's Savannah River Site in South Carolina for testing the integrated NRDA framework and demonstration how NRDA concerns could be integrated into the environmental restoration activities at a complex site (Bascietto and Sharples, 1995). Further, the integration of remediation and restoration may obviate the need for NRDA if the natural resource trustees agree on the level and type of restoration.

As early as the 1990s, scientists suggested that NRDA should be integrated with remediation and restoration, particularly at federal facilities (Malone, 1990; Helvey, 1991; Sharples et al., 1993), and that compensatory mechanisms should inform remediation (Hawke and Karr, 2000). Thus the desired process is to integrate remediation and restoration such that natural resources are restored to either the previous state, or to a desired state, obviating the need for a formal NRDA process. Integration of remediation and restoration with NRDA is not a trivial task, since it must involve agreement among all the natural resource trustees and the responsible parties about the preferred end state (the preferred ecosystem), the degree and type of remediation required, and the kinds and level of restoration that will be necessary to restore or create that end state.

Collaborations, and inclusion of remediation, restoration and NRDA has the advantage of reaching a timely settlement to restore natural resources. Focusing on a rapid settlement can result in a quick and efficient restoration. For example, an NRDA conducted by federal and state officials in the Salmon River region of central Idaho resulted in a monetary settlement with the owners of a mine to bring salmon back to the area's streams (Renner, 1998). Partly

it was successful because a settlement was reached in only two and a half years, it targeted a glaring environmental problem, and it achieved a quick and efficient restoration.

Collaboration should save time and money because the activities will occur together, there is economy of scale in completing all the physical work at the same time, and each of the natural resource trustees will not be required to complete their own NRDA to assess injuries. The latter is not insignificant, since with NRDA claims, all resource trustees may be compelled to conduct their own assessment of injuries. Instead, if natural resource trustees agree at the beginning of the process what resources have been injured, and that they should be restored to healthy populations within a functioning ecosystem with appropriate structure, then there will be no need for each natural resource trustee to evaluate injuries at the end of each phase (prior to remediation, during and after remediation, during and after restoration). The costs of such evaluations are not trivial in either time or money, especially if disagreements lead to legal actions.

7. Integration and iteration of ecological evaluations, environmental management, and sustainability to achieve long-term stewardship

Overall the goal of environmental evaluation is to provide information to maintain healthy ecosystems that are sustainable, and that provides appropriate structure and functions that can continue to provide ecological goods and services (Costanza, 1993; Leitao and Ahern, 2002). Such systems should have functioning food chains, nutrient cycling, energy flow, predator–prey relationships, resiliency and feedback loops (Burger, 2007c,e). Consumptive use or extraction should not compromise the biological integrity of the system (Cabezas et al., 2005), nor its cultural or sacred values (Harris, 2000; Harris and Harper, 2000; Zender et al., 2004; Bridgen, 2005; Burger et al., in press).

Since ecological evaluation forms the basis for so many different types of environmental management, it seems reasonable to integrate all of the necessary management options together to achieve economies of time, energy, and costs. That is, if managers wish to remediate a site, restore a given ecosystem, and manage wildlife, it seems reasonable to clearly define the overall objectives of each management strategy at the beginning so that they can work in concert, and simultaneously where appropriate, instead of in a linear sequence. That is, with the end state goals in mind (both the physical ecosystem type, and the desired plants and animals), then remediation and restoration can be designed to achieve this objective together. If all three (remediation, restoration, establishment of a given plant/animal community) are integrated, then each will be designed to achieve the end state at the same time with a savings in time and money.

The primary and key step in achieving integration of different management objectives is cooperation and collaboration to formulate the problem and the desired end state. This must involve the identification of all managers, natural resource trustees, policy-makers, regulators, and publics interested and affected by the management actions. Thus, I suggest that the problem formulation phase should not only include the traditional aspects of identification of stressors (e.g. contaminants), receptors, pathways, and geographical/temporal dimensions, but the identification and inclusion of all interested and affected

parties; this includes local, state and federal agencies, as well as designated natural resource trustees and the public, particularly in the site neighborhood. Equally important is the identification of all the relevant management objectives, including remediation, restoration, wildlife management, recreation, and species recovery plans, among others. Once all the management objectives have been clearly identified, than reasonable time-lines can be developed for the entire project leading to the desired end state.

Long-term stewardship involves ensuring the sustainability and health of environmental systems. Assuring sustainability and health of ecosystems usually involving a plan to regularly assess the health of those systems (often by monitoring), with procedures for corrections or improvements. For DOE sites, stewardship involves programs to assure the integrity of engineered and institutional controls in perpetuity, as well as achieving sustainable development through ecosystem management (Malone, 1998; NRC, 2000, 2007b; Burger and Gochfeld, 2001a; Lowrie et al., 2003). Long-term stewardship of lands, whether contaminated (now or in the past) or not, and sustainability both require ecological evaluations to assure that healthy ecosystems are maintained. Remediation and restoration are important aspects of environmental management and sustainability (Urbanska et al., 1997; Burger, 2000). The ecological information gathered for remediation and restoration can serve as a baseline for long-term stewardship.

Previously I suggested (Burger, 2007c) that six factors are essential to the sustainable protection of humans and the environment: 1) governmental, institutional and public support (including financially), 2) agreement on the ideal or desired ecosystem, 3) agreement on the goods and services that ecosystems should provide, 4) methods of monitoring the status of the ecosystem (including contamination status), 5) methods of evaluating the trends and changes within that system, and 6) methods of managing or restoring components of the system. To this list should be added three additional factors: 1) a continuous feedback loop that evaluates status and trends within the ecosystem, and suggests remedial action where necessary (iteration; see Fig. 1), 2) the legal ability to devote special attention and priority to endangered/ threatened species, habitats and ecosystems, and to special at-risk populations (human and others), and 3) the continued inclusion and involvement of a wide range of Native American Tribes and stakeholders during every phase (Stein et al., 1999; Burger et al., 2001a, 2006b, 2007b; Greenberg et al., 2007). These nine factors need to be addressed for the long-term management of ecosystems, and should be examined for each type of environmental management, including wildlife management, fisheries, forestry, remediation, and restoration.

Iteration and interactions among all disciplines and stakeholder groups are essential to forge partnerships that will solve environmental problems, rather than deal with only one aspect in isolation (Fig. 1). With increasing human populations, and the concentration of these populations in and around urban centers, there is the potential to overlook unique and rare habitats, endangered and threatened species, and species that are particularly vulnerable. And finally, without continuous feedback loops to examine both the status of various aspects of the environment and changes, it will be impossible to have sufficient warning to be able to correct engineering or other remediation/restorations that have failed or that have developed in unusual or unpredictable ways. Failure analysis is an important aspect of

environmental evaluation and assessment, as well as adaptive management (Gunderson et al., 2002).

8. Summary and conclusions

Environmental management is not a simple task, nor is it one that can be conducted in isolation from other considerations that range from social and cultural, to ecological and physical. Ecological evaluation is the base for all types of environmental and ecological management. There are many different continuums that intersect environmental management. These include: one-time evaluations to complex temporal and spatial studies, field inventories to controlled field experiments (sometimes involving sentinels), field inventories to laboratory assessments of effects of contaminants, laboratory experiments with animals to extrapolations to humans, case reports to population or epidemiological studies, standard univariate statistical analyses to complicated computer generated models, deterministic to probabilistic risk assessments, and environmental descriptions to formal risk assessments, to name a few. The solutions to our complex environmental problems must involve collaboration and cooperation among a wide range of management disciplines and stakeholders to clearly and carefully delineate the problem, design the plans to acquire the required environmental information, and integrate and implement the necessary management strategies (remediation, restoration, environmental, ecological or wildlife management) to achieve the desired ecosystem that is sustainable. Effective long-term stewardship requires integration among disciplines, continued iteration, and a willingness of a range of agencies, Tribal Nations, and stakeholders to collaborate toward an agree-upon goal. In summary, all types of environmental management and long-term stewardship require ecological evaluation as a basis for sound decisions.

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Fig. 2. Ecological risk assessment as established by the National Research Council (after NRC, 1983, 1993).

Fig. 3. Ecological risk assessment paradigm developed by the U.S. Environmental Protection Agency (after Norton et al., 1992).

Fig. 4. Ecological risk assessment and management paradigm developed by the DOE (after Burger and Gochfeld, 1997). Dotted line indicates the formal risk assessment phase.

Fig. 5.
Methods of reducing risk to receptors as a function of chemical/radiological stressors.

Fig. 6. Schematic of time for ecosystem recovery following an anthropogenic disruption as a function of types of environmental manipulation (none, remediation, restoration (after Burger, 2007a).