Environmental Management (2017) 59:357–372
DOI 10.1007/s00267-016-0798-8

PROFILE

A Methodology to Evaluate Ecological Resources and Risk Using Two Case Studies at the Department of Energy's Hanford Site

Joanna Burger[1,2] · **Michael Gochfeld**[2,3] · **Amoret Bunn**[4] · **Janelle Downs**[4] · **Christian Jeitner**[1,2] · **Taryn Pittfield**[1,2] · **Jennifer Salisbury**[2] · **David Kosson**[2]

Received: 3 March 2016 / Accepted: 31 October 2016 / Published online: 30 November 2016

Abstract An assessment of the potential risks to ecological resources from remediation activities or other perturbations should involve a quantitative evaluation of resources on the remediation site and in the surrounding environment. We developed a risk methodology to rapidly evaluate potential impact on ecological resources for the U.S. Department of Energy's Hanford Site in southcentral Washington State. We describe the application of the risk evaluation for two case studies to illustrate its applicability. The ecological assessment involves examining previous sources of information for the site, defining different resource levels from 0 to 5. We also developed a risk rating scale from non-discernable to very high. Field assessment is the critical step to determine resource levels or to determine if current conditions are the same as previously evaluated. We provide a rapid assessment method for current ecological conditions that can be compared to previous site-specific data, or that can be used to assess resource value on other sites where ecological information is not generally available. The method is applicable to other Department of Energy's sites, where its development may involve a range of state regulators, resource trustees, Tribes and other stakeholders. Achieving consistency across Department of Energy's sites for valuation of ecological resources on remediation sites will assure Congress and the public that funds and personnel are being deployed appropriately.

Keywords Risk evaluation · Ecological resources · Remediation · Risk methodology · Risk rating · Assessment method

Introduction

Assessing the effects of management actions, including remediation and restoration of contaminated sites, is an important societal goal. The public, conservation organizations, and governmental agencies (both United States and Tribal) are interested in remediation, restoration and long-term stewardship of contaminated lands. The legacy of the Cold War and industrial development from the 20th century left us with many contaminated sites and brownfields that require remediation and restoration to allow future land uses (DOE 1991, 2000, 2002; NRC 1995, 2000; Burger 2000, 2007, 2008; Burger et al. 2004, 2015; Gochfeld et al. 2015). There are often disagreements about the importance of particular lands, the level of cleanup required, who should pay for it, and the future land uses for these parcels (Cairns and Niederlehner 1992; Nuissl et al. 2009) but there is little disagreement that they should be cleaned up (Prach 2004; Burger et al. 2015). Future land use determines the cleanup required; thus there is a reciprocal relationship between the desired land uses and the degree of cleanup required (Gochfeld et al. 2015).

✉ Joanna Burger
burger@biology.rutgers.edu

[1] Division of Life Sciences, Rutgers University, Piscataway, NJ 08854-8082, USA

[2] Consortium for Risk Evaluation with Stakeholder Participation (CRESP), Vanderbilt University, Nashville, TN 37235, USA

[3] Rutgers, robert Wood Johnson Medical School, Piscataway, NJ 08854, USA

[4] Pacific Northwest National Laboratory, Richland, WA 99354, USA

The U.S. Department of Energy (DOE), Department of Defense, other federal facilities, and state and private industry have land holdings with chemical and radiological waste that require remediation and restoration (NRC 1995; DOE 2001a, 2002; Crowley and Ahearn 2002). The DOE alone has several large sites requiring extensive remediation: Hanford Site, Oak Ridge, Idaho National Laboratory, Savannah River, and Nevada Test Site. Many of the DOE sites also have important and valuable ecological resources (Brown 1998; Dale and Parr 1998; see also DOE environmental reports, DOE 2001a, b, 2013a, including many that are critical to Native Americans (Burger et al. 2008). While valuing these resources economically may be difficult, it is possible to value the resources ecologically (Bingham et al. 1995; Costanza et al. 1997; De Groot et al. 2002; Lemming et al. 2010, 2012; Burger et al. 2011, 2015). Incorporation of ecology and ecological evaluation into long-term stewardship at DOE is an important social goal (NRC 1995; Burger 2002; Duncan et al. 2007; Burger et al. 2008, 2013), and tools to manage prioritization of risk management decisions are needed (Sorvari and Seppala 2010).

Decisions about cleanup should consider sustainability, both in terms of on-going remediation processes and decision-making. One goal of cleanup is monitoring to reduce and remediate risks in real time (Varley et al. 2015), and to reduce or manage ecological risk in a sustainable manner (Glasson et al. 2013; Sample et al. 2015). Phytoremediation is often a state-of-the-art, key method of sustainable remediation (Sharma et al. 2015; Thijs et al. 2016; Bleicher 2016). Sustainable remediation also requires decision-making whereby environmental, economic, and social aspects of remediation options are considered (Cappupyns 2016). This requires tools or methodologies that can be used to support balanced decision-making.

Development of a methodology that can be used across a cleanup site would improve planning and implementation of remediation and restoration based on risk to human, cultural and ecological resources (Burger et al. 2015). For the Department of Energy's sites, both the States where the site resides, and the Environmental Protection Agency have responsibility for overseeing cleanup. Although some species are protected by law to prevent further declines and to increase current population levels, protection of sensitive habitats is less clear. The U.S. Endangered Species Act (1973) provides legal protection and recovery efforts for plant and animal species listed as threatened or endangered. States also have lists of threatened and endangered species. Thus, at a basic level, understanding potential impacts to endangered, threatened, and species of special concern is paramount when determining ecological risks.

Species and their populations, however, do not live in isolation, but live in habitats. While being on the Endangered Species List results in legal protection of the species, the Act only affords limited protection for the habitat of listed species. Many states are now interested in preserving unique habitats, and there is considerable concern for sensitive or rare ecosystems (Downs et al. 1993; Knick et al. 2003). The habitats most at risk include those that are limited in quantity or extent, and which contain one or more endangered species, endemic species (species that occur only in those areas), or threatened species assemblages (e.g., migrant songbirds, breeding frogs, hibernating snakes). Unique habitats are those that are rare locally (e.g., Hanford Site) and regionally (e.g., Washington State, the Pacific Northwest). Such habitats are limited and often fragmented, and any decreases in quantity or declines in quality have severe consequences.

In this paper, we use two case studies at the Hanford Site to illustrate a field methodology for evaluating ecological resources on a remediation site. Our objective is to: (1) describe an overall methodology to evaluate risk to ecological resources on remediation sites; (2) describe a valuation method for ecological resources; (3) describe a field methodology to evaluate ecological resources; (4) provide two case studies to illustrate the field methodology. We use an ecological resource rating scale to balance risk with remediation planning and design. Our overall goal is to present a methodology than can be used at individual DOE sites to provide uniformity among sites.

General Approach

Our overall protocol was to assess the available biological and ecological information for the Hanford Site and previous resource evaluations, and then to develop a methodology for rapid ecological resource evaluations. The development of our methodology was based on our combined ecological field experience at the Hanford Site, other DOE sites, and other ecological sites in several states. Most of the authors have over 25 years of ecological field experience each, and a basic assumption of the authors is that considerations of human health and ecological health need to be balanced (Suter et al. 1995; Wolf et al. 2013; Hough 2014; Sandifer et al. 2015; Whitmee et al. 2015).

Evaluating the risks from any management, remediation, or restoration project must involve defining the geographical extent of the project, evaluating the resources that are present on the site, characterizing the contaminants that are present, defining the remediation or management actions, identifying the area impacted by remediation, and determining how the actions will affect the resources on and adjacent to the site. Each of these components of our risk evaluation paradigm will be described below. Each step should involve a range of stakeholders in the conceptualization, including environmental justice communities (Greenberg and Lowrie 2002; Nez Perce Tribe 2003;

Burger et al. 2010; Burger and Gochfeld 2011; Gochfeld and Burger 2011; DOE 2013b; Flanagan et al. 2016; Kyne and Bolin 2016).

The Risk Methodology

The method for evaluating risk has 4 steps: (1) Defining resource levels, (2) Developing a risk rating, (3) Defining boundaries for an evaluation unit (EU), (4) Field investigations, (5) Defining remediation or management actions, and (6) Melding remediation with resource value to determine risk. All the steps are critical to the process, but here we concentrate on the field protocol in detail. The first two steps are common to all risk evaluations of the ecological resources on a site, such as Hanford. The last four steps comprise the site-specific evaluation of a defined remediation area (called an Evaluation Unit, or EU).

Step 1: Defining Resource Levels

Valuing ecological resources is a difficult task, and we were fortunate that several years of thought and experience of State, Federal and Tribal ecologists and managers had developed a ranking system for ecological resources at Hanford based mainly on vegetation types. Ratings ranged from 0 to 5, where 5 was the highest value (DOE 2013a). These valuations were developed in conjunction with federal and state regulators and resource trustees, and were originally developed based on field surveys 10–15 years ago. Most of the levels are easily understood and applied to the individual sites (Table 1). Levels 3–5 designate sites with important ecological resources. While these descriptions will obviously differ for different sites, the descriptions below relate to Hanford (from DOE 2013a; Burger et al. 2015).

Table 1 Resource level categories that were developed for Hanford (DOE/RL-96-32 2013) and could be adapted for other sites, especially the species

Resource level	Description
0	Non-native plants and animals.
1	Industrial and developed
2	Habitat with high potential for restoration
3	Important habitat
4	Essential habitat for important species.
5	Irreplaceable habitat or federal threatened and endangered species (including proposed species, and species that are new to science or unique to Washington state).

The category types (e.g., Grasslands, Forest Species, Endangered/Threatened Species) may not be adaptable

Level 0 includes areas that are largely covered by buildings or concrete, with no native plants or animals; they are industrial or waste disposal units. Level 1 resources are habitats where DOE is not required to complete habitat replacement, but habitat could be restored there. Level 2 resources include migratory birds and state-monitored plants and animals, as well as non-native plants.

Level 3 resources are state sensitive plants and animals that are being considered for listing by states, or plants and animals that may have cultural importance. There is a climax shrub-steppe with native grasses. It also includes some wetlands and riparian habitat and conservation corridors.

Level 4 resources include state threatened or endangered species, federal candidate species, upland stands with native climax shrub over story and native grass understory, and wetlands and riparian habitats. They are designated for preservation, with avoidance/minimization of disturbance as a key component of remediation. They require habitat replacement (DOE 2013a). The other levels of concern are either designated as conservation (Levels 3, 2) or mission support (Levels 1, 0). Conservation areas can have habitat replacement at a less stringent level and may be areas where mitigation actions are needed.

Level 5 resources include not only federally listed species, but also sensitive and/or rare habitats. Irreplaceable habitats included cliffs, lithosols, dune fields, ephemeral streams, and vernal ponds, as well as Fall Chinook Salmon (*Oncorhynchus tshawytscha*) and Steelhead (*Oncorhynchus mykiss*) spawning areas. Rare habitats on the Hanford Site are shown in the original report (DOE 2013a). The Hanford Site evaluation includes only these as Level 5 resources, largely because they are exceedingly rare on the site. Bluebunch wheatgrass (*Pseudoroegneria spicata)* habitats are also considered critical and unique because they are rare on the Hanford Site, decreasing at a more rapid rate in the Ecoregion, and are very vulnerable to cheatgrass (*Bromus tectorum*) invasion. Shrub-steppe communities, at the lowest elevation on the Hanford Site and the Hanford Reach National Monument are at greater risk from the invasion of exotic species than are those at higher elevations. Bluebunch wheatgrass steppe communities above 800 ft elevation are less at risk because they are more resistant to invasion by exotic species. The management goal is preservation, with an avoidance of management actions. Monitoring changes in habitat quality is laborious and not a high priority, especially when funds for cleanup actions are tight.

Step 2: Developing a Risk Rating Scale

A rating scale was developed by the authors for the Consortium for Risk Evaluation with Stakeholder Participation (CRESP), Hanford Site-Wide Risk Review Project (Table 2). The goal for the rating was the need for a simple

Table 2 Rating scale for risk to ecological resources applied to evaluation units at Hanford

	Definition
ND (non-discernible)	Not discernible from the surrounding conditions; no additional risk
Low	Little risk to disrupt or impact level 3–5 ecological resources
Medium	Potential to disrupt or impact level 3–5 ecological resources, but the remedial action is not expected to disrupt ecological communities permanently.
High	Likely to disrupt and impair level 3–5 ecological resources of high value or resources that have restoration potential, and can cause permanent disruption.
Very high	Very high probability of impairing or destroying ecological resources of high value (level 3–5 resources) that have typical and healthy shrub-steppe species, low percentage of exotic species, and may have federally listed species. The remediation likely results in permanent destruction or degradation of habitat.

scale (non-discernible to very high) that could be easily understood and used by the full range of stakeholders (DOE, Tribes, regulators, resource trustees, the public). The rating scale used the potential damage to the different resource levels with different remediation options. Our assumption was that resource levels 3–5 are the critical, habitats and ecosystems requiring protection. Ratings medium to high carried some potential for disruption of resource levels 3–5, and very high was defined as a very high probability of impairing or destroying resources of high value (Table 2). Remediation of an evaluation unit with a very high rating could result in permanent destruction or degradation of the habitat, suggesting the possibility that the risks from remediation to ecological receptors outweigh the advantages.

The above two steps (defining resource levels, developing a risk rating scale) should be the same for all evaluation units at one location (e.g., Hanford Site), and could in theory be similar across the DOE complex. In our two case studies described below, we determined a risk rating for three time periods: current, during cleanup, and 100 years after clean up. This provides information to DOE, regulators, Tribes and other stakeholders on the potential benefits and costs of remediation for ecological receptors.

Step 3: Defining Boundaries

Evaluating risks to ecological resources requires establishing the area of direct impact, which we define as the Evaluation Unit (EU). The boundaries for the EU at Hanford were drawn around the area expected to be directly impacted by the remediation. The EU boundary was assumed to represent the estimated boundary or extent of potential habitat removal (e.g., complete soil and vegetation removal) and direct disturbance due to remediation. That is, at the extreme or worst-case scenario, remediation might involve the complete removal of soil (down to varying depths), with loss of associated soil invertebrates, vegetation, and animals using the site. The EU boundaries are polygons, and may have convoluted shapes to encompass the various waste areas as well as lay down yards or roadways.

Some ecological resources around the EU, however, may be affected by actions within the EU due to personnel or vehicular traffic, introduction of invasive species, or disruption of ecological patches (including creating more edge). We suggest that a buffer around the actual EU is essential to adequately evaluate risk to ecological resources from remediation, restoration, or other management actions. Thus, a second boundary (polygon) outside the EU was established to evaluate indirect effects and assess the remediation in relation to adjacent landscape features. This polygon was centered on the EU and encompassed a circular area with a radius 1 times the maximum width of the EU and is referred to as the adjacent landscape buffer. While this is arbitrary, we felt that the area was sufficient to assess potential effects to adjacent habitat in the area of direct and indirect impact.

Step 4: Field Investigations

Given that the vegetation analysis for the original evaluations was completed a number of years ago, it was essential to develop a field method of assessment based on field work. Other information considered was knowledge of exotic plants (WNWCB 2014), threatened and endangered species, threatened habitats, habitats critical to threatened and endangered species, and species of special concern (for ecological, economic or cultural reasons, USFWS 2014; WDFW 2008, 2014. This methodology also reviews rankings and information in the Natural Heritage database WSDNR 2014, as well as information from the Pacific Northwest National Laboratory (PNNL) data base (Becker and Chamness 2012) and other sources (Downs et al. 1993; McAllister et al. 1996; Duncan et al. 2007; WNWCB 2014).

Field assessments of a selection of EUs were essential to provide up-to-date information of the ecological value of both an EU and the buffer area. A visual survey was conducted within the EU boundary by experienced shrub-steppe ecologists who have worked in the habitat for many years.

Biologists also reviewed the observations and biological data[1] available from surveys or monitoring completed in the past 5 years for the EU to determine the status and resource level of the habitats within the EU. Previous wildlife or plant species observations supplemented the evaluation. The field evaluation made use of previous evaluations of ecological resources on Hanford (DOE 2013a).

A reconnaissance survey of the boundary of the EU was conducted to confirm the validity of past mapping of biological resources (DOE 2013a). Aerial imagery from 2012 was reviewed to identify any significant changes in habitat and resource levels (such as new well pads, roads, or other ground disturbance not captured by the available biological resources mapping) within the EU and adjacent landscape buffer. Where significant change was evident from ground survey or imagery, the biological resource map was updated to reflect the change in resource level.

The spatial extents of habitat classified at each of 6 resource levels (0–5) (DOE 2013a) within the EU and adjacent landscape buffer area were assessed and compared using a Geographic Information System (GIS) to examine habitat condition. For purposes of assessing indirect effects on the adjacent landscape, this evaluation assumes the maximum potential change in biological resources—that is, all habitat within the EU is assumed to be lost to remediation and cleanup activities and resources in the EU are considered level 0 after remediation (Table 1).

Biologists assembled the information from field survey, reconnaissance, and spatial analyses of resource availability to provide a subjective evaluation of potential effects on habitat connectivity in the vicinity of the EU. High connectivity indicates that high quality habitat (level 3, 4, 5) in the EU and buffer also extend beyond the buffer boundary. That is, for each EU and the buffer area, we determined the percent of the habitat that fell into each resource value category (from 0 to 5). This methodology results in a field report for each EU, with particular emphasis on the cumulative percent of level 3, 4 and 5 lands, which can then be used to rate relative risk to ecological resources based on the value of the resources, and other considerations (e.g., remediation type, presence of contamination).

Additional information used in the ecological evaluation included: (1) current Endangered and Threatened Species (Federal and State lists) distribution data; (2) priority habitats as defined by Washington Department of Fish and Wildlife; (3) available current aerial imagery, locations of Hanford Site waste units, and infrastructure spatial data; (4) available information about species of concerns, including data previously collected by PNNL and Mission Support Alliance. This supplemental information was provided in an overall description of the ecological resources at risk.

Step 5: Defining the Remediation or Management Actions

Assessing the potential risk to ecological resources from any remediation, restoration or management action requires knowing what those actions are. We suggest that the "actions" must be defined sufficiently to allow for a full evaluation of their effects. While it is clear that complete removal of soil is going to completely disrupt and destroy any ecological resources on site, it is not clear how much disruption will be caused by other remediation options, especially natural attenuation. It is essential to also know how long the actions will continue, how many personnel and trucks will be involved, and how much of an area is necessary to store equipment while remediation is occurring, over what time intervals, among other things. Thus we suggest that it is essential to understand the potential remediation options, the preferred options (for economic, logistic, workforce, health and safety considerations), and the component of those options (numbers and duration of people, trucks, other equipment, operations, continued monitoring, to name a few). There will be spillover of impacts on the buffer area and one goal of the process is to minimize adverse impacts inevitable on high quality habitats in the buffers areas as well.

Step 6: Melding Remediation with Resource Value to Determine Risk

This step involves melding the level of ecological resources on site, with the preferred remediation option to arrive at a risk rating to the ecological resources on the EU. Similar analyses are conducted for ecological resource information for the buffer area. The risk categories were defined in Table 2. This final evaluation of risk is a combination of field-based, quantitative information on the percent of different resource levels on the EU, and the availability of information on preferred or determined remediation option, to develop a risk rating that depends upon professional judgement.

Application of Field Methodology at Hanford

The relative success of an evaluation methodology for ecological resources depends on its applicability to actual remediation sites. In this section, we use two different EUs at Hanford to illustrate its usefulness, one a deactivation and decommissioning site (D & D, PUREX plant), and one a legacy site (618–11 burial ground). These are two separate areas on the Hanford Site. D & D sites are slated to be

---

[1] Biological survey data for the Hanford Site for 1999-2011 is archived in PNNL's Environmental Compliance Assessment Project database and was queried to retrieve any applicable survey data for the EU and surrounding buffer area. Mission Support Alliance provided more recent Hanford biological survey data.

deactivated, decontaminated, decommissioned, and demolished. A burial ground is a site where radioactive wastes or other contaminant sources are buried. The steps that are essential for the field methodology include defining the boundaries of the remediation site (step 3), field investigations (step 4), determining the remedial action (step 5) , and determining the potential risk (step 6). Steps 1 and 2 apply to all EU's.

Plutonium-Uranium Extraction (PUREX) Plant

The Plutonium-Uranium Extraction (PUREX) plant facilities in the Hanford 200 East area, include canyons, tunnels, ancillary building, structures, and associated near-surface and contaminated soils. Steps 1 and 2 were determined generally for all EUs on Hanford, and were available for use with each EU evaluation. Each of the EU-specific steps for evaluating risk were followed for the PUREX facility (steps 3–6).

Step 3

Defining the extent of the PUREX EU required drawing boundaries around the facilities to encompass the area that might be impacted by remediation, including areas needed for equipment and storage. The boundaries included all the facility components listed above, including the canyons, tunnels and structures. The EU boundary (polygon) is assumed to represent the estimated boundary or extent of potential habitat removal and direct disturbance due to remediation. The boundaries for the EU are illustrated in Fig. 1. In this case, the EU is not a neat polygon because of the extended horizontal nature of the canyons. Once the boundary for the EU was determined, a buffer area was defined that was equal to the maximum diameter of the EU. A second boundary (polygon) outside the EU was established to evaluate indirect effects and assess the remediation in relation to adjacent landscape features. This buffer polygon is centered on the EU and encompasses a circular area with a radius 1 times the maximum width of the EU and is referred to as the adjacent landscape buffer (Fig. 2). For ecological resources, this area is critical because it is the area that would provide the seed bank to re-establish an onsite ecosystem after completion of remediation.

Step 4

The most-important aspect of the methodology is the valuation of resources in the field. This involved examining

Fig. 1 Site Map of the PUREX facility at Hanford with evaluation unit boundaries

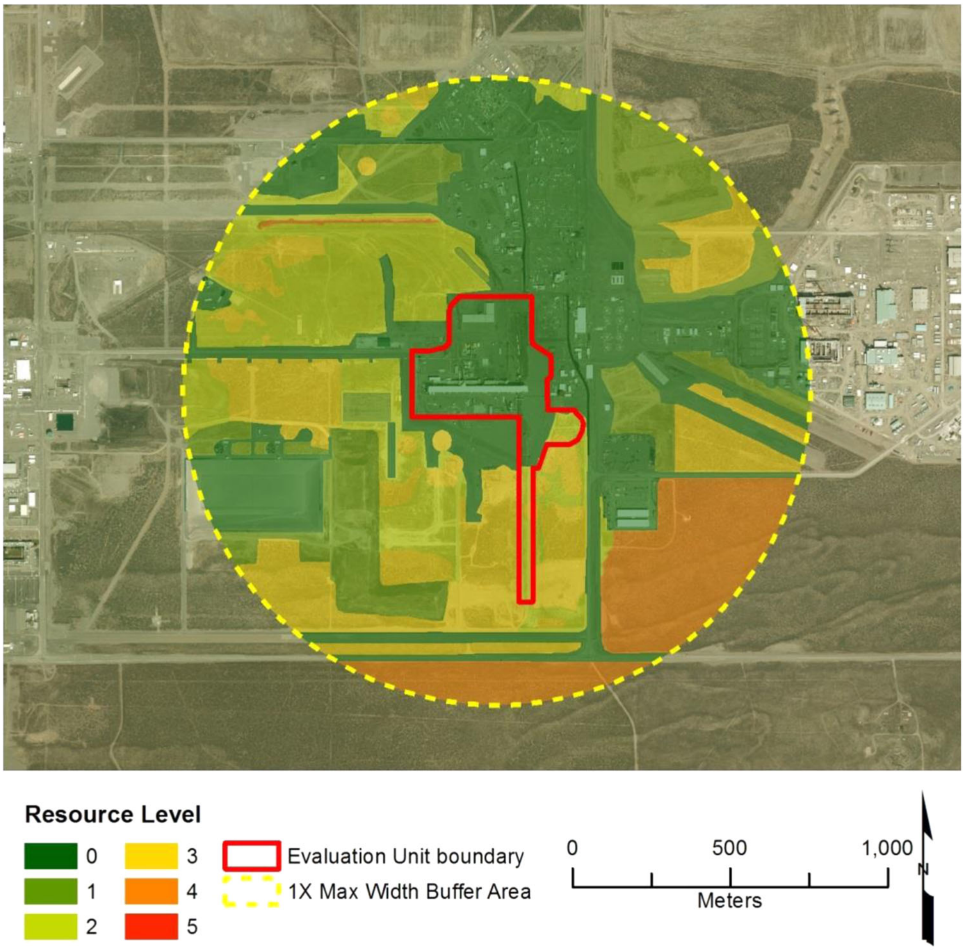

Fig. 2 Biological resource level classifications based on October 2014 surveys at the PUREX evaluation unit (red solid line) and adjacent landscape buffer area (*yellow dashed line*)

the previous evaluation of the resource level of the EU and buffer area (DOE 2013a).

1. A visual survey was conducted within the EU boundary by experienced shrub-steppe ecologists. PNNL biologists also reviewed the observations and biological survey data for the EU available in the Ecological Compliance and Assessment Project (ECAP) database from the past 5 years to determine the status and resource level of the habitats within the EU and supplement the evaluation with previous wildlife or plant species observations.
2. A reconnaissance survey of the boundary of the EU was conducted to confirm the validity of past mapping of biological resources both within the EU and in the buffer area. Aerial imagery from 2012 was reviewed to identify any significant changes in habitat and resource levels (such as new well pads, roads, or other ground disturbance not captured by the available biological resources mapping) within the EU and adjacent landscape buffer, since the original evaluation (DOE 2013a). Where significant changes were evident from ground survey or imagery, the biological resource map was updated to reflect the change in resource level.
3. The spatial extent of habitat classified at each of 6 resource levels (0–5) (DOE 2013a; Table 1) within the adjacent landscape buffer area and the EU were assessed and compared using GIS to examine potential indirect effects on habitat condition within the adjacent landscape. For purposes of assessing indirect effects on the adjacent landscape, this evaluation assumes the maximum potential change in biological resources—that is, all habitat within the EU is assumed to be lost to remediation and cleanup activities and resources in the EU are considered level 0.
4. Biologists assembled the information from field survey, reconnaissance, and spatial analyses of resource availability to provide a subjective evaluation of potential effects on habitat connectivity in the vicinity of the EU.

The EU associated with the PUREX facilities was surveyed by vehicle and on foot and with field measurement of remaining habitat on the southeast side of the area in October 2014. The majority of the EU consists of buildings, disturbed areas, parking lots, and facilities, except for the extension of the unit to the south and a small area just south of the parking lot on the east side of the unit. Field measurements in the southeast habitat (Table 3, Fig. 2) confirmed that the area consisted of level 2 habitat resources. Patches of level 3 resources within the EU were associated with individual occurrences of sensitive plant species: Piper's daisy (*Erigeron piperianus*) had been noted in previous ECAP surveys and an Erigeron spp. was noted in the field survey, but could not be verified as Piper's daisy. Wildlife observations within the level 2 habitat included several side-blotched lizards (*Uta stansburiana*), small mammal burrows and trails, coyote (*Canis latrans*) tracks, and a common raven (*Corvus corax*) flying overhead. No wildlife species were observed within the fenced area around PUREX facilities.

Table 3 Percent surface habitat cover measured at the PUREX evaluation unit

Vegetation/surface cover	Southeast side of EU
Bare ground	19.8
Crust	51.6
Litter	25.8
Introduced forb	1.0
Introduced grass	1.0
Native forb	11.0
Native grass	8.2
Climax shrubs	2.4
Successional shrubs	14.3

The acreage of each level of biological resources at the PUREX EU was examined within a circular area radiating approximately 995 m from the geometric center of the unit (equivalent to 768 acres or 311 ha). Within the 44.6 acres (18 ha) of the EU, only 2.2 acres (0.9 ha) were classified as level 3 habitats, but these consisted of fragmented and narrow patches (Table 4). Table 4 contains information on the amount of each resource level in the EU and buffer areas, and serves as a basis for ecological evaluations. Approximately 31 % of the total combined area (EU plus adjacent landscape buffer) consists of level 3 or greater resources

The field survey provided the following conclusions about the PUREX plant:

- The majority of the EU consists of buildings, disturbed areas, parking lots, and facilities.
- Patches of level 3 resources within the EU are associated with individual occurrences of sensitive plant species, Piper's daisy.
- Removal or loss of individual occurrences of the sensitive plant species, Piper's daisy, would be unlikely to alter population viability for this species.
- Remediation actions would result in only a 0.3 % change in level 3 and above biological resources at the landscape scale.
- Because the PUREX facilities are adjacent to and contiguous with other disturbed and industrial areas within the 200 East Area, the loss of habitat that could potentially occur within this EU would not be expected to impact habitat connectivity on the 200 Area plateau.

Table 4 Area and proportion of each biological resource level within the evaluation unit in relation to adjacent landscape and potential maximum change in resources for PUREX

Resource level[1]	Evaluation unit area (ac)	Adjacent landscape buffer (ac)	Combined total area (ac)	Percent of resource level in combined total area	Percent of resource level in combined total area after cleanup[2]	Percent difference at landscape scale after cleanup[2]
0	37.6	269.0	306.6	39.9 %	40.8 %	0.9 %
1	0.0	115.4	115.4	15.0 %	15.0 %	0.0 %
2	4.8	112.6	117.4	15.3 %	14.7 %	-0.6 %
3	2.2	144.3	146.5	19.1 %	18.8 %	-0.3 %
4	0.0	82.0	82.0	10.7 %	10.7 %	0.0 %
5	0.0	0.0	0.0	0.0 %	0.0 %	0.0 %
Total	44.6	723.3	767.9	100.0 %	100.0 %	

[1] Resource levels for both the evaluation unit and adjacent landscape boundary were reviewed in the field and via imagery during October 2014 and revised to reflect current habitats conditions

[2] Potential maximum change in area of a given resource level within the combined total area (Evaluation unit + adjacent landscape buffer) that would occur assuming that all habitat within the evaluation unit is destroyed by remediation activities and the resource level of the evaluation unit is level 0

Step 5

All available sources (DOE documents) were used to determine the current preferred remediation for the site. This task is not trivial for some sites. The remediation options for the PUREX facility are varied, and include remove, treat and disposal, backfill and revegetate, and institutional controls.

Step 6

Determining the potential risk to the EU involves using the field evaluation of resources (Tables 3 and 4), the remediation options, the potential for harm from remediation, and the risk rating chart (Table 2). The current risk evaluation for the PUREX facility is reported in a table following the next EU (618-11 burial ground).

618-11 Burial Ground

The CRESP Hanford Risk Review Project developed a common methodology that could address the many varied EUs. Therefore, the general ecological methods for the burial grounds are similar to those described above for PUREX.

Step 3

The EU boundaries were drawn using the same procedure described above, and are illustrated in Fig. 3, and the buffer areas are identified on Fig. 4.

Step 4

The field survey, along with the literature search described above was the most important step in the assessment process. The same process was followed as was followed for the Purex plant (see above), and included the following steps: (1) visual survey was conducted within the EU boundary by experienced shrub-steppe ecologists; (2) reconnaissance survey of the boundary of the EU was conducted to confirm the validity of past mapping of biological resources both within the EU and in the buffer area; (3) the spatial extents of habitat classified at each of six resource levels within the adjacent landscape buffer area and the EU were assessed and compared using GIS; (4) biologists assembled the information from field survey, reconnaissance, and spatial analyses of resource availability to provide a subjective evaluation of potential effects on habitat connectivity.

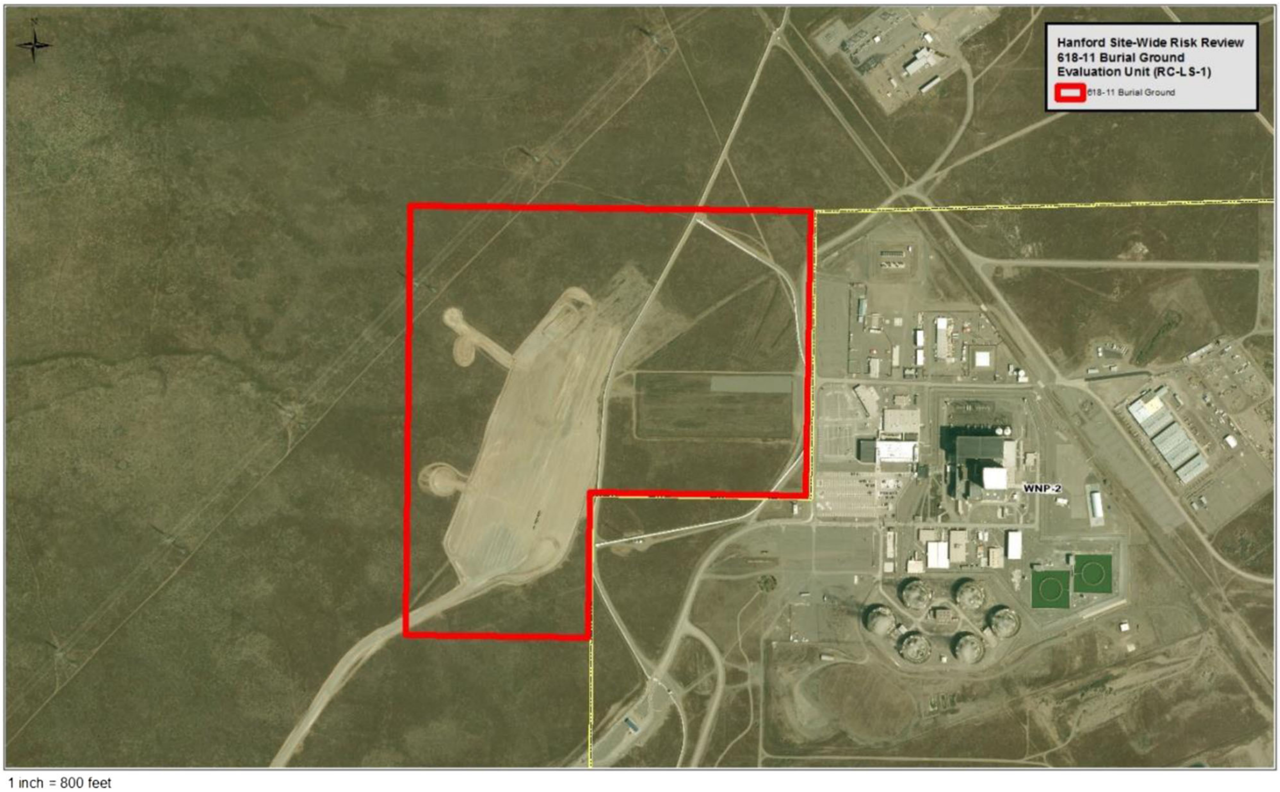

Fig. 3 618–11 Burial Ground Site Map with Evaluation Unit Boundaries. The facility to the east is Energy Northwest's nuclear power plant

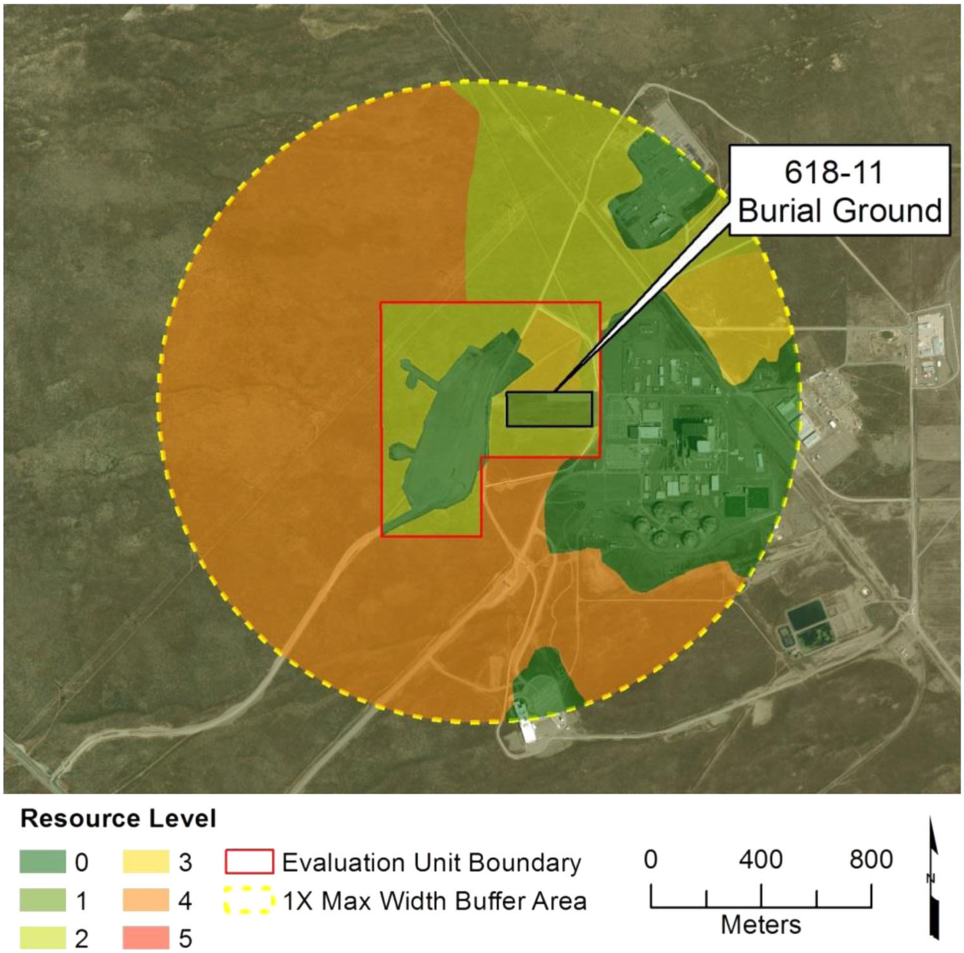

Fig. 4 Map of Biological Resource Level Classifications at the 618–11 Burial Grounds Evaluation Site (red boundary) and Landscape Buffer Area (*yellow dashed line boundary*)

The results of the field investigation were as follows. Vegetation on the area of the 618-11 Burial Ground within the EU was visually estimated to be composed of approximately 30 to 40 % crested wheatgrass (*Agropyron cristatum*), an introduced perennial bunchgrass planted for erosion control, and approximately 10 to 20 % Russian thistle (*Salsola tragus*) (which becomes "tumbleweed" at the end of the growing season).

Vegetation was measured in habitat patches in the buffer zone to the north in a stand dominated by big sagebrush (*Artemisia tridentata*) and gray rabbitbrush (*Ericameria nauseosa*), in grasslands to the west and south of the burial ground, as well as within the bladed laydown area visible in Figs. 3 and 4 to the far west of the burial ground. A summary of this data is provided in Tables 5 and 6. The burial ground was divided into sections because of its odd shape (see Fig. 3). The amount of bare ground and vegetation varied greatly, but the amount of litter ranged from 28 to 40 % (Table 5). This variation resulted in over 50 % of the area having resources 3 and above (although there were no level 5 resources, Table 6).

No information was found documenting previous wildlife surveys of the 618-11 Burial Ground. Wildlife species (or their sign) observed during the field survey include horned lark (*Eremophila alpestris*), loggerhead shrike (*Lanius ludovicianus*), western meadowlark (*Sturnella neglecta*), common raven (*Corvus corax*), unknown hawk (*Buteo spp.*), northern pocket gopher (*Thomomys talpoides*), coyote (*Canis latrans*), and American badger (*Taxidea taxus*).

The EU was originally characterized as containing habitats classified as levels 0, 2, and 4 (DOE 2013a). However, those areas of the EU that were originally classified as level 4 habitat were reclassified in this assessment as level 0 (bladed lay down area to west), and level 2 and 3 habitats based on field observations and data collected during the field visit. Resource levels within the landscape buffer area outside the EU were not re-classified for this assessment. Table 6 summarizes the areal extent of existing biological resources and potential changes or impacts due to clean up activities within the landscape buffer area.

The field survey resulted in the following conclusions:

- More than half of the EU consists of level 2 (mixed native and non-native grassland) resources. Approximately 5.2 ha (13 acres) of the EU contain a mixed sagebrush and rabbitbrush stand that qualifies as level 3 habitat, although it is degraded by invasion with nonnative grasses and forbs. This area is also adjacent to another operable unit.
- The EU is adjacent and contiguous to a large industrial site. Because this industrial area already affects habitat connectivity, cleanup activities inside the EU are not expected to impact habitat connectivity through loss of habitat or fragmentation.
- No species of concern were observed within or in the vicinity of the EU during the 16 July 2014 surveys.
- Approximately 56 % of the total landscape area evaluated (see Fig. 2) is classified as level 3 or higher biological resources, which are not expected to be significantly impacted by cleanup actions within the EU.

Table 5 Percent canopy cover and surface cover measured at 618–11 burial ground

Vegetation/ surface cover	618–11 South	618–11 West	618–11 North	Borrow/ laydown Area
Bare ground	3.0	30.5	19.3	22.8
Crust	2.5	4.5	17.6	5.5
Litter	40.0	29.3	32.4	28.5
Introduced forb	20.0	14.8	3.7	6.3
Introduced grass	17.8	15.0	16.1	27.5
Native forb	2.8	3.8	1.1	–
Native grass	14.0	2.3	9.7	11.5
Climax shrubs	–	–	9.6	–
Successional shrubs	<1	< 1	.3	–

Step 5

DOE documents were used to determine the remediation options for the site, which include removal, treat and dispose, temporary surface barriers, enhanced attenuation, rewetting, and institutional controls (DOE 2013b).

Step 6

Determining the potential risk to the EU involved using the field evaluation of resources (see Tables 5 and 6), the remediation options, the potential for harm from remediation, and the risk rating chart (see Table 2) to determine the risk. The risk evaluations for the 618-11 burial ground are reported in Table 7. All resources within the EU are assumed to be lost during cleanup and classified as 0 level habitats for evaluation of post-cleanup conditions.

The relative risk ratings for both the PUREX plant and the 618 Burial Grounds indicate little risk currently, and low to medium risk during remediation. The post-remediation risk varied for the two sites. The risk was non-discernible to medium for the PUREX plant, but low to medium for the 618 Burial Grounds (Table 7). This difference reflects the re-vegetation that will occur following remediation, and the potential for disturbances from invasive species. Because there are some level 3 and 4 resources currently on the 618 Burial Grounds and buffer, the potential for increasing

Table 6 Area and proportion of each biological resource level within the 618–11 burial ground evaluation unit in relation to adjacent landscape and potential maximum change in resources

Resource level[1]	Evaluation unit area (ac)	Adjacent landscape buffer (ac)	Combined total area (ac)	Percent of resource level in combined total area	Percent of resource level in combined total area after cleanup[2]	Percent difference at landscape scale after cleanup[2]
0.0	41.4	197.9	239.4	22.7 %	31.8 %	9.1 %
1.0	11.5	0.0	11.5	1.1 %	0.0 %	−1.1 %
2.0	70.1	130.6	200.7	19.1 %	12.4 %	−6.7 %
3.0	13.8	33.3	47.1	4.5 %	3.2 %	−1.3 %
4.0	0.0	553.6	553.6	52.6 %	52.6 %	0.0 %
5.0	0.0	0.0	0.0	0.0 %	0.0 %	0.0 %
Total	136.8	915.4	1052.2	100.0 %	100.0 %	

[1] Resource levels for the evaluation unit were reviewed in the field and via imagery during July 2014 and revised to reflect current habitats conditions

[2] Potential maximum change in area of a given resource level within the combined total area (Evaluation unit + adjacent landscape buffer) that would occur assuming that all habitat within the evaluation unit is destroyed by remediation activities and the resource level of the evaluation unit is level 0

invasive species during remediation could result in a medium risk to native resources.

Table 7 Example of evaluation for the PUREX plant and 618.11 burial grounds at Hanford. these are examples only, and will change over time

evaluation unit (eu)	% resources level 3 or above	Time Period	Rating	Comments
PUREX plant		Current	ND to low	Generally ND on EU because there are few ecological resources (5 % level 3 resources), Low because of possible contamination to ecological receptors on buffer area (31 % level 3 and 4 resources)
		During cleanup	Low to medium	Few high level resources in EU (5 % level 3 resources), but low to medium in buffer area because of high value resources (nearly a third of area has level 3 and 4 resources).
		100 years after	ND to low	Remote chance of penetration of roots into contaminated site, allowing exposure to residual contamination.
618 burial grounds		Current	ND	ND because currently there is no disturbance to site, although 10 % of EU is level 3 resources and over half of buffer area is level 4 resources
		During cleanup	Low to Medium	Low in EU because only about 10 % is level 3 resources (none higher), but low to medium in buffer zone because 65 percent is level 3 and 4 resources. Disturbance could result during soil removal.
		100 years after	Low to Medium	Re-vegetation in EU will result in some additional level 3 and 4 resources potentially at risk because of disturbance, especially from invasive species and change of species composition. Similar effects in buffer zone.

Discussion

Methodological Considerations

Methodological issues with the development and application of our evaluation paradigm include the following: (1) existence of an agreed upon valuation scale; (2) prior evaluations for many of the habitats on site; (3) availability of biologists who had worked for many years at Hanford; (4) documents defining remediation alternatives for different EUs, (5) critical timing for field evaluations; (6) sufficient funds and personnel to conduct the field evaluations, and to use GIS to compute amount of habitat in different resource categories.

It was possible to develop a methodology for Hanford because a range of stakeholders, including state and federal agencies, Tribes, scientists, and others had contributed to the development of a valuation scheme that had public support (DOE 2013a). While not perfect, the scale could be applied at other remediation and restoration sites because it relies upon generally acceptable definitions of habitat value. That is, the highest value was given to unique and rare habitats and to those with federally endangered and threatened species. The lowest value was given to sites that are completely developed with buildings, pavement, and a lack of any natural resources.

Much of the habitat on Hanford had been previously evaluated and thus maps were available for most of the EUs. These were useful, especially for the buffer areas. Upon further study, we discovered that not all areas had been evaluated. Further, we mainly used the resource evaluation scale to value the resources on the EUs (which were small enough to sample with a grid pattern in a reasonable time period). However, the prior habitat evaluations were very useful for the large buffer areas because they allowed us to determine if the habitat had changed over a period of 10–15 years.

Hanford has a long and distinguished history of conducting ecological field work to examine plant and animal usage on site. This meant that trained personnel with field experience at Hanford were available to conduct the field evaluations. This may not be the case at other DOE sites or at non-DOE remediation sites. Local biologists may be able to step in, but previous in-depth ecological evaluations from the site may not be available. Experience enriched the process at Hanford.

Similarly, there were documents that laid out the remediation options for many sites, including preferred alternatives. Such documents should be available for most DOE sites, but may not be available for other remediation or restoration sites. Where the final remediation option is undetermined, the ecological assessment may inform the selection process. Furthermore, timing is critical for ecological evaluations. Evaluations cannot be conducted when snow is on the ground, or when vegetation is brown and dead. Timing issues could thus delay a project because the ecological evaluations need to wait until spring. Finally, sufficient time, personnel and costs may not be available to conduct the necessary field work, or to compile documents on past ecological studies and remediation options. Field work is time consuming, particularly for large EUs with diverse and complex ecologies.

Impact Assessments, Natural Resource Damage Assessment and our Risk Evaluation Methodology

There are many different methods for evaluating and remediating damage to ecological systems. Remediation options vary from natural attenuation to complete removal of contaminated soil. Natural attenuation (no active remediation, only monitoring) is the option that has the least effect on functioning ecosystems, while removal of soil destroys the ecosystem and removes the seed bank. Evaluating damages to ecosystems from remediation can occur before any action (Environmental Impact Assessments, EIA, Knox 2002; Glasson et al. 2013), or after (Natural Resource Damage Assessment, NRDA, DOE 2013b; Kennedy and Cheong 2013). In both cases, formal risk assessments require a specific set of data on species and ecosystems (NRC 1993), which is often not available for remediation sites. The formal risk assessment process is lengthy and time-consuming, and by itself, does not necessarily allow for comparisons among remediation sites. The formal process does not necessarily take into account the eco-cultural and social aspects of the goods and services provided (Burger et al. 2013; Paavola and Hubacek 2013). Further, predicting ecological effects is difficult (Mouquet et al. 2015), especially for complex systems.

In contrast to NRDA and EIA, the process we propose in this paper provides a consistent methodology to relatively rapidly assess the value of ecological resources on a site, and rate the potential risk before, during and after cleanup. It is applied to specific remediation units where the ecological resources can be assessed. It provides guidance on delineating the evaluation unit and associated buffer, as well as ecological resource levels and a rating scale. A full range of managers, resource trustees, regulators, Tribes, and the public can participate in the development and refinement of the resource levels, and the rating scales. The methodology can be applied to different evaluation units within a site (e.g., Hanford), or across a complex of sites (e.g., DOE facilities nationwide). Likewise, states could modify the methodology to use for state-wide assessments.

Risk Trade-Offs

Applying a consistent paradigm or method to evaluate the risk to ecological resources of different remediation, restoration, or management actions could provide information to examine risk trade-offs. For example, there might be some situations in which the decision that provides the least risk to ecological resources is to not disrupt them by remediation. In other situations, where contamination is sufficient to provide a current or future risk to the health and well-being of eco-receptors (including humans), removal of contaminants may be the option of choice. However, it is not possible to make this decision without understanding the relative ecological risks of different remediation options (including no remediation). We recognize that there are other societal considerations (such as existence values, wanting a “clean environment”) that impact remediation decisions. We suggest that comparing the relative risks of cleanup alternatives to ecological resources using the same paradigm will allow for more cost-effective remediation. Remediation and restoration decisions at any large DOE site obviously involve several trade-offs, as well as the use of multiple lines of evidence from a range of disciplines and stakeholders. This is especially true with examining risks to ecological receptors (a weight of evidence approach, Hall and Giddings 2000). This paradigm recognizes, but does not address the future habitat improvement level that might be achieved by different active restorations or by natural reseeding and succession processes.

Application to DOE Sites

The DOE is a large and diverse complex, with a broad range of ecological habitats that vary in local and regional importance. Some of the DOE sites have important and rare ecological habitats by virtue of their size and history of *de facto* preservation (DOE 1994a, b, 2013a; Brown 1998; Dale and Parr 1998). The application of a site-wide method of evaluating the risk to ecological resources from different remediation options provides another tool to help in making remediation decisions.

The paradigm outlined above can be generally applicable to a wide range of remediation, restoration and management projects where it is essential to evaluate the ecological resources at risk. It depends upon the commitment of all concerned to describe and evaluate both ecological resources on site, and remediation or management options. Developing and accepting an overall paradigm for a large DOE site, or the entire DOE complex of sites has the advantage of allowing for comparisons of ecological risk across the complex. This approach would allow sequencing of cleanup projects, comparison of impact of different projects on ecological resources, and determination of the vulnerability of ecological resources on different sites. Because developing definitions of resource levels, and defining risk ratings, depends upon involvement of a wide range of stakeholders (including DOE and regulators), the process can partly address eco-cultural values and the goods and services that ecosystems supply (Burger 2011; Corcoran and Casebolt 2004; Costanza et al. 2014). Inclusion of this range of stakeholders contributes to assuring sustainable remediation (Cappupyns 2016).

Conclusions

The process of valuing ecological resources at Hanford involved selection of indicators that were used to characterize the different levels of ecological sensitivity. That is, the value of a habitat as low or high (e.g., levels 0–5) depended upon using indicators of value. For example, endangered and threatened species are indicators of high quality habitat, and concrete pavement is an indicator of very low quality habitat (e.g., 0 Level ecological habitat). Particular plants that were unique to intact shrub-steppe habitat were used as indicators of quality, and conversely, invasive species were indicators of lower quality habitat (Azerrad et al. 2011). Similarly, unique habitats are valued highly, such as shrub/steppe. Such ecological indicators are both science-based (e.g., rarity, uniqueness, a keystone species) and policy based (USEPASAB 2002; EEA 2003; Müller and Lenz 2006; Turnhout et al. 2007; Goodsell et al. 2009). Using ecological indicators for assessment will help formulate policy, which is essential to maintaining biodiversity. Protecting biodiversity is a societal decision with policy implications and requires the monitoring of indicators at the species, population, and landscape level (Leitao and Ahern 2002; Burger and Gochfeld 2004; Lamb et al. 2009). In turn, maintaining biodiversity is essential to maintaining regional sustainability (Mascarenhas et al. 2010).

For DOE, evaluating ecological resources at specific remediation units across the complex is essential to ensure protection of those resources in a fair, comprehensive, and cost-effective manner. Assessment is essential for environmental management, particularly for the protection of human health and the environment on large DOE sites. A conceptual framework for selecting environmental indicators, such as the one proposed in this paper, is critical (Niemeijer and de Groot 2008), and is valuable for implementation of a field protocol. The evaluation tool provided in this paper can be used at small evaluation sites, and can be scaled up to larger remediation sites, which allows it to be used across a range of remediation sites.

Acknowledgments The authors acknowledge other members of CRESP and PNNL for valuable discussions about risk, exposure assessments, and ecological evaluations, including J. Clarke, E. Golovich, K Hand, W. Johnson, K. Brown, and M. Chamness. This research was funded by the Consortium for Risk Evaluation through the Department of Energy (DE-FC01-95EW55084). PNNL's funding was provided by the U.S. Department of Energy Office of River Protection and Richland Operations Office. PNNL is operated by Battelle Memorial Institute for the U.S. Department of Energy under Contract DE-AC05-76RL01830.

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no competing interests.

References

Azerrad JM, Divens KA, Livingston MF, Teske MS, Ferguson HL, Davis JL (2011) Site-specific management: how to avoid and minimize impacts of development to shrub-steppe. Washington Department of Fish and Wildlife, Olympia, WA. http://wdfw.wa.gov/publications/01335/wdfw01335.pdf. Accessed 11 Feb 2016

Becker JM, Chamness MA (2012) Annual ecological survey: pacific northwest national laboratory site, pnnl-21164. Pacific Northwest National Laboratory, Richland, WA. http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-21164.pdf. Accessed 11 Feb 2016

Bingham G, Bishop R, Brody M, Bromley D, Clark ET, Cooper W, Costanza R, Hale T, Hayden G, Kellert S, Norgaard R (1995) Issues in ecosystem valuation: improving information for decision making. Ecol Econ 14:73–90

Bleicher A (2016) Technological change in revitalization–phytoremediation and the role of nonknowledge. J Environ Manage. 184:78–84. doi:10.1016/j.jenvman.2016.07.046 (in press)

Brown KS (1998) The great DOE land rush. Science 282:616–617

Burger J (2000) Integrating environmental restoration and ecological restoration: long-term stewardship at the department of Energy. Environ Manage 26:469–478

Burger J (2002) Incorporating ecology and ecological risk into long-term stewardship on contaminated sites. Remediation J 13:107–119

Burger J (2007) A framework for analysis of contamination on human and ecological receptors at DOE hazardous waste site buffer lands. Remediation J 17:71–96

Burger J (2008) Environmental management: integrating ecological evaluation, remediation, restoration, natural resource damage assessment, and long-term stewardship on contaminated lands. Sci Tot Environ 400:6–19

Burger J (2011) Stakeholders and scientists: achieving Implementable Solutions to Energy and Environmental Issues. Springer, New York, NY

Burger J, Gochfeld M (2004) Bioindicies for assessing human and ecological health. In: Wiersma GB (ed) Environmental monitoring. CRC Press, Boca Raton, FL, pp 541–556. 2004

Burger J, Gochfeld M (2011) Conceptual environmental justice model for evaluating chemical pathways of exposure in low-income, minority, Native American, and other unique exposure populations. Amer J Public Health 101:S64–73

Burger J, Carletta MA, Lowrie K, Miller KT, Greenberg (2004) Assessing ecological resources for remediation and future land uses on contaminated lands. Environ Manage 34:1–10

Burger J, Gochfeld M, Pletnikoff K, Snigaroff R, Snigaroff D, Stamm T (2008) Ecocultural attributes: evaluating ecological degradation in terms of ecological goods and services versus subsistence and tribal values. Risk Analysis 28:1261–1272

Burger J, Harris S, Harper B, Gochfeld M (2010) Ecological information needs for environmental justice. Risk Analysis 30:893–905

Burger J, Clarke J, Gochfeld M (2011) Information needs for siting new, and evaluating current, nuclear facilities: ecology, fate and transport, and human health. Environ Monitor Assess 172: 121–134

Burger J, Gochfeld M, Clarke J, Powers CW, Kosson D (2013) An ecological multidisciplinary approach to protecting society, human health, and the environment at nuclear facilities. Remediation J 23:123–148

Burger J, Gochfeld M, Salisbury J, Bunn A (2015) An approach to evaluating and monitoring ecological resources for sustainability on DOE remediation sits: Hanford as a cast study. Waste Management Symposium, Waste Management Proceedings Phoenix, Arizona, 14–20 March 2015

Cairns Jr J, Niederlehner BR (1992) Predicting ecosystem risk: genesis and future needs. Predict Ecosys Risk 1:327–343

Cappupyns V (2016) Inclusion of social indicators in decision support tools for the selection of sustainable site remediation options. J Environ Manage. Available online 21 July 2016. In Press 184:45–56

Corcoran J, Nichols-Casebolt A (2004) Risk and resilience ecological framework for assessment and goal formulation. Child Adol Soc Work J 21:211–235

Costanza R, d’Arge R, Limburg K, Grasso M, de Groot R, Faber S, O’Neill RV, Van den Belt M, Paruelo J, Raskin RG, Hannon B (1997) The value of the world’s ecosystem services and natural capital. Nature 387:253–260

Costanza R, de Groot R, Sutton P, van der Ploeg S, Anderson SJ, Kubiszewski I, Farber S, Turner RK (2014) Changes in the global value of ecosystem services. Global Environ Change 26:152–158

Crowley KD, Ahearn JF (2002) Managing the environmental legacy of U.S. nuclear-weapons production. Amer Sci 90:514–523

Dale VH, Parr PD (1998) Preserving DOE’s research parks. Issues Sci Technol 14:73–77

De Groot RS, Wilson MA, Boumans RM (2002) A typology for the classification, description and valuation of ecosystem functions, goods and services. Ecol Econ 41:393–408

Department of Energy (DOE) (1991) Natural resource damage assessment: preassessment screening and integration with CERCLA ecological evaluations. EH-231-008/0991. Washington, DC: Department of Energy, Office of Environmental Guidance. homer.ornl.gov/sesa/environment/guidance/cercla/nrda2.pdf. Accessed 9 Aug 2016

Department of Energy (DOE) (1994a) Stewards of a national resources. Department of Energy, Office of Energy Research, Washington, DC

Department of Energy (DOE) (1994b) National environmental research parks. Department of Energy, Office of Energy Research, Washington, DC

Department of Energy (DOE) (2000) Status Report on Paths to Closure, DOE/EM-0526 Washington, DC: Department of Energy, Office of Environmental Management. http://energy.gov/sites/prod/files/2014/03/f8/StatusReportOnPathsToClosure_2000.pdf. Accessed 9 Aug 2016

Department of Energy (DOE), DOE/RL 96-32 (2001a) Hanford site biological resources management plan, appendix D: Hanford’s biological resources: geographic information system-based resource maps, species of concern data tables, and their technical basis. DOE/RL 96-32. Department of Energy, Richland Operations Office, Richland, WA

Department of Energy (DOE), DOE/RL 96-32 (2001b) Hanford site biological resources management plan, appendix C: hanford biological resources in a regional context. DOE/RL 96-32. Department of Energy, Richland Operations Office, Richland, WA

Department of Energy (DOE) (2002) A review of the environmental management program. Department of Energy, Office of Environmental Management, Washington, DC

Department of Energy (DOE), DOE/RL 96-32 (2013a) Hanford Site Biological Resources Management Plan, Revision 0. DOE/RL-96-32. Richland, WA: Department of Energy, Richland Operations Office. http://www.hanford.gov/files.cfm/DOE-RL-96-32-01.pdf. Accessed 9 Aug 2016

Department of Energy (DOE) (2013b) Hanford natural resource damage assessment: injury assessment plan. DOE, Richland, WA

Downs JL, Rickard WH, Brandt CA (1993) Habitat types on the Hanford site: wildlife and plant species of concern. Pacific Northwest national Laboratory, Richland, WA, PNL-8942, UC-702

Duncan JP, Burk KW, Chamness MA, Fowler RA, Fritz BG, Hendrickson PL, Kennedy EP, Last GL, Poston TM, Sackschewsk MR (2007) Hanford Site National Environmental Policy Act (NEPA) Characterization, PNNL-6415. Pacific Northwest National Laboratory, Richland, WA, Rev.18

European Environment Agency (EEA) (2003) Environmental Indicators: Typology and Use in Reporting, EEA; Copenhagen, p 20

Flanagan CA, Byington R, Gallay E, Sambo A (2016) Chapter seven-Social justice and the environmental commons. Adv Child Dev Behav 51:203–230

Glasson J, Therivel R, Chadwick A (2013) Introduction to environmental impact assessment. Taylor and Francis, London

Gochfeld M, Burger J (2011) Disproportionate exposures in environmental justice and other populations: the importance of outliers. Amer J Public Health 101:S53–63

Gochfeld M, Burger J, Powers C, Kosson D (2015) Land use planning scenarios for contaminated land: comparing EPA, State, Federal and Tribal approaches. Waste Management Symposium, Waste Management Proceedings Phoenix, Arizona, 14–20 March 2015

Goodsell PJ, Underwood AJ, Chapman MG (2009) Evidence necessary for taxa to be reliable indicators of environmental conditions or impacts. Mar Poll Bull 58:323–331

Greenberg M, Lowrie K (2002) External stakeholders’ influence on the DOE’s long-term stewardship programs. Fed Facil Environ J 13:108–125

Hall Jr L, Giddings JM (2000) The need for multiple lines of evidence for predicting site-specific ecological effects. Human Ecol Risk Asess 6: 679–710

Hough RL (2014) Biodiversity and human health: evidence for causality? Biodivers Conserv 23:267–288

Kennedy CJ, Cheong SM (2013) Lost ecosystem services as a measure of oil spill damages: a conceptual analysis of the importance of baselines. J Environ Manage doi:10.1016/j.envman.2013.04.035 Epub

Knick ST, Dobkin DS, Rotenberry JT, Schroeder MA, Vander Haegen WM, van Riper III C (2003) Teetering on the edge or too late? Conservation and research issues for avifauna of sagebrush habitats. Condor 105:611–634

Knox JH (2002) The myth and reality of transboundary environmental impact assessment. Am J Intern Law 96:291–310

Kyne D, Bolin B (2016) Emerging environmental justice issues in nuclear power and radioactive contamination. Int J Environ Res Public Health 13:700–718

Lamb EG, Bayne E, Holloway G, Schieck J, Boutin S, Herbers J, Haughland DL (2009) Indices for monitoring biodiversity change: Are some more effective than others? Ecol Indic 9:432–444

Leitao AB, Ahern J (2002) Applying landscape ecological concepts and metrics in sustainable landscape planning. Landscape Urban Plan 59:65–93

Lemming G, Friis-Hansen P, Bjerg PL (2010) Risk-based economic decision analysis of remediation options at a PCE-contaminated site. J Environ Manag 91:1169–1182

Lemming G, Chambon JC, Binning PJ, Bjerg PL (2012) Is there an environmental benefit from remediation of a contaminated site? Combined assessments of the risk reduction and life cycle impact of remediation. J Environ Manag 112:392–403

Mascarenhas A, Coelho P, Subtil E, Ramos TB (2010) The role of common local indicators in regional sustainability assessment. Ecol Indicat 10:646–656

McAllister C, Beckert H, Abrams C, Bilyard G, Cadwell K, Friant S, Glantz C, Maziaka R, Miller K (1996) Survey of ecological resources at selected U.S. Department of Energy sites. DOE/EH-0534. Pacific Northwest National Laboratory, Richland, WA. http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/29/015/29015260.pdf. Accessed 11 Feb 2016

Mouquet N, Lagadeuc Y, Devictor V, Doyen L, Duputie A, Eveillard D, Faure D, Garnier E, Gimenez O, Huneman P, Jabot F (2015) Review: predictive ecology in a changing world. J Appl Ecol 52:1293–1310

Müller F, Lenz R (2006) Ecological indicators: theoretical fundamentals of consistent applications in environmental management. Ecol Indicat 6:1–5

National Research Council (NRC) (1993) Issues in risk assessment. National Academy Press, Washington, DC

National Research Council (NRC) (1995) Improving the environment: An evaluation of DOE's environmental management program. National Academy Press, Washington, DC

National Research Council (NRC) (2000) Long-term institutional management of US Department of Energy legacy waste sites. National Academy Press, Washington, DC

Nez Perce Tribe (2003) Treaties: Nez Perce perspectives. US DOE and Confluence Press, Washington, DC

Niemeijer D, de Groot RS (2008) A conceptual framework for selecting environmental indicator sets. Ecol Indicat 8:14–25

Nuissl H, Haase D, Lanzendorf M (2009) Environmental impact assessment of urban land use transitions—a context-sensitive approach. Land Use Pol 26:414–424

Paavola J, Hubacek K (2013) Ecosystem services, governance, and stakeholder participation: an introduction. Ecol Soc 18:42–48

Prach K (2004) The restoration and management of derelict land: modern approaches. Restor Ecol 12:310–317

Sample BE, Lower J, Seeley P, Markin M, McCarthy C, Hansen J, Aly AH (2015) Depth of the biologically active zone in upland habitats at the hanford Site, Washington: implication for remediation and ecological risk. Integr Environ Assess Manag 11:150–160

Sandifer PA, Sutton-Grier AE, Ward BP (2015) Exploring connections among nature, biodiversity, ecosystem services, and human health and well-being: opportunities to enhance health and biodiversity conservation. Ecosyst Serv 12:1–15

Sharma S, Singh B, Manchanda VK (2015) Phytoremediation: role of terrestrial plants and aquatic macrophytes in the remediation of radionuclides and heavy metal contaminated soil and water. Environ Sci Pollut Res Int 22:946–962

Sorvari H, Seppala JA (2010) Decision support tool to prioritize risk management for contaminated sites. Sci Tot Environ 408:1786–1799

Suter II GW, Cornaby BW, Hadden CT, Hull RN, Stack M, Zafran FA (1995) An approach for balancing health and ecological risks at hazardous waste sites. Risk Analysis 15:221–231

Thijs S, Sillen W, Weyens N, Vangronsveld J (2016) Phytoremediation: state-of-the-art and a key role for the plant microbiome in future trends and research prospects. Int J Phytoremediation doi:10.1080/15226514.2016.1216076

Turnhout E, Hisschemöller M, Eijsackers H (2007) Ecological indicators: between the two fires of science and policy. Ecol Indicat 7:215–28

United States Environmental Protection Agency-Science Advisory Board (USEPASAB) (2002) A framework for assessing and reporting on ecological condition: An SAB report. EPA Science Advisory Board, Washington, DC, EPA-SAB-EPEC-02-009

United States Fish and Wildlife Service (USFWS) (2014) Rare, threatened, or endangered Species: Hanford Reach. http://www.fws.gov/refuge/Hanford_Reach/Wildlife_Habitat/Rare_Species.html. Accessed 16 Feb 2016

Varley A, Tyler A, Smith L, Dale P, Davies M (2015) Remediating radium contaminated legacy sites: advances made through machine learning in routine monitoring of "hot" particles. Sci Total Environ 521:270–279

Washington Department of Fish and Wildlife (WDFW) (2008) Washington state priority habitats and species list. Olympia, WA. p 174. http://wdfw.wa.gov/conservation/phs/list/. Accessed 16 Feb 2016

Washington Department of Fish and Wildlife (WDFW) (2014) Species of concern in Washington. http://wdfw.wa.gov/conservation/endangered/. Accessed 16 Feb 2016

Washington Noxious Weed Control Board (WNWCB) (2014) Noxious weed List. http://www.nwcb.wa.gov/. Accessed 16 Feb 2016

Washington State Department of Natural Resources (WSDNR) (2014) Washington natural heritage program plant ranks. http://www1.dnr.wa.gov/nhp/refdesk/lists/plantrnk.html. Accessed 16 Feb 2016

Whitmee S, Haines A, Beyrer C, Boltz F, Capon AG, de Souza Dias BF, Ezeh A, Frumkin H, Gong P, Head P, Horton R (2015) Safeguarding human health in the anthropocene epoch: report of The rockefeller foundation–Lancet Commission on planetary health. Lancet 10007:1973–2028

Wolf KL, Blahna DJ, Brinkley W, Romolini M (2013) Environmental stewardship footprint research: linking human agency and ecosystem health in the Puget Sound region. Urban Ecosyst 16:13–32