Initiating events, functional remediation, and assessment of risk to ecological resources

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Abstract The United States faces a massive task to clean up legacy nuclear, chemical, and structural wastes remaining from the Cold War, and industrial and hazardous wastes, as well as the decommissioning and spent nuclear fuel removal of numerous commercial nuclear facilities nearing the end of useful life. Many sites are on or adjacent to open spaces or waterbodies of varying ecologic quality and utility. Assessing the risks to ecological resources is thus a challenging task that usually involves consideration of the direct risk to these receptors from the ongoing exposure to the contamination before remediation. Here we address impacts during and after remediation. Different remediation types and activities (digging and removal, containment/capping, decommissioning/demolition, pump and treat, in situ treatment), as well as transportation and ultimate disposition can have direct ecological effects including disruption, displacement and death to plants and animals on the remediation site and on surrounding areas. For each type of remediation, two aspects require consideration: the functional aspects of remediation (how many and what types of people, cars, trucks, hoses, heavy equipment, drilling rigs are on the remediation site), and initiating events that can interact with remediation causing harm to ecologic receptors. In this paper we 1) describe initiating events and functional remediation, 2) provide a conceptualization of interactions between them, and 3) examine the types of effects that result from natural and anthropogenic stressors due to the interactions between functional remediation and initiating events. Initiating events are low probability, high consequence events, including “natural” disasters (e.g. earthquakes, hurricanes, floods, fires) and anthropogenic (building collapses, structural failures) events, that start or cause a response in species or ecosystems. Functional remediation includes the elements of remediation that occur in combination under different remediation types. Interactions between the two may be overlooked when determining the factors to consider in developing bioindicators, assessment

39 tools, and monitoring plans to protect human and ecological health. Each can exacerbate the
40 ecological impacts of the other. We use the Hanford Site in Washington State as a case study, but
41 the principles are broadly applicable.

42 **Keywords** Environmental assessment. Remediation. Functional remediation. Initiating events,
43 Ecological assessment

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45

1. Introduction

The USA and other countries are cleaning up and restoring lands that were contaminated during periods of rapid industrialization(19th and 20th century) and during the Cold War (post-1989), and must look forward to the decommissioning of hundreds of nuclear reactors and their stored wastes. These legacy wastes (nuclear, chemical, structural) require complex and expensivemanagement, including environmental assessment followed by cleanup to regulatory standards (NRC 1995; Crowley and Ahearne 2002; Greenberg et al. 2005). Some of the legacy wastes are from the nuclear arms race, but much derives from the various fuel life cycles (nuclear, coal, petrochemical) involved in production of energy for the World's increasing populations and growing per capita demand for energy (Sheffield 1998; Gochfeld 2011). A continued need for energy may result in increased stockpiling of commercial, chemical, and nuclear materials and wastes, and an even greater need for assessment, cleanup and continued monitoring. It is clear that governmental agencies, Tribal nations, and the public are interested not only in immediate cleanup of contaminated sites, but of continued assessment and monitoring to assure that the public and environment are protected (Burger 2008). Some of the concern for contaminated wastes involves security issues and the potential for accidents (e.g. Chernobyl, Davydchuk 1997), but much concern also involves protecting human health, and the "environment". This environment includes not only media (air, soil, water), but the need to maintaining healthy ecosystems that provide the goods and services that people desire and value (NRC 1995, 2000; Burger 2002; Costanza et al. 2014).

Facilities requiring remediation, even in highly developed urban areas, may sit adjacent to wetland, lake, or river ecosystems. Facilities in rural areas may be surrounded by open spaces with ecological resources in various stages from highly degraded to relatively pristine. While no

69 Truly pristine habitats exist because humans dominate every part of the World, some areas are
70 less disturbed than others. Depending on proposed future land uses, protecting and restoring a
71 natural ecosystem is often a priority. Some remediation activities are intrinsically destructive
72 and disruptive to ecological receptors. Their impacts may be worsened if they coincide with
73 natural or anthropogenic disastrous events (initiating events).

74 Part of the assessment process for contaminated lands includes evaluating the risk to
75 human and ecological receptors, which is generally straight-forward and involves examining
76 exposure scenarios, threshold levels, and screening risk levels, as well as risk assessments (Suter
77 et al. 1995; EPA 1997). One approach for risk evaluation is to develop conceptual site models
78 that identify the sources of contamination, pathways of movement, barriers to movement (or lack
79 thereof), and exposure of receptors (ASTM 1995; Burger et al. 2006; ORNL 2011). Site-specific
80 information for risk evaluations and risk assessments is essential (Bingham et al. 1995; Prach
81 2004; Burger et al. 2004, 2007), using a range of tools such as conceptual models, bioindicators,
82 and checklists of needed information and uncertainties (de Groot et al. 2002; Niemeijer and de
83 Groot 2008; Burger et al. 2010a, 2013). An understanding of what assessment endpoints are
84 required is just as important as selection of indicators or indicator sets (NRC 1983; EEA 2003;
85 Heink and Kowarik 2010; Zurlini and Girardin 2008). The final phase of remediation should be
86 rehabilitation or restoration to a functioning ecosystem (Cairns et al. 1992; Cairns 1994; Baird
87 2005). Further, long-term monitoring is essential for environmental assessment and to assess
88 potentially serious environmental problems before it is too late to act (Peterson et al. 2011;
89 Burger and Gochfeld 2016).

90 It is clear that more decision tools are essential for management of contaminated sites
91 (Sorvari and Seppälä 2010). In this paper we 1) describe initiating events and functional

remediation, 2) provide a conceptualization of interactions between them, and 3) examine the types of effects that result from natural and anthropogenic stressors due to the interactions between functional remediation and initiating events. This paper is an outgrowth of the Consortium for Risk Evaluation with Stakeholder Participation's (CRESP) "Risk Review Project" on the Hanford Site in the shrub-steppe area of central Washington State (Poston and Sackschewsky 2007). The CRESP project provides an independent assessment of the resources at risk on the Hanford Site from remaining cleanup sites (CRESP 2015; Burger and Gochfeld 2016). Receptors considered were the Columbia River, ground water, and future human using the site, ecological organisms and systems, and cultural health and well-being. Understanding the interactions among initiating events and functional remediation will allow managers to design status and trends assessment methods that can be employed over long time periods post-remediation. The setting for our paper is the planning, conduct and evaluation of remediation. Although we use the Department of Energy's Hanford Site as a case study, the principles are applicable to a broad range of remediation activities, at diverse facilities, in a variety of ecological settings. Our paper considers the question – Once the risks from remediation to eco-receptors, populations and landscapes are considered, what other issues need to be considered in developing risk evaluations, future monitoring, and environmental planning?

The Hanford Site is one of many Department of Energy (DOE) sites that was involved in producing nuclear weapons during the Second World War and the Cold War. Many of these DOE sites have valuable ecological resources of local, regional and national importance, which have been modified or destroyed outside of the sites (Brown 1998; Dale and Parr 1998; Bartell et al. 2002; Whicker et al. 2004). Less than 10 % of the land area on some of the large DOE sites was developed, and the rest remained as security buffer lands (Burger et al. 2004, 2006, Gray

2004). Thus, over 90 % of the land was left relatively undisturbed for decades as it was guarded and protected to ensure there were no security breaches. One of the missions of the Environmental Management office (EM) of DOE is protection of human health and the environment, now and in the future (USDOE 1999, 2001). This paper focuses on that “environment” and addresses an aspect of ecological protection that is rarely assessed or monitored (How do unusual or catastrophic events interact with remediation to cause adverse effects to ecosystems?).

2.Methods

As part of the CRESP project, initiating events were examined in detail, and we defined functional remediation types (CRESP 2015). Based on our experience of 40 years each with ecological systems and ecological risk assessment, and 25 years of experience at DOE sites, we developed a conceptual model of the relationships between functional remediation and initiating or catastrophic events, and used our experience and the literature to describe examples of how these two interact.

3.Results

3.1 Initiating events and functional remediation

Initiating events are defined as events that have the potential to trigger new, usually sudden, and often catastrophic cascades that do not or would not otherwise occur. Initiating events are typically rare or low probability, and of high consequence. They include catastrophic and unusual events such as severe hurricanes and tornadoes, and unpredictable and low probability

events, such as a tsunami that coincides with a very high tide, a superstorm, and excessive winds (CRESP 2015). Initiating events can be both natural (hurricane, tornado, el nino) and anthropogenic (chemical exposures, building collapse, explosion), and interactive (climate change has both natural and anthropogenic causes, IPCC 2007, 2014). The types and interactions are illustrated in figure 1.

The term initiating event refers to low-probability high-consequence events, but they need not be catastrophic, for example, a power outage. However, their very rarity discourages planning and design. There are different approaches to classifying an event as extreme or catastrophic (Easterling et al. 2016). Natural initiating events (storms, volcanos, flooding, earthquakes) occur annually somewhere in the world. Extreme events are those that are beyond the 99th percentile of prior experience, whether it refers to the force of a hurricane, the amount of precipitation, or the height of flooding (Easterling et al. 2016)). However, Sornette (2002) argued that catastrophic events are true outliers, with statistically different properties than events in general, raising a challenge of unifying a prediction science. This would be of particular importance for predicting earthquakes (Sornette et al. 1992). Predicting the probability of a severe earthquake solely on the basis of human historic experience can be supplemented by exploring paleoseismic data, which led Goldfinger et al. (2012) to predict major earthquake activity in the Pacific Northwest in the present century.

Initiating events are typically acute and of short duration, from seconds in the case of quakes and explosions, to days for fires, floods, and storms. This differs from chronic exposure to contamination which may be worsened by an initiating event. The consequences can also be roughly divided into acute (sudden death of individuals or populations) to chronic (reduced populations, shifts in food webs that may take many years to recover to the original or to a

different ecosystem). The acute events may cause lasting damage. Hurricanes and tornados can change the structure and composition of forests (Wang and Xu 2008). Seawater flooding destroys freshwater plants (Neyland 2007) and animals (Lance et al. 2010).

Functional remediation refers to the elements of remediation, such as the number and activities of personnel, cars, trucks, heavy equipment, drilling, drilling rigs, and drilling pipes. These can occur in any combination for any remediation type (e.g. pump and treat, capping, excavation, soil removal and trucking). The functional remediation elements can occur on site at a low or high intensity, over a few or many locations, or over a short or long period. The variation in the occurrence and number of functional remediation elements will determine the ultimate effect on ecological receptors.

3.2 Conceptual model for functional remediation and initiating events

Natural initiating events are tornados, hurricanes, floods, and earthquakes, while anthropogenic are chemical events, collapses, and containment failures. Other events are caused by both – fires, floods, sea level rise and climate change (interactive or hybrid events). Ultimately, all the initiating events may change habitat, destroying some or increasing other. The immediate effects are usually loss of plants and animals, leading to population and ecosystem changes. Habitat loss occurs through erosion, removal of soil and sediment, and destruction of ecosystem components, such as vegetation diversity and complexity. Chemical contamination, explosions, and fires can result in death, sublethal deficits or abnormalities, and fetal malformations (Fig. 1). All these effects, habitat loss, species and population effects, death, abnormalities and other deficits can result in systems that are either unable to recover, or able to recover through evolved mechanisms (resiliency).

Ultimately, the effect of these on the ability of organisms to recover can be severe when faced with the interaction of initiating events with functional remediation. We suggest that recovery to the initial ecosystem following an initiating event partly depends upon whether it is natural or anthropogenic (or a combination of the two, hybrid events). Plants and animals have had thousands of years to evolve with natural events, but not to anthropogenic ones. They have not evolved with many of the chemicals that are now produced and are released into the environment, either in an acute event (e.g. massive spill) or chronically (e.g. atmospheric deposition).

3.3 Interactions of functional remediation and initiating events

Species, populations, and ecosystems have evolved mechanisms over many thousands of years to recover from natural events and catastrophes (Gaillard et al. 2003). That is, birds that nest on the ground in coastal environments have evolved with regular tides, with excessively high tides, and with the combination of high tides and storm tides occurring together. For example, many coastal birds have a clutch size of 3 eggs (gulls and terns), while others may lay 4-6 (herons, egrets, ibises). In most cases, they are unable to provision them all and raise their full clutch. However, if populations have been devastated because of storms or other natural events that killed individuals, then competition for nest sites and food resources within that species will generally be lowered, which may make it possible for pairs that survive, to raise more than they might otherwise raise. These adaptations also function when birds are faced with anthropogenic catastrophe or initiating event. For example, if thousands of coastal birds die in an excessive oil spill, it may reduce competition among conspecifics for nest sites, nest materials, mates, and food resources.

We suggest that the mechanisms that evolved to adapt and respond to natural catastrophes operate under most circumstances, and with time, recover to an intact system. Responses to anthropogenic initiating events or catastrophes may result in slower recovery for several reasons, including 1) non-point source contamination is a constant pressure (as opposed to a hurricane or storm that happens, and then reverts to usual conditions, allowing recovery), 2) chronic exposure events do not allow time for system recovery (e.g. small oil spill continue to happen on a regular basis), and 3) habitat loss due to a natural event may displace (or even kill) organisms, but some can move elsewhere in a timely manner (as they have over thousands of years). This may not happen if chemical exposures happen with too high a frequency. This results in a delayed recovery to an intact ecosystem state (gray area on Fig. 1). The interactions of functional remediation with natural initiating events (Table 1) and anthropogenic initiating events (Table 2) can be important for species and ecosystems.

3.4 Effect of interactions of anthropogenic and natural initiating events with functional remediation

Natural initiating events, such as storms, floods and sea level, can be (and often are) influenced directly by anthropogenic initiating events. The interactions can increase the effects of either alone. Possible effects of the interactions are described in Table 3. That is, the natural process of cyclic changes in climate (with sea level rise) is being enhanced by anthropogenic effects (IPCC 2007, 2014). The interaction has resulted in increases in sea level rise, with the resultant effect that in coastal areas, nesting habitats for birds have disappeared, leaving them with no safe places to nest without human disturbances and predators (Burger and Gochfeld 2016). At Hanford, this may take the form of increased drought caused by global warming that increases the process of desertification with changes in vegetation types.

Floods interact with habitats that people have degraded, amplifying the effects. This is particularly evident along stream and river corridors where vegetation that stabilized shorelines and banks has been cut so that a flood has a greater erosional effect that it would otherwise have. Droughts, occurring over a time frame of months or years, don't fit the image of initiating events, but they certainly influence the impact of remediation activities on the surrounding landscape, as well as predisposing to fires (Siegert et al. 2001).

4. Discussion

4.1 Complexity of ecological evaluation

Governmental regulators, Tribes, and the public are all committed to remediating waste sites to protect human health and the environment, now and into the future, allowing a variety of future land uses. To some, "Cleanup" connotes the complete decommissioning and demolition of structures and digging up and removal of contaminated soil and debris. All of these functions, including transport to permanent, secure disposal sites, proceeds within a context of ecological integrity and complexity (Lloyd 2001; Muller 2005; Harris 2007; Lamb et al. 2009; Parrott 2010), economic stability (Costanza et al. 1997, 2014; Burger et al. 2008; Lemming et al. 2010), cultural protection, and environmental justice (Harris and Harper 2000; Nez Perce Tribe 2003; Burger et al. 2008a,b, 2010b; Burger 2009; Burger and Gochfeld 2011; Gochfeld and Burger 2011). These aspects all benefit from public participation in addition to the usual risk assessment considerations (Suter 1990; NRC 2008). Inspection and monitoring are essential features of long-term stewardship (Suter et al. 2003) and remedy sustainability. Essential features include evaluating the effectiveness of engineered barriers and institutional controls, success of

248 restorations, performance of containment barriers (Trayham et al. 2008), and considering
249 different environmental scales (e.g. regional and landscape scale, Hunsaker et al. 1990; Leita
250 and Aherne 2002; Ruiz-Jean and Aide 2006; Trayham et al. 2008; Mascarenhas et al. 2010).
251 Clearly, environmental management needs an integrated management strategy (Pastorok 1997;
252 Reagan 2005), and this includes consideration of the potential for initiating and catastrophic
253 events.

254 The benefits of complete cleanup of contamination (future protection of human lives and
255 health) may clearly outweigh the costs of remediation, but this is not always the case for
256 ecosystems. Risk balancing is always a consideration, including balancing the risks to humans
257 and ecological receptors (Suter et al. 1995; Lemming et al. 2012), and balancing science and
258 policy (Turnhout et al. 2007). Approaches for the use of ecological indicators should include a
259 social science perspective, as well as inclusion of stakeholders (Turnhout et al. 2007; Burger
260 2011).

261 The tenet “above all, do no harm” can be applied to the role of remediation in ecological
262 systems. The buffer areas on many of the DOE sites have literally been undisturbed by people
263 for more than 60 years, and many have valuable ecological resources (Brown 1998; Dale and
264 Parr 1998; Burger et al. 2004; Whicker et al. 2004). Efroymson et al. (2004) suggested a
265 framework for net environmental benefit analysis for remediation and restoration of
266 contaminated sites. By virtue of the complexity of ecological systems (e.g. even the total
267 number of species present), there are going to be many data gaps for a net environmental benefit
268 analysis of type of remediation (including no remediation).

On grasslands and shrub/steppe habitat, the primary habitat at Hanford, bird assemblages have been shown to be good indicators (Wiens and Rotenberry 1981; Bradford et al. 1998). Other good indicators of biological integrity are soil invertebrates (Kimberling et al. 2001) and cryptogamic crusts (Johansen 1993). Measures other than the number of species may prove most useful; for example, fragmentation affects reproductive success of birds in shrub/steppe landscapes (Haegan 2007). Not only must diversity, ecological integrity, and complexity (Lloyd 2001; Muller 2005; Harris 2007; Lamb et al. 2009; Parrott 2010) be examined, but multiple lines of evidence are needed to predict site-specific ecological effects (Goodsell et al. 2009; Hall and Giddings 2000). Even seemingly dramatic negative impacts on biodiversity may have beneficial repercussions as when fire, storms or tornados destroy canopy or climax vegetation re-setting succession to earlier stages favorable to other species (Brown et al. 2011, Prather and Smith 2003).

4.2 Functional remediation and initiating/catastrophic events

While the above considerations clearly are very important for evaluations of ecological systems, the effects from remediation and from unforeseen, initiating, and catastrophic effects need to be considered as well since they can amplify ecological effects. This is especially important given global changes, when unexpected, low probability event may happen more frequently. For example, more frequent or severe storms will result in more severe effects from functional remediation because the conditions may occur for longer (e.g. wetter or drier conditions).

The interaction between anthropogenic events (e.g. dam failure) and other hazards are recognized as “hybrid events”. Failure to take into account these interactions is a very narrow approach. Take for example, Fukushima, in which an extreme natural event (>9.2 Earthquake)

triggered a prolonged loss of electricity, a failing nuclear cooling system, and nuclear meltdown and explosion (Boyarsky and Schneidermann 2002). The timing of the interaction is important, but the timing with respect to crucial ecological cycles, such as synchronized nesting of sea turtles (Milton et al. 1994) or conception in deer (Labisky et al. 1999) is more critical.

We proposed that the recovery time to an intact ecosystem, whether the original or a slightly altered one, will be greater when the initiating events are either anthropomorphic, or enhanced by man (e.g. climate change, Fig. 1). Other examples included fires that may be started or modified by people. People often prevent fires, and when fires do occur, they are hotter and more severe because there is a build-up of flammable materials. This suggests that managers need to consider the increased effects of initiating events when they are augmented by humans. Flooding around the world has been ameliorated by the building of dams and reservoirs, yet these have direct effects (lack of annual flooding that restores soil nutrients), and indirect severe effects if a dam breaks or heavy rains cause waters to overflow dams, flooding fields and towns.

5. Conclusions

Evaluating the risk to ecological resources from different remediation activities, as well as the risk to human health and cultural resources, is a high priority for government agencies, Tribal nations, and the public. Traditional methods of risk evaluation and risk assessments that involve conceptual site models, screening thresholds, and effects assessment are the main components of assuring protection of human health and the environment. We suggest, however, that for long-term stewardship and sustainability of remediated sites, the effects of functional remediation,

initiating events, and interactions among these factors should be evaluated as part of the process of protecting human health. They should be added to assessment and monitoring protocols.

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549 Table 1. Examples of potential effects among functional remediation types and natural initiating
 550 events.

Functional Remediation Types	Tornados	Hurricanes	Flood	Earth- quakes
Personnel traffic through buffer area and EU	Possible destruction of vegetation if tornadoes removed some vegetation, making it vulnerable to human trampling; could change seed dispersal to EU. Increased traffic in either buffer or EU could	Excess wind and water makes the effect of human traffic greater because the ground is wet and compression can occur. Can also lead to erosion.	Plants that are already stressed by wet soil are more vulnerable to trampling. If the native vegetation dies, it provides more opportunities for invasive species to move in.	Little effect
Car and pick-up traffic in buffer and EU	Cars and light trucks are heavier than people, and in combination with tornado damage to	Excess wind and destruction of trees, shrubs and other vegetation, along with more vehicular traffic	Car and truck traffic can cause more compaction following floods (soil becomes brick-like) because	Little effect

	vegetation, could result increased death of some native species, and increase in invasive species	can result in increased destruction to vulnerable vegetation already weakened by the hurricane	plants are already stressed. Flooding could decrease oxygen to sensitive roots, and increase the sensitivity of plants to diseases.	
Truck traffic on roads through buffer and EU	Truck traffic following tornadoes could bring in seeds from quite far away that were first dispersed by the tornado.	Traffic on roads can bring in invasive seedlings, and hurricanes and other high wind storms can move these farther from roads, increasing the area of vulnerability.	Truck traffic on roads bring in invasive seedlings, and in combination with excess water, invasive seeds can outcompete local species because they are usually more adaptable.	Little effect
Heavy equipment	Heavy equipment causes compaction of the soil, killing some invertebrates and plants, and in combination with tornados could amplify the effects	Heavy equipment compacts soil, killing some invertebrates and plants, and in combination with hurricanes that have an effect over a greater spatial area can destroy	Heavy equipment compacts soil and kills some soil invertebrates and plants, and in combination with floods, the compacted soil would prevent any native seedlings from	Little effect

		broader areas of shrub/steppe and other habitats.	germinating. Germination of native species would be delayed because of the twin stresses of too much water and compacted soil.	
Heavy wide-hoses	Heavy hoses provide a barrier to movement of small animals, and tornados can shift the location of hoses, destroying additional habitat and organisms. The former locations of hoses are then vulnerable to invasive species. If moved by tornados can sweep the ground as they	Heavy and large hoses can provide barriers to movement of small animals, and in combination with hurricanes can increase the area of disruption, thus decreasing patch size and leading to fragmentation	Heavy and large hoses provide a barrier to movement of small animals, take away habitat, and change the wind/humidity climate. Under flood conditions, the plants and animals living near the pipes would experience increased heat and flooding, or wet soil.	Little effect

	move, killing and injuring vegetation, making it more vulnerable to human activities			
Drill rigs	Drill rigs are heavy, can cause soil compaction and loss of habitat, and the twisting wind can move them small distances, or pick them up and deposit them on pristine environments.	Heavy drill rigs cause soil compaction, penetration down into the soil, and loss of habitat; hurricanes can dislodge them, moving them over the ground and destroying vegetation. The soil penetration of drills can result in increased moisture movement down the drill holes.	Drill rigs cause soil compaction, penetration of soil, and loss of habitat; in combination with floods, the soil compaction, and drill holes can cause increased wetting of subsoil near the drill rigs.	Little effect
Construct buildings	Building construction removes habitat, and partly destroys a space around the	Building construction removes habitat and destroys buffer areas around the site, and in combination with a	Building constructions removes habitat and destroys buffer areas around the site. In combination with	Little effect

	building because of construction activities. Tornadoes can remove or collapse the buildings, destroying additional habitat nearby	hurricane, particularly a prolonged one, can increase destruction of vegetation and habitat around the buildings.	floods, building construction could amplify soil compaction.	
Caps, other containment	Caps are supposedly secure, but an unusual even could dislodge containments, or destroy vegetation on some caps, leading to opportunities for invasive species to move in the region.	Containment types remove habitat from the region, and if higher than the surrounding environment, change the water balance. In combination with hurricanes, which can last for longer than a tornado, they have the potential to destroy containment types more, shift them about the landscape, causing	Containment types remove habitat from the region, and flooding could make it more difficult for restoration efforts on caps and other more natural containment types.	Little effect

		damage to sensitive vegetation and soil invertebrates		
Soil Removal Dig and Truck	This remediation type removes the living environment, and a tornado could bring in invasive species to the dig site, allowing them to become established.	This remediation type removes the living environment, and a prolonged hurricane with continuous high winds has a greater potential to destroy either caps or other containment types, shifting them around and destroying vegetation. Prolonged winds can remove vegetation from some covers, providing space for invasive species to become established.	The removal of all soil and the living environment leaves sterile soil. Flooding would make it more difficult to restore the area, including the restoration of native vegetation. Many invasive species are more tolerant of water conditions, and may establish themselves more quickly than native species.	Little effect

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553 Table 2. Examples of potential interactions effects between functional remediation types and
 554 anthropogenic initiating events.

Functional Remediation Types	Chemical and Radionuclide Contamination	Explosions/collapses of Buildings	Containment Failures	Institutional Control Failures
Personnel traffic through EU and buffer area	<p>People walking through a site can destroy sensitive vegetation and bring in invasive species seeds.</p> <p>People can spread contaminated soil on their shoes to other pristine areas</p>	<p>People walking through a site can destroy sensitive vegetation and bring in invasive species.</p> <p>If there is an explosion or a building collapses, any fallout might fall on places people have walked, allowing invasive or other species to move in.</p>	<p>If containment failures occur, people walking through to correct the problem can spread contamination, invasive seeds, and change the water patterns (and thus the vegetation)</p>	<p>Little effect from functional remediation, but is the public comes in on food then they can compact soil, kills sensitive plants, bring in invasive seeds, and overharvest some plant.</p>
Car and pick-up traffic in EU and	<p>Cars and trucks can spread contamination on their tires, and</p>	<p>Cars and trucks that carry away part of the debris can spread contamination and</p>	<p>Cars and trucks that come to repair containment can bring in seeds of</p>	<p>Failure of institutional controls can result in people and their</p>

buffer	shoes of people walking through can also spread contamination and carry invasive species seeds.	carry invasive seeds,	invasive species, and create ruts that hold water. If pieces fly about, trucks used to pick up pieces can go into sensitive ecosystems, making ruts, carrying seeds and killing sensitive vegetation.	trucks going into sensitive patches of shrub step, creating ruts, spreading invasive seeds, and overharvesting sensitive plants or animals.
Truck traffic on roads through EU and buffer	Truck traffic through any area can carry invasive species seeds, water, and contamination through the buffer and the EU. The increased remediation required may increase the	Truck traffic on roads will increase if a building collapses, and they can carry more seeds of invasive species into buffer areas or areas of high ecological value	Truck traffic on roads will increase with failure of containment structures, with the potential to carry more seeds into regions, kills sensitive plants and soil invertebrates if they have to leave the road to retrieve	Truck traffic on roads will increase if institutional controls fail, allowing people into a sensitive area, increasing invasive seed dispersal, differentially affecting some native plants, and

	potential for contamination to be spread over a greater area of roads inadvertently		items	animals
Heavy equipment	If there is a contaminant release, and heavy equipment is used, compaction of the soil will keep the contamination localized, and if some spills from heavy equipment, may create hot spots of contamination	If buildings collapse, and heavy equipment is required to deal with it, then compaction of soil will occur, killing or displacing sensitive plants and animals; debris pieces can be blown or thrown into sensitive ecosystems, requiring secondary movement of people and vehicles into these areas, destroying plants and animals, and bring	Containment failures that require the use of heavy equipment to fix will result in compaction of soil, killing and displacing sensitive plants and animals, if not removed completely, then it will lead to increased monitoring and the potential for trampling and disruption of	Failure of institutional controls that bring in the public can lead to the need for additional remediation to make the region safe, either at the beginning or after the public has built structures. Heavy equipment will disrupt sensitive ecosystems, and associated plants and animals; and

		invasive seeds.	functioning ecosystems	the public may use of inadvertently destroy native plants and animals
Heavy wide-hoses	Hoses can trap any contamination in pockets, especially if it is in dry soil that can be blown. If tumbleweeds are contaminated, they can be trapped there. These hot spots will be difficult to contain unless removed, which will interrupt any on-going pump and treat	A building collapse that requires use of heavy hoses will result in habitat destruction, possible killing of sensitive plants and invertebrates, disruption of normal movement of small animals, and the trapping of soil along the hoses	Containment failures that require the use of heavy hoses will result in habitat destruction, and the failures may inadvertently release contaminants to the environment, affecting sensitive plants and animals, and providing an opportunity for contaminated animals and tumbleweeds to move into other sensitive ecosystems	Increases in the public into areas with heavy hoses may result in accidents and injuries to the public. If further remediation is required because of public presence, then the hoses can cause damage to sensitive plants and animals, and serve as a trap for movement of soil and contaminated soil.
Drill rigs	Drill rigs can also	If buildings collapse,	Containment	If the public moves

	<p>trap any contamination carried by wind or plants (Tumbleweeds) in pockets of high concentrations</p>	<p>exposing contaminated soil once contained, and drill rigs are essential, then both the building materials and drill rigs can kill or injure sensitive plants and soil invertebrates, act as a sand trap, and require additional equipment that may compact soil or injure plants or animals, or force mobile animals to flee</p>	<p>failures that require drill rigs can result in increases in local contamination, with the potential for mobile animals or tumbleweeds to carry contamination to other more sensitive habitats. Drill rigs will open pathways to sub-surface contamination.</p>	<p>into an area with contamination because of failure of institutional controls, and drill rigs are present, it may result in injuries to the public, contamination to the public, and the potential of increased ecological damage through trampling, killing sensitive plants and animals</p>
Construct buildings	<p>Construction of buildings creates places for contaminated, blowing sand to</p>	<p>If will constructing buildings, there are collapses, then more and different types of equipment may be</p>	<p>Failure of engineered barriers in a region where buildings will be constructed may</p>	<p>Failure of institutional controls that brings the public to a place where buildings are</p>

	collect, as well as contaminated tumbleweeds; their collapse will require equipment to remove pieces, which if blown elsewhere, will create ruts with potential contamination from truck wheels.	required, which will have physical effects on ecosystems (killing sensitive plants and animals, causing some to flee), as well as increasing the potential for materials to be thrown into nearby sensitive habitats, requiring disruption to these habitats.	expose workers and the public to contamination, causing increases in other forms of remediation to deal with the problem. The increased remediation can cause injury to sensitive plants and animals, allow contaminated soil to be trapped and increase potential for contamination to move off site	being constructed may result in injury, but can also affect ecological resources if they trample or collect sensitive plants or bring in invasive seeds. If they move building materials, this may cause ruts and injure sensitive plants.
Caps, other containment	If there are unexpected releases from caps or other containments, then they could	If buildings or other structures collapse near where caps are being constructed, then these materials may injure or kill	Failure of caps or other containment structures may result in releases of contaminants, which will cause local	If the public enters an area with caps or other containment areas, they risk exposure and injury, but the

	move into either the EUs or buffer areas, carrying contamination, which will then require vehicles to remove, causing ecological damage, including affecting sensitive plants and animals	sensitive plants and animals. The collapse of a building may also destroy nearby caps, thereby releasing contaminants, or allow water to penetrate a cap.	exposures, and potentially move contaminants off the site due to movement of animals and plants such as tumbleweeds.	increased activity may damage sensitive plants and animals, ruts will be created, water balance will be changed, invasive plant seeds may be brought in, and some compaction of soil may occur
Soil Removal Dig and Truck	Removing contaminated soil and trucking it away provides opportunities for contaminants to be carried by tires, or otherwise to move into	If there is collapse of a building in a location where the soil has been removed without restoration, this will require more equipment to remove this material, which	Failure of containment structures or caps near a place where the soil has been removed may result in contamination of the soil, plants and animals, may	If the public moves into an area where the soil has been removed with no restoration, they the bare soil will be compacted, invasive seeds may be brought in, and

	<p>buffer areas.</p> <p>Restoration will be required, and any remaining contamination or contamination from nearby facilities will affect sensitive plants and animals.</p>	<p>might injure and destroy any plants and animals that have moved in naturally, if a building collapses where restoration occurred, then the material may destroy the seedlings that were planted, and removing building materials will destroy the new, sensitive habitat being restored</p>	<p>require additional personnel and equipment to correct, and will increase the potential for destruction of a recovering ecosystem and the invasion of exotic species.</p>	<p>water dispersion on the site may change. If there has been restoration, then the public can injure new seedlings, bring in plant seeds that will outcompete those plant for restoration.</p>
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557 Table 3. Examples of potential interactions effects between functional remediation types and
 558 interactions from initiating events. These events can be caused by nature, man, or an interaction
 559 of the two. These are only meant as examples.

Initiating Type	Functional Remediation Type	Possible Ecological Effect
Flood	Personnel on site	Following a flood, the wet soil is more easily compacted, seeds on boots can be pressed into soil and germinate because of the moisture, and tracks made in mud are deep, and will create pockets for water to gather.
	Heavy equipment	Heavy equipment on a flooded area that has not dried out to its usual state will cause additional compaction, allow invasive seeds to grow, prevent native species from germinating due to compaction, and kill sensitive soil invertebrates.
Fire	Personnel on site	Following a fire, the presence of people on site can destroy sensitive plants that were weakened by a fire, and set back succession by potential compacting soil.
	Trucks and cars	Any increase in vehicles on a habitat that has

		experienced a recent fire can lead to compaction, create tire tracks, can kill delicate seedlings and young plants, and can kill some surface invertebrates. Effects will partly depend upon the timing of entrance of vehicles after the fire.
Climate change	Personnel on site	Climate change is a gradual event, and over time may change the plant species diversity and dispersion on any site. If temperature changes are slow enough, there will be a gradual shift in plant diversity. A prolonged period of unusual cold or heat can destroy sensitive plants, especially if they are being trampled by people. Prolonged hot or cold spells, in combination with people, or vehicles moving about may change which species germinate and survive.
Sea Level Rise	Trucks and cars	Presence of trucks and cars in coastal edge areas can cause further erosion and breaking away of land and vegetation, as well as injuring sensitive plants that can be dislodged.

		Obviously, this is not a problem at Hanford and other inland sites.
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Figure 1