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Towards a clean and sustainable future: Green technologies, restoration and management of contaminated sites

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Abstract

Poor handling and disposal of hazardous substances have left a legacy of contamination in sites all across the United States that affect human and ecosystem welfare. The U.S. Environmental Protection Agency (EPA) addresses these contaminated sites under the Comprehensive Environmental Response Compensation and Liability Act (CERCLA) commonly known as the "Superfund Program." The management and cleanup of these impacted areas is a matter of national security and environmental justice as it is estimated that one in four Americans live near a Superfund site and that minorities, particularly Hispanics are more likely to live near affected areas. Green technologies such as bioremediation and sustainable practices represent a solution to treat and restore these sites; but several factors including scientific and regulatory considerations hinder the implementation of these technologies. Changes in environmental regulations, better management of the Superfund sites and the creation of initiatives that promote collaboration between academia and federal agencies should be made to safeguard the livelihood of U.S. citizens and enhance the restoration of contaminated sites.

Background and Introduction:

Environmental degradation is a threat in industrial and developing countries due to population growth, increased use of resources, and a legacy of poor handling and disposal of hazardous substances. The **Comprehensive Emergency Response Compensation and Liability Act** (CERCLA, 42 U.S.C. §§ 9601–9675) is the federal statute that addresses uncontrolled and abandoned contaminated sites and requests these areas be investigated, evaluated and ultimately restored (S. US EPA) . This law gives authority to the EPA to compel responsible parties to perform cleanups at impacted sites and also establishes a trust fund to finance restoration of orphan sites, where no responsible party exists. After an evaluation by our federal government, locations that represent a high threat to human and ecosystem welfare are declared as "**Superfund sites**" and the worst cases are listed in the **National Priority List (NPL)**. CERCLA was enacted in 1980 under the Reagan Administration after the discovery of toxic waste impacting sites such as Love Canal in New York and Times Beach in Missouri. Today the Superfund (or NPL) has become one of the nation's largest government programs, and as of January 24, 2014, there were 1,372 proposed or declared NPL sites (S. US EPA 2014b) (Table 1 and Figure 1)

Superfund and toxic waste impacted sites can be treated with various remedial technologies that can include physical methods (e.g., removal of the hazardous substances by excavation or incineration), application of biological processes (e.g., biodegradation of a particular waste by microorganisms, plants or fungi), and chemical treatments (e.g., the addition of certain compounds to induce chemical reactions that would transform hazardous compounds to inert or less toxic compounds). **Sustainable remediation** (also referred as green remediation) can be defined as remedial methods used to treat and restore areas considering all environmental effects of technology implementation; maximizing the environmental and human welfares and minimizing cost and the use of limited resources. Cleanup strategies that involve the application of biological processes to achieve detoxification, cleanup and restoration of contaminated sites are of particular interest since these are often considered environmentally friendly, and are widely accepted by the scientific community. Special attention has been given to *in situ bioremediation* approaches (the use of microorganisms which can degrade the contaminants of interest at the site) since it has the potential to be a non-intrusive, non-waste generating and cost efficient natural method. However, there are four factors

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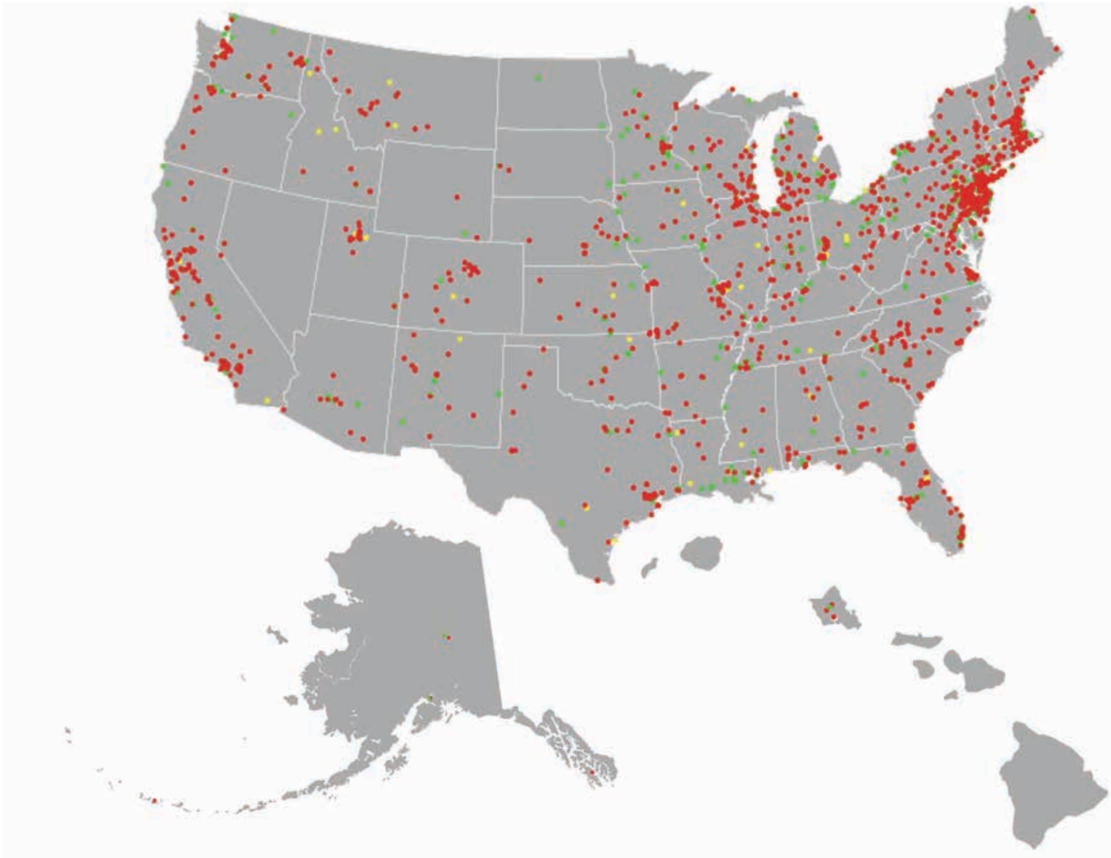

Figure 1. Map of Superfund sites in the United States as of March 31, 2010. Red dots indicate final sites in the National Priority List, yellow are proposed sites, and green are deleted sites (S. US EPA).

that hinder implementation of this green technology in Federal Superfund sites. These include: (1) scientific and regulatory aspects that limit the implementation of these technologies; (2) the current state of the CERCLA statue and management of the Superfund sites which have no clear language for implementation of sustainable practices; (3) the absence of incentives to promote the use (implementation) of green technologies over other strategies; and (4) lack of collaboration between agencies, practitioners and academia.

This paper will review the history of the Superfund Program and the CERCLA statue, the current management of contaminated sites and describe how bioremediation as well as other sustainable approaches represent feasible and attractive cleanup methods to treat these locations. Emphasis will be given on addressing why the conditions of these areas are important to minority and Hispanic communities and the regulatory aspects of the program that could be amended regarding site management, contaminant removal actions, research and innovation and implementation of green sustainable remedial practices. Lastly, a set of recommendations is delineated to enhance the restoration of these sites.

Why should we care?: Racial and ethnic minorities at risk

The EPA estimates that one in four Americans live within three miles of a toxic waste contaminated site and around 10 million children under the age of 12 live within four miles of a Superfund site (S. US EPA). A study focused on evaluating 50 Superfund sites across the United States revealed between 205,349 and 803,100 people live within one mile of these areas. Furthermore, this study revealed these sites are in neighborhoods whose household incomes are below the national average. Moreover, 60% of the U.S. Census tracts in these regions comprised 40% or more racial or ethnic minorities (Steinzor et al. 2006).

On August 2, 1978, the New York State Health Department declared the site in a state of emergency and more than 800 families were relocated. Five days later, President Jimmy Carter declared a federal state of emergency in the Love Canal's surrounding areas and later allocated federal funds to remediate the area.

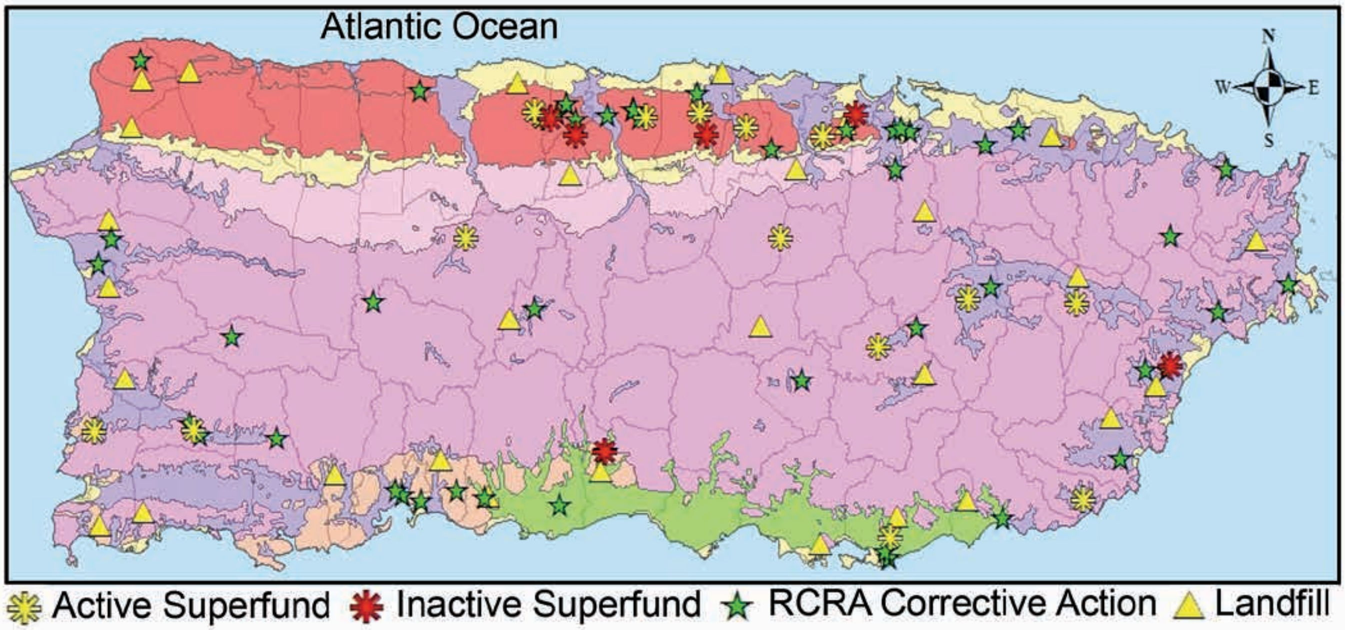

Figure 2: Impacted areas in Puerto Rico. Hydrogeology and contaminated sites are indicated; the north coast limestone aquifer is depicted in orange and light pink color. Resource Conservation and Recovery Act (RCRA) facilities are also included, these are sites where releases of hazardous waste into soil, ground water, surface water, sediments, and air have occurred; requiring the investigation and cleanup, or remediation. Forty-five percent of all Superfund sites are located in the northern karst region of the island which includes one of the largest and most productive sources of groundwater. Evidence suggests that the higher preterm birth rates in Puerto Rico cannot be explained by changes in obstetric practices and that exposure to hazardous chemicals contributes to preterm birth (Padilla, Irizarry, and Steele 2011; "Puerto Rico Testsite for Exploring Contamination Threats (PROTECT): Dynamic Transport and Exposure Pathways of Contaminants in Karst Groundwater System" 2014).

Other studies have also shown that Blacks, Hispanics and low-income individuals are more likely (i.e., positively associated) to live near Superfund and NPL locations (Stretesky and Hogan 1998; Burwell-Naney et al. 2013; Wilson et al. 2012). Executive Order 12898 entitled "Environmental Justice for Low Income & Minority Population" is intended to protect individuals and communities against unfair treatment due to color, race or nationality with respect to environmental policies, laws and regulations. However, a study conducted by O'Neil (2007) indicated that, since the enactment of EO 12898 in 1994, "marginalized and poor populations are less likely to benefit from a cleanup program such as Superfund despite their overrepresentation in proximity to environmental hazards." (O'Neil 2007). Another study by Anderton et al. (1997) also concluded that areas with a higher percentage of minorities are less likely to receive NPL status, thus delaying the cleanup process (Anderton, Oakes, and Egan 1997).

The Commonwealth of Puerto Rico, a U.S. territory with a 99% Hispanic population, serves as an example of a minority community impacted with hazardous waste by having more than 150 contaminated sites ("Puerto Rico Testsite for Exploring Contamination Threats (PROTECT): Dynamic Transport and Exposure Pathways of Contaminants in Karst Groundwater System" 2014; Padilla, I.Y. 2011) (Figure 2). Remarkably, as of January 24, 2014, Puerto Rico has 16 NPL sites; the same as states like Tennessee, Georgia and Utah; and more than states like Oregon, Delaware and Oklahoma which have 14, 13 and 7 NPL sites, respectively (S. US EPA). Concerns exist that exposure to contaminants may contribute to the birth incidence in Puerto Ricans, which is among the highest in the United States (Ghasemizadeh et al. 2012; Padilla, Irizarry, and Steele 2011). Overall, these studies and occurrences reflect that racial and ethnic minorities (especially Hispanics) are among the most vulnerable and at-risk communities when it comes to Superfund

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sites, suggesting a case of inequality and environmental justice. Therefore, the management and state of restoration of these areas is a matter of national security to ensure livelihood of all U.S. citizens.

History of CERCLA

In the 1970s, the Love Canal in upstate New York, made headlines in what is considered to be "one of the most appalling environmental tragedies in American history" (Beck 1979). Located near the Niagara Falls, this body of water and its adjacent community suffered the consequences of 21,000 tons of toxic waste that were disposed by a nearby chemical industry since the 1940s. The hazardous waste (which included pesticides such as DDT, carcinogenic solvents and heavy metals) was lined with clay and buried under the canal. The chemical company that owned the area sold it to the city for one dollar and included a warning about the chemical wastes buried and a disclaimer absolving the industry of any future liability. But on 1976, the waste was exposed after record-breaking rainfall; nearby vegetation started to die, corroding barrels were exposed to the surface, chemicals leached forming toxic puddles and a fouling smell covered the residential area. In the years that followed, astonishing levels of miscarriages and stillbirths were recorded, and 56% of the children born between 1974–1978 had at least one birth defect. For two years, the local community battled to prove the industrial waste buried in the area was responsible for the citizens' illnesses, and finally their united efforts and mobilization brought attention at the state and federal level. On August 2, 1978, the New York State Health Department declared the site in a state of emergency and more than 800 families were relocated. Five days later, President Jimmy Carter declared a federal state of emergency in the Love Canal's surrounding areas and later allocated federal funds to remediate the area. This incident represented the first time that federal monies were used to assist in a man-made disaster. The Love Canal incident was a "wake up call" creating awareness on the dangers of public exposure to toxic waste and the need to compel the parties liable for the incidents. Consequently, extensive House and Senate committee hearings were held during 1979, which led to Congress enacting CERCLA in 1980. On September 1, 1983, the Love Canal was added to the NPL list and the chemical company that generated the hazardous waste was found liable of the disaster and negligent in the way it handled the waste and sale of the area. Although the company had followed all U.S. applicable laws at the time of disposing the waste, the EPA sued the company for $129 million under a retroactive liability provision underlined in CERCLA (section 107) and the families were compensated for their properties. In, 2004 after great efforts, over $400 million dollars, and after 21 years of its inception as an NPL, the Love Canal was clean enough to be taken off the Superfund list.

Management of Superfund Sites

EPA's Office of Solid Waste and Emergency Response (OSWER) in Washington, D.C. oversees the Superfund Program. A representation and summary of the phases and milestones for a site cleanup under CERCLA are illustrated in Figure 3. In aggregate, the Act requires a **preliminary site assessment** to identify if the environment poses or not a threat to human health, and identifies sites where possible response actions are needed. These include removal actions (e.g., immediate control of the spread of hazardous substances during a spill) and remedial activities (e.g., prolonged monitoring and ultimate restoration). If the environment and sites are considered a threat, further investigation is required and a **site inspection** is made to determine the nature and extent of the contamination and the potentially responsible parties. The information collected in these first two phases will be evaluated and sites will be given a score from 0 to 100 using the "Hazard Ranking System" (as stated in section 105(a)(8)(B) of CERCLA, as amended). Sites with a score of 28.50 or higher are eligible for listing as NPL. The NPL serves as an informational and management tool indicating which sites are priorities for cleanup, as they pose a high threat to the community. Only sites in the NPL list can use federal funds for cleanup. After a site is listed as an NPL, a **remedial investigation** and **feasibility study** are concurrently conducted for more detailed investigations on site contamination and exposure. At this phase, treatability studies of alternatives methods for treatment are considered and evaluated. Once the assessments and investigations are complete, a document identifying the treatment procedure to be used at the site is made public, this is known as a "**record of decision"**.

Consequently, **remedial designs** and **remedial actions** are followed, which involve the design and implementation of the site cleanup strategies. The EPA designates sites as **"construction complete"** when any type of construction or containment activity at the site has been completed or when the site qualifies for NPL deletion. Complex sites with ongoing cleanup activities that require long term treatment and monitoring are overseen by **"post construction completion activities"**. During this time, **five-year reviews** are requested to evaluate implementation and performance at sites where hazardous substance levels are higher than

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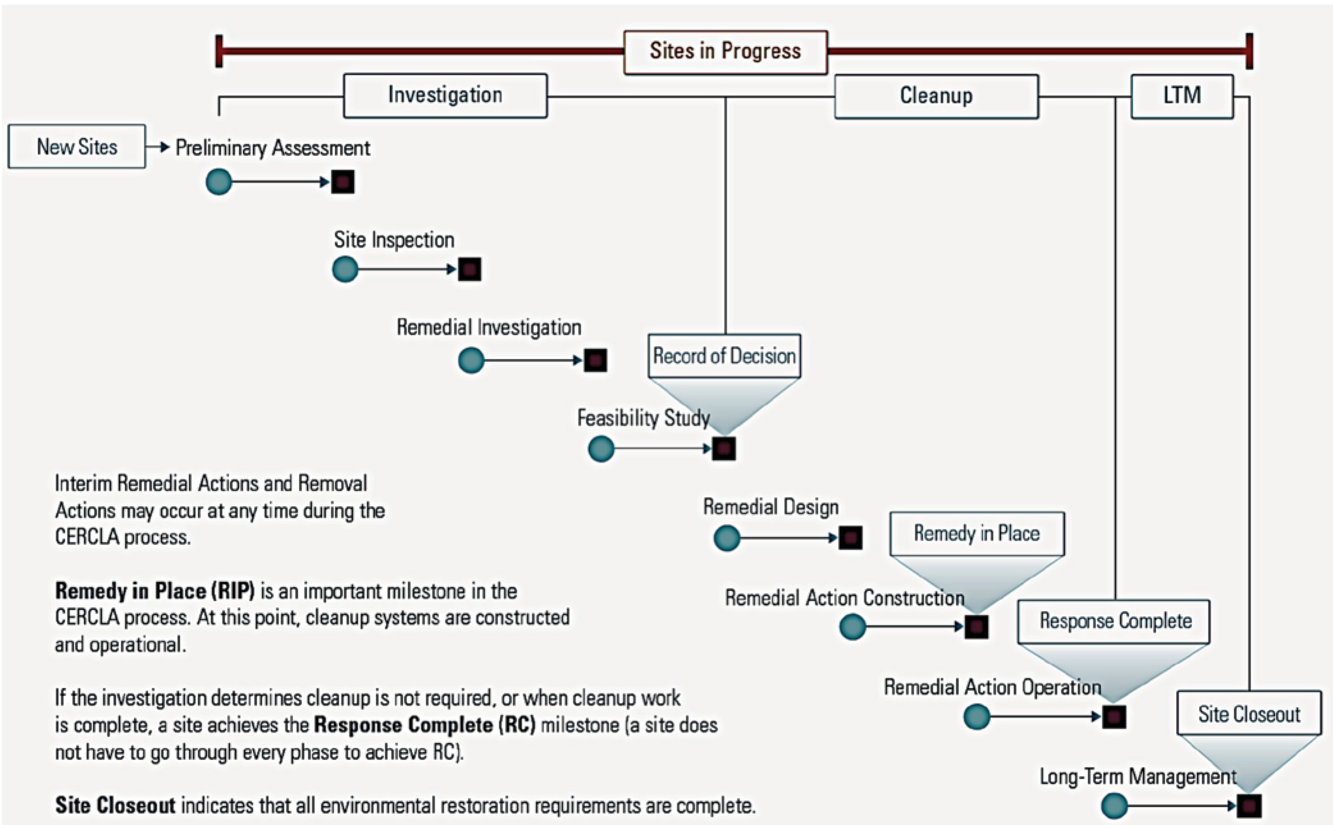

Figure 3. DoD CERCLA environmental restoration phases and milestones.
SOURCE: Figure from the National Academies Report (National Research Council 2013)

permitted. These reviews receive recommendations from the EPA, and aim to help determine whether the remedies in use protect human health and the environment. Finally, sites can be deleted from the NPL when the EPA, in conjunction with the State, considers that no further response action is needed to protect human and ecosystem health.

Remediation Technologies used for site restoration

Remediation technologies are techniques applied to impacted sites to achieve environmental restoration. Contaminated water, soil or sediments can be treated on site (*in situ*) or they can be removed and transferred to a different location for disposal or treatment (*ex situ*). Methods for restoration include biological, physical methods, chemical treatments, among others. *Ex situ* approaches that involve the **excavation** and removal of large quantities of water or soil are not ideal, transporting the hazardous materials imposes additional risk, cost and environmental impacts by adding to fossil fuel consumption and green house (CO_2) emissions. **Incineration** is subjected to technology-specific regulations and handling requirements because certain materials can only be incinerated offsite, while others produce ashes that require further stabilization impacting applicability and cost. Another remedy referred to as **"pump and treat"** is also considered an expensive, slow and energy-intensive technology. This process requires groundwater to be extracted out of the subsurface with vacuums pumps and then transferred to vessels where either chemical reagents are added for treatment or materials like activated carbon are used to absorb the contaminants. The addition of **chemical**

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additives for treatment *in situ* (to neutralize or precipitate the contaminants in place) can also be costly and considered a major capital investment, as the synthesis or purchase of these additives can be expensive and can create hazardous products that need subsequent disposal.

Conversely, the application of biological treatment using nature-encountered microorganisms (**bioremediation**) can be used to degrade toxic waste at impacted sites. Bacteria have thrived over three billion years on this planet having evolved effective mechanisms to gain energy by utilizing a wide variety of substrates, including hazardous chemicals. Microbes can use materials like gasoline, diesel and other hydrocarbons as "food" (carbon source) while others can "respire" compounds like carcinogenic chlorinated solvents, pesticides and radioactive waste (uranium) similarly as we humans respire oxygen (Löffler and Edwards 2006). An excellent example of microbiological processes aiding during environmental disasters was during the BP Deepwater Horizon, where indigenous marine bacteria degraded the oil plume to nearly undetectable levels within a few weeks of the spill (Hazen et al. 2010). Furthermore, bioremediation has proven effective in other massive spills like the Exxon Valdez in the coast of Alaska and the Gulf War oil spill (Atlas and Hazen 2011; Bragg et al. 1994; Thomas, Ellwood, and Longyear 1979; Höpner and Al-Shaikh 2008).

Table 1. Number of Federal and general sites for each status and milestone as of January 24, 2014:

Status	Non-Federal (General)	Federal	Total
Proposed Sites	49	49	53
Final Sites	1162	157	1319
Deleted Sites	358	17	375
Milestone	**Non-Federal (General)**	**Federal**	**Total**
Partial Deletions	42	18	60
Construction Completions	1085	72	1157

Analysis

Highlights and limitations of the Superfund Program

The Superfund Program has been considered the "world's most advanced hazardous waste program in the world" (Macey 2007), and its significance is portrayed in the Love Canal's story. A study led by researchers at the Massachusetts Institute of Technology deduced that Superfund cleanups had reduced the incidence of congenital anomalies by 20–25 percent (Currie, Greenstone, and Moretti 2011). Furthermore, since its inception, it has lowered the risks for cancer and poisoning of many citizens by reducing their exposure to hazardous substances. CERCLA has also increased knowledge on how to deal (planning and response) of accidents and established the Agency for Toxic Substances and Disease Registry (ATSDR) which nowadays conducts health surveys, assessment, surveillance and toxicological studies associated with exposure of hazardous chemicals. ATSDR also focuses on disseminating information via education and outreach initiatives, managing accessible databases of toxics incidents, and chemical profiles of substances of concern. By the end of FY 2013, the Superfund Program had controlled or reduced human exposure to contamination in 1,389 NPL sites, controlled groundwater contamination in 1,091 NPL sites and completed a cumulative total of 92,282 remedial assessments since the program's creation in 1980 (S. US EPA).

Superfund cleanups also have positive economic benefits. Mastromonaco (2001) showed the impact on property values in residences near a Superfund site; by looking at houses within 3 km of a site. Results indicated that houses increased in value by 7.3 percent after cleanups were completed (Mastromonaco 2011). Restored areas can also serve as sources of revenue, recreation and job creation; an example of this is the Anaconda Co. NPL site in Montana. At this site cleanup and restoration has included the removal of heavy metals in contaminated water and soil and the re-vegetation of more than 250 acres. EPA's coordinated efforts led to the creation of a park, trails and a golf course, which have then increased the commercial and residential growth in the area. (S. US EPA)

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The Superfund program has also been the center of many environmental debates, long scrutiny and criticism. One of the aspects is that sites take too long time to remediate (8-11 years in average but many linger in the NPL for decades, like the Love Canal) and residual contamination remains at least 126,000 sites (National Research Council 2013). Additional limitations include: insufficient information on sites that have been delisted but still have residual contamination, and the absence of resources (e.g., databases) to compare remedial technology performances across sites (National Research Council 2013). Recently, the situation with deleted sites has been referred as THE PARADOX OF "CLOSED" SITES. The EPA defines **site closure** as when "no further Superfund response is necessary to protect human health and the environment" while EPA's site closure guidelines include the intent to provide an approach for conducting five-year reviews at these sites (S. US EPA). However, the EPA states that a five-year review is only required when hazardous contaminants are left in place in levels higher than the current safety standards (S. US EPA). This contradiction in the current definition and language may confuse stakeholders as "operation and maintenance of a remedy may continue for many decades after closure" (National Research Council 2013). Other concern is that the **construction complete** milestone may be misleading to many, as it does not necessarily mean that restoration is completed or the levels of hazardous substances are safe. The presence of emerging contaminants (those substances that have not historically been considered as hazardous), can impose an additional problem when evaluating the level of contamination at a site. These chemicals, which are not yet regulated and their toxicity not yet completely understood, are a problem that could affect the Hazard Ranking System score given to a site and its inception or deletion as an NPL. Controlling "the unknown" is a challenge, plus it may lead to the selection and implementation of inadequate remedial responses.

A GAO report for FY 2010 investigated four Superfund sites deleted from the NPL. The investigation revealed gaps and errors in EPA's long-term monitoring reports and residual contamination at these sites that was previously unknown. The same GAO investigation also highlighted the following weakness in EPA's Superfund management: (1) not completing the performance evaluations of Superfund contractors, (2) not managing efficiently the recommendations of Five-Year Reviews (84 percent of the review recommendations were overdue), (3) fines and penalty billings were not consistently recorded, and (4) errors in internal receipts and/or expenditures totaling about $2.5 million were discovered. Since site assessment, investigation and clean up can cost up to be hundreds of millions of dollars (S. US EPA), it is imperative that EPA's oversight and management is strong and consistent.

Bioremediation as a possibility for Superfund remedial actions: principles and case studies

Bioremediation approaches include **natural attenuation**, a process that involves no intervention, letting natural occurring microbial communities degrade the contaminants, and **enhanced bioremediation** practices that require the application of procedures to promote the removal or containment of the hazardous substances. The methods of **bioestimulation** and **bioaugmentation** are among the most used *in situ* enhanced bioremediation procedures. During **bioestimulation**, injection of amendments are applied at the site to promote growth and activity of indigenous microbes; additions can include nutrients, oxygen (to promote the specific growth of aerobic microorganisms) and vegetable oil and molasses that serve as hydrogen supply to promote growth of anaerobic microbial populations. At times the site does not harbor the microorganisms capable of degrading or transforming the contaminants; in these cases **bioaugmentation** can be implemented by introducing microbial populations that are not native to the site but that can carry out the desired reactions. (Philp and Atlas 2005)

Bioremediation has the advantage of being a more cost effective technology (Saaty and Booth 1994; Wijensinghe et al. 1992; Philp and Atlas 2005). As reviewed by Megharaj et al (2011) bioremediation technologies are 80–90% cheaper than other approaches that rely merely on chemical or physical methods, and have been successfully applied in more than 400 areas in the United States (Megharaj et al. 2011). For example, the cost of cleaning 120 km of shoreline after the Exxon Valdez spill using biological methods resulted in less than a day's cost of performing physical washing (Philp and Atlas 2005). Furthermore, it has been estimated that applying non-biological approaches to remediate the current listed waste sites across the United States would cost around $750 billion (in a time frame of 30 years); while with bioremediation the cost would be an order of magnitude less, only $75 billion (Pimentel et al. 1997) . Finally, Hunter-Cevera (1998) projected that worldwide bioremediation approaches would cost $14 billion compared to $135 billion per year if other technologies were used (Hunter-Cevera 1998).

As previously stated, microbial-mediated bioremediation represents an alternative to degrade waste to benign products or to immobilize inorganic contaminants such as heavy metals and radionuclides. In the case of toxic chlorinated solvents, a recent review of 32 sites indicated that contaminant levels were reduced by 60–90% when *in situ* bioremediation approaches were implemented (Stroo et al. 2012). Another example is that of *Anaeromyxobacter dehalogenans*, a bacteria that can respire uranium. Although uranium cannot be biologically degraded or removed bacteria like *Anaeromyxobacter* can transform it, by reducing it from insoluble and mobile U(VI) to insoluble U(IV) oxide. This microbial reduction holds significant promise, as the insoluble uranium can then be contained in groundwater, preventing it from reaching aquifers and posing a human health risk. Bioestimulation can be achieved in these cases by the addition of acetate (diluted vinegar) to the subsurface, which will promote growth of uranium-reducing bacteria. Pilot studies have shown that this technique has a reduced cost when compared to pump and treat (U.S. Nuclear Regulatory Commission 2008).

Finally, two particular case studies of **sustainable *in situ* bioremediation** are listed below showing the benefits and potential of the technology.

A) In a chlorinated solvent contaminated site in Cape Canaveral (Kennedy Space Center), bioremediation and biostimulation were implemented with approaches to minimize the environmental footprint caused by the chosen clean-up remedy. Treatment was optimized in various ways including the use of solar powered units for water recirculation and strategic and careful selection of additives (for microbial growth) to avoid the need of multiple interventions. This strategic and greener approach resulted in less CO_2 equivalents released than technologies like pump and treat, air sparge and multiphase extraction (Daprato, R.C., J. Langenbach, R. Santos-Ebaugh, R. Kline)

B) Another case study is a DuPont site contaminated with approximately 10 million tons of toxic waste. At this site excavation, stabilization and bioremediation were considered, and after evaluation, bioremediation was selected. Compared to excavation, bioremediation would impose a lesser disturbance to the nearby community and represented a reduction of 2.5 million tons of CO_2.

Shortcomings of Bioremediation and possibilities on other Sustainable approaches

Although bioremediation is a promising technique it may not be applicable to all sites. Some of drawbacks of bioremediation are listed below:

1. Not all contaminants are biodegradable, example of these are 1,4-diozane and chloroform, which are recalcitrant chemicals.
2. The process is sensitive to the geochemical conditions at the site, and changes could lead to incomplete detoxification. Inhibitory conditions like certain chemicals, pH, temperature can inhibit biodegradation, these may be adjusted but can result in higher cost.
3. The response of biological systems cannot always be predicted which can lead to a longer restoration time.
4. Constant monitoring is needed to quantify the rate of biodegradation, and ensure that the right densities and levels of the organisms of interest are present.
5. Preliminary pilot studies and laboratory experiments are encouraged before the complete site is treated. These trials help in evaluating the feasibility of treatment but require time and funding to conduct the investigations.

Therefore, the nature of contamination and conditions at the site may require a different technology than bioremediation to restore the area, or a combined approach including biological, physical and/or chemical remediation methods. For example, after evaluating several methods to restore a landfill with vast soil contamination, excavation resulted in the most viable and sustainable approach. In this case, excavation was the most cost efficient method among the remedial options considered, and resulted in a third less CO_2 emissions and a shorter restoration time frame. Another case is the California Gulch Superfund NPL Site in Leadville, Colorado, an area impacted by past mining activities. At this Superfund site, an intelligent and strategic plan of remediation was implemented to minimize environmental disturbances. Excavation and offsite disposal was avoided and soil was treated *in situ*, therefore reducing air emissions associated with equipment work and transportation. Natural amendments present at the site (compost consisting of agricultural and forestry byproducts) were used for soil treatment instead of using synthetic materials (Kathleen S. Smith Katherine Walton-Day and Pietersen 2012; S. US EPA). Efforts were coordinated with Colorado's Division of Natural Resources, Colorado Department of Public Health and Environment, U.S. Fish and Wildlife Service, and the U.S. Bureau of Land Management.

Hence, it is clear that when evaluating treatment options, site-specific circumstances may not lead to bioremediation as the appropriate choice, but it is important that the techniques implemented are still cost-effective and also sustainable. This optimal decision-making process follows President Obama's Executive Order (EO) 13514, "Federal Leadership in Environmental, Energy, and Economic Performance" issued on October 5, 2009. EO 13514 calls for energy reduction, awareness of green technologies and practices "to establish an integrated strategy towards sustainability in the Federal Government". Following the EO, the EPA and Interstate Technology & Regulatory Council (ITRC) have published guideline documents for green remediation practices that provide an overview of the subject, current efforts and best practices (ITRC 2014; S. US EPA). These documents aim to "educate and inform state regulators and other stakeholders in the concepts and challenges" but **currently there is no regulation that specifically governs the green sustainable process.** Actually the ITRC report clearly states how "There is no industry-wide consensus on the definitions of the term "green and sustainable"; therefore, discussions on this area may not be addressing consistent concepts." The EPA has defined green remediation as "the practice of considering all environmental effects of remedy implementation and incorporating options to minimize the environmental footprints of cleanup actions" (S. US EPA) ; but this narrow definition leaves behind social and economic aspects. Bardons et al. (2011) as well as a recent NRC report have indicated the importance of considering those aspects as elements of sustainable development but yet "ethical and equity considerations, indirect economic costs and benefits, and employment and capital gain (among others) are not explicitly provided for in any cleanup statute or existing programs" (Bardos, Harries, and Smith 2011).

Research, education and innovation needs

It is the impression of many that there is a lack of collaboration between academia, the private sector (consultants, practitioners) and regulators (government) when it comes to Superfund sites. A recent National Academies report alluded to the impression that federal research funding for groundwater remediation has "generally declined over the past decade" (National Research Council 2013). This is not surprising since overall research investments by federal agencies has declined in the last years due to budget cuts and financial constraints (NSF 2014). During 1996-2011 the National Institute of Environmental Health Sciences (NIEHS) awarded funding of approximate $500-800 millions on research related to groundwater remediation (National Research Council 2013). But NIEHS gives funding to projects investigating the exposure and impacts of contaminants on human health; it does not fund research on contaminant removal or the implementation of remedial technologies. During the same time period, the EPA only awarded approximately $14 million; while most of the applied research on groundwater remediation in this area was funded by the Department of Defense (DoD) and the Department of Energy (DOE) with $315 and $138 million, respectively (National Research Council 2013).

The DoD supports field demonstrations, application and validation of technologies under their Environmental Security and Technology Certification Program (ESTCP) (DOD 2014a). DoD also funds basic research and development under the Strategic Environmental Research and Development Program (SERDP) (DOD 2014b). These programs are unique, providing funding to academia, the private and federal sector on a peer review, competitive basis. ESTCP is operated solely under DoD while SERDP operates in partnership with DOE and EPA, but EPA's support in recent years has been minimal. Programs like SERDP and ESTCP have opened many doors, for example vinyl chloride (a proven carcinogen and pervasive groundwater contaminant) was thought to be recalcitrant to biotic degradation. After much dedicated research, SERDP-funded investigators proved that bacteria can use this compound for growth and nowadays specific tools are addressed to monitor these microbes in vinyl chloride-contaminated sites during remediation efforts (He et al. 2003; Löffler and Edwards 2006). Therefore, more research is needed to decipher the toxicity, environmental fate, and removal of toxic chemicals, including those considered recalcitrant, unregulated or not yet completely understood. This is imperative as sites become more complex by the presence of emerging and multiple contaminants. Furthermore, research efforts need to encompass the molecular basis of chemicals under controlled laboratory studies, but also their behavior at bigger scales (e.g., pilot and field studies); it is in these scenarios where interdisciplinary efforts are most needed for righteous remedy implementation. Investigations leading to discovery and innovation of novel remediation procedures are crucial, but there's also constant need for optimization of classical environmental engineering technologies as more efficient and sensitive instruments are developed.

Research on remediation technologies can also turn a negative environmental incident into an opportunity for development. For example, if an investigator wants to find a bacterium capable of breaking down chloroform, having access to samples from a chloroform-contaminated site increases his chances of finding it, since natural processes (evolution and natural selection) would have already selected for microorganisms with those capabilities. In other words, scientists thrive on the opportunity to work with "unusual" samples that will give rise to discoveries, while the industry and community benefits from the applications of these findings for site restoration. Finally, without the right funding researchers cannot address the needs of practitioners at the sites, and correspondingly, practitioners and regulators will not keep pace with the latest cutting-edge technologies gestated at the laboratories of universities and research centers. For example, a responsible party or contractor may consider and choose more conservative methods instead of the latest "state to the art" sustainable and green technology due to misinformation and pressure, as EPA and CERCLA penalties are strict and can result up to $37,500 for each day of non-compliance. The isolation and miscommunication of "different professional and scientific cultures" is detrimental leading to stagnant practices and much longer cleanups of NPL sites.

Final Policy Recommendations:

To promote bioremediation practices and sustainable technologies:

- Government and private sector need to reach a consensus on the definition of sustainability and clarify the role of green remediation. Once a consensus is reached, specific regulations for green sustainable remediation can be drafted.
- Amend CERCLA to include sustainability criteria on remedy selection. The language should specify that after evaluation of all parameters, the remedy selected is not only efficient and cost effective but also sustainable.

- Create legislation that provides incentives to companies that voluntarily select and implement more sustainable remedial approaches, including bioremediation.

To foster education, research and development across all sectors especially with academia:

- Establish a Research Program (led by the EPA) that gives grants on a competitive basis to remediate projects at Superfund sites. For a proposal to get awarded it needs to show a united effort between the private sector, regulators, and academia; united in the restoration of a site.
- The SERDP-ESTCP Program should be a model to follow by other institutions to foster collaborations and dialogue to better link science with practice (e.g., promoting institutional innovations to develop and improve techniques for environmental monitoring assessment).
- Create more education and training programs for regulators and practitioners. It is the impression of many academics (who are in more close contact to the state-of-the-art, cutting edge techniques) that regulators (government) and practitioners simply don't know enough about the technologies, hindering the selection and implementation of bioremediations practices.

To improve management of contaminated sites:

- Track sites after they are deleted from the NPL, especially when those have indicatives of residual contamination.
- Require liable parties and contractors to file reports exclusively on their green remediation practices, environmental impact, remedial action procurement, as well as the cost and energy use.
- During the decision-making and remedy selection process, the anticipated land use should be considered.
- Follow an "adaptive management" that will allow decisional flexibility in the clean up process, as discussed by Cannon (2005).
- Firmly state that the remedy selected needs to serve not only the natural environment but also the surrounding community.
- Enforce oversight and adequate performance documentation to the contractors and liable parties.
- The creation of databases that can be used to compare the effectives of different technologies at different sites.

To improve strategies for sustainable remediation implementation:

- Establish incentives to promote the selection and implementation of bioremediation and other sustainable approaches (e.g., reduce fines for those liable parties that choose green remediation over other technologies).
- Standardize and reach a consensus on the metrics used to measure green and sustainable remediation actions (e.g., CO_2 emissions, use of renewable energy, environmental impact footprint, and community job creation).
- Reduce the use of natural resources (e.g., water), maximize use of renewable sources while considering social and economic impact. Identify innovative and optional uses for onsite materials and byproducts otherwise considered waste.
- Educate and train the local workforce (especially low income communities and minorities) on remedial technologies. This opens doors for quicker cleanups, job creation and better social relationships leading to community empowerment.

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