Assessing the Economic and Societal Benefits of SRP-Funded Research

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BACKGROUND: The National Institute of Environmental Health Sciences (NIEHS) Superfund Basic Research and Training Program (SRP) funds a wide range of transdisciplinary research projects spanning the biomedical and environmental sciences and engineering, supporting and promoting the application of that research to solving real-world problems.

OBJECTIVES: We used a case study approach to identify the economic and societal benefits of SRP-funded research, focusing on the use of potentially hazardous substance remediation and site monitoring tools. We also identified successes and challenges involved in translating SRP grantees’ research findings and advances into application.

DISCUSSION: We identified remediation and detection research projects supported by the SRP with the most potential for economic and societal benefits and selected 36 for analysis. To examine the benefits of these applied technologies, we interviewed 28 SRP-supported researchers and 41 partners. Five case studies emerged with the most complete information on cost savings—total savings estimated at >$100 million. Our analysis identified added societal benefits such as creation of small businesses, land and water reuse, sustainable technologies, exposure reduction, and university—industry partnerships.

CONCLUSIONS: Research funded by the SRP has yielded significant cost savings while providing additional societal benefits. https://doi.org/10.1289/EHP3534

Introduction

Since its inception in 1987, the National Institute of Environmental Health Sciences (NIEHS) Superfund Basic Research and Training Program (SRP) has brought together researchers from the biomedical and environmental science and engineering fields (NIEHS 2018). SRP researchers work together to study the health effects of potentially hazardous substances and to investigate effective and sustainable ways to clean up those substances at hazardous waste sites (Landrigan et al. 2015; Henry and Suk 2017).

The SRP was established by the U.S. Congress to provide scientific support for the U.S. Environmental Protection Agency (EPA) and the Agency for Toxic Substances and Disease Registry (ATSDR) via the Superfund Amendments and Reauthorization Act (SARA) of 1986. SARA established a broad mandate and a set of objectives for the NIEHS to pursue within the SRP. Those objectives include the development of (a) advanced techniques for the detection, assessment, and evaluation of the effects on human health of hazardous substances; (b) methods to assess the risks to human health presented by hazardous substances; (c) methods and technologies to detect hazardous substances in the environment; and (d) basic biological, chemical, and physical methods to reduce the amount and toxicity of hazardous substances (NIEHS 2015a).

The cornerstone of the SRP is the university-based, multiproject center grant program. SRP centers build teams of scientists and engineers from different disciplines to address issues related to reducing exposures to potentially hazardous substances, reducing environmental cleanup costs, and improving public health. The SRP places importance on research translation, putting research findings into the hands of the stakeholders who need them; this is done through efforts that include promoting application of research and moving technologies to the field (NIEHS 2015b).

The time between developing novel technologies and achieving economic and societal benefits can create challenges for quantifying the resulting benefits (Guinea et al. 2015). We contend that a first step in determining and understanding the full range and breadth of the economic and societal benefits of SRP research is to examine SRP-funded projects from their research findings to application and to identify benefits that may stem from this application. In this commentary, we focused our assessment on remediation and site monitoring technologies aimed at addressing the SARA mandate to develop methods to reduce the amount and toxicity of potentially hazardous substances.

Identifying Benefits

Remediation research supported by the SRP places a focus on developing new technologies or methods to reduce or eliminate exposure to suspected hazardous substances that are faster, less expensive, and better than existing approaches. When selecting a remediation approach, a cost–benefit analysis of available remediation technologies is important. Some of these analyses focus on direct costs, such as comparing the costs of copper-recovery approaches with the financial benefits of selling recovered copper (Volchk et al. 2017). Others extend beyond the remediation process to cover potential liabilities, employment gains/losses, and damages averted (Farr et al. 2016; Hardisty et al. 2006; Wan et al. 2016).

In addition to typical measures of economic impact, we incorporated the unique and varying contributions of university-based research into a case study–based approach that includes societal and economic benefits criteria (Milat et al. 2015; Salter and Martin 2001). For this commentary, we identified applications of SRP-funded projects with evidence of saving public or private funds or of reducing exposures to potentially hazardous substances. We also examined projects that have applied their research to create new companies, to pursue patents and licensing of technologies, to create new scientific instruments and methods, to form partnerships with stakeholders or with other researchers, to increase capacity for scientific and technological problem solving, and to train skilled graduates.
We identified 36 remediation, site monitoring, and detection research projects that met one or more of these criteria. We followed up with 28 researchers whose projects satisfied the criteria to learn more about the process that led to the application of their research in the field. Of note, a majority of the 28 were performing work with a goal of saving public or private funds and are in the process of developing technologies with potential cost-saving applications. We also followed up with relevant contacts in U.S. government agencies (19) and in the private sector (22), whom the researchers identified and/or who were involved at a site where the technology was applied, for a total of 69 primary and follow-up interviews.

Based on these interviews, we identified five research projects with the most complete information available on cost savings. These five projects serve as our case studies discussed below. The case studies demonstrate how SRP’s support of basic research has provided fundamental knowledge to develop and apply these technologies. The case studies also provide evidence that the integrative research environment within the multidisciplinary centers has encouraged collaboration and has facilitated innovation.

Our assessment focused on implementation of new remediation and detection technologies aimed at reducing exposures. The recent Lancet Commission on pollution and health comprehensively assessed the impacts of air pollution and found massive economic impacts on productivity and health care costs (Landrigan et al. 2018). That report highlighted how investing to reduce exposures can yield far-reaching human health and economic benefits.

In our assessment, we examined the cost savings achieved by new technologies that produced the same or better results compared with conventional technologies. These savings reflect a low-end estimate of cost savings that does not consider the additional benefits of reduced pollution, which may be realized when a new technology is more efficient or effective. However, trying to capture those additional benefits is difficult and, at this stage, would be speculative.

Discussion

Case Studies with Documented Economic Benefits

Here, we present five case studies that highlight SRP-funded projects with the most complete information on cost savings. These projects also show the breadth of remediation and detection research funded by the SRP.

Case study 1: Phytoremediation with hybrid poplar and cypress trees. Researchers led by Milt Gordon, Ph.D., and Lee Newman, Ph.D., at the University of Washington (UW) SRP Center pioneered the use of hybrid poplar trees to remove trichloroethylene (TCE) and other chlorinated contaminants from groundwater. TCE is a known human carcinogen that is widely used as a metal degreasing agent and has been found in groundwater at many military and Superfund sites (National Toxicology Program 2016). The research from this project was the first to show conclusively that plants themselves, not just microorganisms associated with plants, are capable of degrading toxic compounds (Newman et al. 1997).

With SRP funding, the researchers demonstrated that hybrid poplars could take up and degrade TCE under greenhouse and laboratory conditions (Newman et al. 1997). They then demonstrated the poplar’s potential for in situ remediation of TCE in the field. Results from a controlled field study showed that trees removed >99% of TCE present in groundwater and that <9% of the TCE transpired from the trees to the atmosphere (Newman et al. 1999).

The phytoremediation system was installed as part of a remediation plan for the cleanup of a Superfund site at the Undersea Naval Warfare Center at Keyport, Washington, to treat TCE-contaminated groundwater leaching from a wetland (Gordon et al. 1997; Newman et al. 1997; Naval Undersea Warfare Center Division 1998). The Naval Undersea Warfare Center Division estimated that the phytoremediation method with trees would cost $3.5 million, whereas more traditional containment methods, including source treatment and removal with aquifer flushing, would cost between $12 million and $14 million. They applied hybrid poplars to the site, which saved an estimated $8.5 million to $10.5 million compared with traditional methods (Naval Undersea Warfare Center Division 1998). The University of Washington continued to study the hybrid poplars on the Keyport site for several years to better understand how the plants take up and metabolize contaminants under real-world conditions and to gain a better understanding of the practical applications of this technology (NIEHS 2002).

In 2001, the U.S. EPA Regional Ground Water Forum released an issue paper on phytoremediation intended for remedial project managers, on-scene coordinators, and others involved in remediation of hazardous waste sites (Pivetz 2001). The report highlights the hybrid poplar approach to degrading TCE and cites Gordon and Newman’s original laboratory results as well as findings from a controlled field study they conducted at a site outside of Fife, Washington (Newman et al. 1997, 1999).

Building off the original SRP-funded research to clean up TCE with hybrid poplar trees, the U.S. EPA used hybrid poplar trees at the Argonne National Laboratory in Batavia, Illinois, saving an estimated $2.4 million (U.S. EPA 2005). A groundwater treatment system using a short-rotation woody crop of hybrid poplars was also demonstrated at Carswell Golf Course within the Naval Air Station Joint Reserve Base, formerly Carswell Air Force Base, in Fort Worth, Texas (L. Newman, oral communication, July 2016; U.S. DoD 2006a). The technology was validated as part of the U.S. Department of Defense’s (DoD’s) Environmental Security Technology Certification Program (ESTCP). The summary of the ESTCP report states, “The hybrid poplar trees used in this study validate an inexpensive alternative method to process and ‘clean’ chlorinated hydrocarbon-contaminated soil and groundwater” (U.S. DoD 2006a). According to the ESTCP estimates, as many as 1,000 U.S. DoD cleanup sites worldwide could use this technology, saving hundreds of millions of dollars (U.S. DoD 2006a).

Case study 2: Vadose-zone characterization technology. Researchers led by Mark Brusseau, Ph.D., at the University of Arizona SRP Center developed a new set of methods to characterize contaminants in the vadose zone, a part of the subsurface that lies above the groundwater table where soil and rocks are not fully saturated with water. The approach can provide a more accurate measurement of vapor-phase contaminant mass discharge, characterize mass-transfer conditions, and provide a higher-resolution characterization of the groundwater source distribution (Brusseau et al. 2010, 2013, 2015; Mainhag et al. 2015). By analyzing contaminant mass discharge, Brusseau and his research team help to better understand the distribution of contaminants at a site, which can influence assessments on the effectiveness of remediation efforts and whether they are still needed (Brusseau et al. 2011). According to Brusseau, results from the initial SRP work were used to leverage additional funding through the U.S. Department of Energy (DOE) and the U.S. DoD (M. Brusseau, oral communication, May 2016).

Soil vapor extraction (SVE) can remove volatile contaminants in high-permeability regions of the vadose zone. However, after SVE has been operating for a while, remaining contamination is located primarily in the lower-permeability zones (Carroll et al. 2012). Brusseau and his team developed methods using data collected at the U.S. DOE’s Hanford site in Washington state during cyclic operation of SVE systems to characterize the magnitude and time scale of the rate of mass flow per area, or mass flux, associated.
with vadose zone contaminant sources (Brusseau et al. 2010). Follow-up testing and demonstration of the methods were conducted at a Tucson, Arizona, site on the National Priorities List (NPL), which documents hazardous waste sites eligible for long-term remedial action (Brusseau et al. 2015; Mainhag et al. 2015).

Working with the Pacific Northwest National Laboratory, the researchers assessed the SVE performance at the Hanford site. Using his modeling strategy to calculate the source mass discharge over time, Brusseau and his team estimated that the mass discharge rate of carbon tetrachloride was expected to decrease to a rate that corresponds to the groundwater cleanup goal within 40 y after the termination of SVE operations, well within the proposed groundwater remedy timespan (Truex et al. 2012; U.S. DOE 2016). The new characterization approach provided more information about the contaminant mass discharge and decreased the amount of work needed for remediation at the site; the U.S. DOE estimated that the approach led to a projected cost savings of $6.35 million (U.S. DOE 2012).

Brusseau and colleagues have used similar tools to assess remediation efforts for groundwater contamination. For example, they have assessed the efforts at the Tucson International Airport Area Superfund site. They projected that the implementation of source-zone remediation efforts, namely in situ chemical oxidation and soil vapor extraction methods, which cost approximately $15 million and were being used at the site, eliminated approximately 50 y of pump-and-treat operations, which cost roughly $1 million per year (Brusseau et al. 2011). Work is also underway at the Monument Valley Department of Energy site in Arizona to determine whether active remediation is needed for identified groundwater contamination (M. Brusseau, oral communication, May 2016).

**Case study 3: Activated carbon to clean up contaminated sediment.** University of Maryland, Baltimore County researcher Upal Ghosh, Ph.D., and colleagues developed a technology for in situ remediation of polychlorinated biphenyls (PCBs) in sediments. The technology involves altering native sediment geochemistry by amending it with activated carbon to reduce the bioavailability, or the ability of organisms to uptake pollutants such as PCBs. SRP grantee Richard Luthy, Ph.D., and Ghosh performed initial studies on in situ sediment amendments at Stanford University (Ghosh et al. 2011) and patented a method to stabilize persistent organic contaminants using carbon sorbents in 2006 (Luthy and Ghosh 2006). Based on this method, Ghosh codified a technology to efficiently deliver amendments to sediments with colleague Charlie Menzlie, Ph.D., through a U.S. EPA Small Business Innovation Research program grant (U.S. DoD 2016b). Ghosh has credited SRP with bringing this previously developed technology into the crucial stage of field application (U. Ghosh, oral communication, June 2016).

The technology, called SediMite™, uses activated carbon in a special pellet form for a low-impact delivery of sorbent amendments to sediments, reducing or eliminating the need for expensive dredging and hauling. The SediMite™ pellet allows for easy application of the amendment in lakes, rivers, and wetlands (Sediment Solutions 2017). SediMite™ is patented (Ghosh and Menzlie 2010) and sold through Sediment Solutions.

The technology also has been validated through a pilot study in Canal Creek, Aberdeen Proving Grounds, Maryland. Based on field-collected sediments or wetland soils, SediMite™-applied activated carbon significantly reduced the bioavailability of PCBs and other persistent organic pollutants over the period of the pilot study with negligible adverse effects on native benthic invertebrate communities (U. DoD 2016a).

The technology was implemented in full scale to remediate a 5-acre lake in Dover, Delaware, in 2013 and has been selected as a component of the cleanup strategy for a contaminated sediment site in Middle River, Maryland. The activated carbon strategy includes removing contaminated sediment from >12.5 acres and in situ treatment over an additional 8.5 acres (Lockheed Martin 2016). The feasibility study for the remediation of the Middle River Complex noted that the remedy they selected, involving in situ treatment with activated carbon, would be approximately $22 million cheaper than complete removal of contaminated sediment (Tetra Tech Inc. 2013). This technology is being evaluated in feasibility studies and has been listed as a component of the selected remedy in several U.S. EPA Records of Decision for Superfund sites, including the Lower Duwamish Waterway and the Housatonic River (U.S. EPA 2014a, 2014b).

**Case study 4: Steam-enhanced extraction method.** As a professor at the University of California (UC), Berkeley, Kent Udl, Ph.D., developed a technology that enhances remediation by injecting steam into the subsurface and extracting volatile organic compounds (VOCs). Steam injection, also known as steam-enhanced extraction (SEE), enhances recovery of contaminants by volatilization, evaporation, and steam distillation of semivolatile and volatile agents (Stewart and Udl 1988).

As an SRP grantee, Udl refined and tested the steam injection method to accelerate remediation of TCE, coal tars, creosote, and other contaminants in groundwater (Udl 1996, 1998a, 1998b; Kingston et al. 2010). His first full application of the SEE method was at the Southern California Edison site in Visalia, California. An innovative full-scale SEE system, consisting of 15 injection wells, was installed to enhance removal of contaminants in soil and groundwater (U.S. EPA 2010). This application, which operated between May 1997 and June 2000, resulted in the successful removal of 1.3 million pounds of creosote from the groundwater (U.S. DoD 2006b). The site was deleted from the NPL on 27 August 2009 (U.S. EPA 2010).

The SEE system increased the rate of contaminant recovery >1,000-fold compared with the continuous pump-and-treat method, shortening the cleanup time from thousands of years to 4 y (C. Eaker, oral communication, January 2017; U.S. DoD 2006b). Thus, using SEE, the site was fully cleaned up at a cost of approximately $30 million (U.S. DoD 2006b; Stark 2009)—roughly $50 million less than the original estimate by Edison International, the responsible party (Edison International 1997).

The technology has been applied successfully at ≥ 18 other sites in the United States and overseas (TerraTherm, Inc., personal communication, March 2017), including Williams Air Force Base, where it removed >2.6 million pounds (>1.1 million kilograms) of contaminants (U.S. Air Force Civil Engineer Center 2017). TerraTherm, Inc. continues to successfully apply this technology for soil and groundwater remediation (TerraTherm, Inc. 2018).

Senior U.S. EPA staff have referred to this system as the “gold standard” for highly VOC-contaminated groundwater remediation (J. Cummings, oral communication, November 2016).

**Case study 5: Bioremediation of methyl tert-butyl ether (MTBE).** With SRP funding, Kate Scow, Ph.D., and her team at the University of California, Davis SRP Center isolated the *Methylibium petroleiphilum* PM1 bacterial strain, which can completely degrade methyl tert-butyl ether (MTBE) (Bruns et al. 2001; Hanson et al. 1999; Hristova et al. 2001). MTBE is a chemical compound once commonly used in the United States as a fuel additive in gasoline. Although the use of MTBE in fuel helped to reduce harmful air emissions, accidental releases and spills have contaminated surface water and groundwater (U.S. EPA 2017).

Researchers led by Scow, in collaboration with other research groups, sequenced the genome of PM1 (Kane et al. 2007) and other contaminants in groundwater (Hristova et al. 2010). His first full application of the SEE method was at the Southern California Edison site in Visalia, California. An innovative full-scale SEE system, consisting of 15 injection wells, was installed to enhance removal of contaminants in soil and groundwater (U.S. EPA 2010). This application, which operated between May 1997 and June 2000, resulted in the successful removal of 1.3 million pounds of creosote from the groundwater (U.S. DoD 2006b). The site was deleted from the NPL on 27 August 2009 (U.S. EPA 2010).

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Researchers led by Scow, in collaboration with other research groups, sequenced the genome of PM1 (Kane et al. 2007) and characterized its MTBE degradation pathway (Hristova et al. 2007; Schmidt et al. 2008).
Their discovery that the PM1 strain frequently occurs naturally led the group to examine if shifting aquifer geochemistry can stimulate its activity to break down MTBE more efficiently without the need to inoculate the site with additional bacteria (Hristova et al. 2003). The PM1 strain degrades MTBE in groundwater via aerobic mineralization, and engineers can boost the effectiveness of bacteria that are already at the site by adding more oxygen and simple nutrients. This approach eliminated the need to purchase bacteria through vendors—at significant cost—to inoculate the site.

In collaboration with Haley & Aldrich, Inc., an engineering and environmental science consulting firm, the researchers applied the technology at the North Hollywood Tesoro Petroleum site in California. Before the treatment, MTBE concentrations were >10,000 ppb in groundwater. The plume was migrating toward and potentially threatening municipal supply wells. The team identified the presence of PM1 and set up a self-seeded field-scale bioreactor for treating the MTBE-affected groundwater (Hicks et al. 2014).

The bioreactor at North Hollywood achieved highly efficient MTBE and tert-butyl alcohol removal in a relatively short time frame. As a result, the California Regional Water Quality Control Board approved a scale-up of the bioreactor after approximately one year of operation. In 2005, the research team increased system capacity to ensure continuous MTBE degradation. The full-scale bioreactor operated as the sole groundwater remediation activity at the site from 2005 until 2008 when the off-site portion of site remediation was completed. Once on-site soil vapor extraction remediation was deemed complete, the entire site was closed in 2011 (Hicks et al. 2014).

Bioremediation decreased groundwater MTBE at North Hollywood from >10,000 ppb to <1 ppb in 3 y. A significant unanticipated outcome was the regulatory permission to return the water treated through this bioremediation process back into a California drinking-water aquifer. The bioreactor removed approximately 134 kg of MTBE from 164 million liters of water, with >113 million liters of treated water reinjected back into the aquifer (Hicks et al. 2014).

In addition to treating the water more quickly and reaching levels that allowed for reuse, the technology also resulted in $14 million to $21 million in cost savings because it eliminated the need to drill two to three replacement wells at the site, which would have cost approximately $7 million each (Paul Tornatore, Principal Consultant, Haley & Aldrich, written communication, February 2017). The technology has also been applied at >12 other contaminated sites (Paul Tornatore, Principal Consultant, Haley & Aldrich, oral communication, February 2017).

### Additional Benefits

In our assessment of the 36 projects, we also found information on other benefits stemming from SRP-funded research projects.

#### Creation of small businesses that promote site assessment and cleanup

Several SRP-funded technologies are being piloted in the field and have led to partnerships, small business start-ups, or both. These small businesses are focused on technologies to improve site remediation or tools to monitor contaminants. For example, Jay James, Ph.D., successfully developed a prototype of a portable sensing platform to detect mercury, resulting in a small business spin-off, which started from an SRP-funded project at the UC Berkeley SRP Center (Mishamandani 2014; Picoyune 2017).

#### Water and land reuse

Some of the research projects led to cleanup of a site or remediation of groundwater, resulting in water or land reuse that may not have been possible with conventional technologies. For example, in North Hollywood, California, Scow’s bioremediation method cleaned up 113 million liters of water to a level where it could be added back into a drinking-water aquifer, providing California with valuable water resources (Hicks et al. 2014).

### University–industry partnerships to improve site cleanup

In some cases, SRP researchers have formed collaborations with industry and have leveraged industry funds to build on their work. For example, in a project led by Raina Maier, Ph.D., University of Arizona researchers are working with mining companies to test ways to minimize the amount of amendments and soil cover needed to successfully revegetate an area above a mining site, which can drastically reduce revegetation costs. After a 2-y industry–university research period, the three mining industry partners were pleased with the results and renewed their contracts in June 2016, agreeing to cover 100% of the research costs moving forward (R. Maier, oral communication, June 2016; University of Arizona SRP Center 2016).

#### Innovative “green” technologies

The SRP supports sustainable remediation technologies that are cost effective and that are appreciated by local communities (Henry and Suk 2017). Many of these technologies are still in development. For example, researchers led by Akram Alshawabkeh, Ph.D., at Northeastern University are developing a solar-powered remediation system to remove TCE from groundwater. They are evaluating the cost effective and sustainable in situ electrochemical process, which uses a solar panel for power, for potential field application (Fallahpour et al. 2016).

#### Serendipitous discoveries that translate to other fields

Some SRP-funded projects have led scientists and engineers to other discoveries outside the scope of SRP research. For example, SRP researchers led by Joan Currie, Ph.D., at the University of Arizona were working to develop an iron carbonate material to sequester arsenic and other metals from soil. They found that this material may be a good alternative to concrete because it is stronger and more flexible, and it can also absorb and trap carbon dioxide, making it a carbon-negative material (NIEHS 2007). Dave Stone, Ph.D., the student working on the project, is reportedly in the early stages of further developing and commercializing the concrete technology (Neithalath et al. 2016; IronKast 2017).

### Themes and Considerations Moving Forward

#### Documenting research benefits can be challenging

Because the time between technology development and realization of benefits can be long (Guinea et al. 2015), we found many projects that are in the process of testing or applying technologies that have potential for substantial benefits in the future. However, many of them have not reached the point where cost savings can be calculated. Cost savings from site monitoring technologies can also be difficult to determine because many of them are not listed as part of the site remedy. In addition, attribution of key contributors to outcomes and multiple funding sources for research projects make it difficult to associate benefits to specific research programs.

Application of technologies after their initial use in the field is difficult to track. Researchers often do not follow technology after its initial application. Because there is not a centralized method of identifying tools and technologies that have been used to clean up hazardous waste sites, a researcher may not know that his or her technology has been taken up by a site manager/ assessor and used at other locations. New technologies may be used at nearby sites or by the same site managers but may not extend beyond that region.

Benefits of negative research results that save money are also difficult to document. In one project, money was saved because researchers used an SRP-funded method to test the proposed remediation technology for a site and found no mechanistic evidence that applying the proposed technology could achieve the desired cleanup goals (S. Chilrud, oral communication, May 2016). This
finding saved the time and money that would have been lost had the application of the technology moved forward, but these cost savings are hypothetical and are difficult to quantify.

Patent success does not equate to successful field application of a technology. SRP-funded researchers have obtained >150 patents for biomedical tools, therapeutic approaches, remediation tools, sensors and detectors, and alternative energy approaches (NIEHS 2010). Some of these technologies are being developed as commercial applications by spin-off companies.

However, some factors beyond the quality or potential of a research project discourage patent filings among researchers and institutions (The Economist 2015). The patent application process is lengthy and costly. Some researchers are uncertain of the benefits of patents, and some said they felt the patent process would inhibit or delay application of their research.

Patents are often filed when a product is still years from application, and only approximately 5% of patents are licensed at universities (Ledford 2013). Consistent with this finding, only a few patents from SRP research have been licensed for commercial application.

SRP efforts support fundamental and transdisciplinary research and training. Researchers noted that the SRP is a key player in supporting basic and applied research for new remedial and site monitoring technologies. In addition, the SRP framework brings together distinct scientific disciplines. One researcher noted how the SRP facilitated an interaction between engineers and microbiologists, which helped to advance a technology related to bioremediation (L. Abriola, oral communication, August 2016). She added that they would not have been able to do that work without SRP support. Another researcher noted that the SRP has successfully supported “risky” technologies, which may be in very early stages of development, that end up promoting innovation and saving money (R. Halden, oral communication, June 2016).

Grantees also emphasized that the SRP provides an excellent platform for grantees to gain experience in problem-solving, solution-oriented investigations. Grantees are encouraged to conduct research in a highly collaborative environment and often work with stakeholders when their projects involve field testing or application (Carlin et al. 2018). The SRP supports research translation, which includes support for assistance on how to commercialize technologies. These wide-reaching networks, like those fostered by the SRP, may be an effective way to share resources and experiences to assist researchers in the commercial realm.

Conclusion

Across many SRP projects, we found examples of how identifying and nurturing cutting-edge transdisciplinary research projects is key to developing new tools and technologies that could save money. It often takes time for researchers to develop partnerships and for the benefits of the research to be realized (Guinea et al. 2015). We contend that funding these projects for periods long enough to support development and application encourages researchers to follow the trajectory of their work. Furthermore, this support may help funding organizations identify the long-term benefits of their investments.

By documenting economic and societal benefits, we also provide insight into how SRP-funded basic research establishes a foundation of knowledge that can be built upon and translated to real-world applications. We found that the use of a customized case study approach to capture examples of how the SRP is addressing one of its mandates—namely, to develop basic biological, chemical, and physical methods to reduce the amount and toxicity of potentially hazardous substances in the environment—was valuable in identifying a diverse range of research outcomes and identifying technologies that provide faster and/or cheaper remediation of potentially hazardous substances. In addition to creating tools that are more cost effective, we also found that SRP-funded researchers provide sustainable solutions that decrease exposures, create collaborative research networks and small businesses, and increase our understanding of potentially hazardous substances.

Our assessment revealed the difficulty of obtaining information on how research findings and technologies are used beyond the aims of a research grant. Nonetheless, it is important to make the connections along the trajectory from fundamental knowledge to application in order to reduce or eliminate exposures to suspected hazardous substances and improve public health. We believe future efforts can be made to refine the research evaluation process so that the value of research can be appreciated. Translation of research findings is a critical component of the SRP. The shared successes and insights we have gained through this process have helped to support application of technologies from the bench to the field. Lessons learned from this approach might be applied to improve benefit analyses in the future by improving data collection during research, technology development, and its application.

This is just the first stage of a project to identify the benefits of SRP-funded research over the last 30 y. In addition to estimating cost savings from new detection and remediation tools, estimating cost savings associated with public health benefits is also important—and is an avenue to explore moving forward.

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References

Bruns MA, Hanson JR, Mefford J, Scow KM. 2001. Isolate PM1 populations are dominant and novel methyl tert-butyl ether-degrading bacteria in compost biotower enrichments. Environ Microbiol 3(3):220–225, PMID: 11321556, https://doi.org/10.1046/j.1462-2930.2001.00184.x.

Brusseau M, Carroll K, Truex M, Becker D. 2013. Characterization and remediation of chlorinated volatile organic contaminants in the vadose zone. Vadose Zone J 12(4): PMID: 2383058, https://doi.org/10.2136/vzj2012.0137.

Brusseau ML, Hatton J, DiGuiseppi W. 2011. Assessing the impact of source zone remediation efforts at the contaminant-plume scale through analysis of contaminant mass discharge. J Contam Hydrol 129(1–4):130–139, PMID: 22115000, https://doi.org/10.1016/j.jconhyd.2011.08.003.

Brusseau ML, Mainhagu J, Morrison C, Carroll KC. 2015. The vapor-phase multi-stage CMD test for characterizing contaminant mass discharge associated with VOC sources in the vadose zone: application to three sites in different life-cycle stages of SVE operations. J Contam Hydrol 179:55–64, PMID: 26047819, https://doi.org/10.1016/j.jconhyd.2015.05.006.

Brusseau ML, Rohay V, Truex MJ. 2010. Analysis of soil vapor extraction data to evaluate mass-transfer constraints and estimate source-zone mass flux. Ground Water Monit Remediat 30(3):57–64, PMID: 23516336, https://doi.org/10.1111/j.1745-6993.2010.01286.x.

Carlin DJ, Henry H, Heacock M, Trottier B, Drew CH, Suk WA. 2018. The National Institute of Environmental Health Sciences Superfund Research Program: a model for multidisciplinary training of the next generation of environmental health scientists. Rev Environ Health 33(1):53–62, PMID: 29059938, https://doi.org/10.1515/reveh-2017-0024.

Carlock KC, Ostrom M, Truex MJ, Rohay VJ, Brusseau ML 2012. Assessing performance and closure for soil vapor extraction: integrating vapor discharge and impact to groundwater quality. J Contam Hydrol 128(1–4):71–82, PMID: 22192346, https://doi.org/10.1016/j.jconhyd.2011.10.003.

Edison International. 1997. “Quarterly Report Pursuant to Section 13 or 15(d) of the Securities Exchange Act of 1934 for the Quarterly Period Ended March 31, 1997.” Washington, DC: Securities and Exchange Commission. http://services.corporate-ir.net/SEC/DocumentService?id=F3yYdD1hSFwY0Y4rVdwywRnhdUwZwR1c1mcGybBZ2Wep7GIOdmZdT0t0M2Y1yc5eFpDNXh5EEwVWdDMSFfXDKyYDqJFUmjacGHNrm5sVDBX7pF608ET1W1M12zyJys1BUVTmdHlXZT0yJmZuPTMzMTA4My5wZGY= [accessed 9 April 2018].
Truex M, Carroll K, Rohay V, Mackley R, Parker K. 2012. “Treatability Test Report: Characterization of Vadose Zone Carbon Tetrachloride Source Strength Using Tomographic Methods at the 216-Z-9 Site.” PNNL-21326. Richland, WA: Pacific Northwest National Laboratory. https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-21326.pdf [accessed 9 April 2018].

U.S. Air Force Civil Engineer Center. 2017. Environmental Action Update: Air Force Environmental Activities at Williams. http://www.afcec.af.mil/Portals/17/documents/BRAC/Williams/AFD-170119-001.pdf?ver=2017-01-19-121924-317 [accessed 10 April 2018].

U.S. DoD (U.S. Department of Defense). 2008a. “Environmental Security Technology Certification Program: Plant Enhanced Bioremediation of Contaminated Soil and Groundwater.” ER-199519. Alexandria, VA: Strategic Environmental Research and Development Program (SERDP)/Environmental Security Technology Certification Program (ESTCP). www.serdp-estcp.org/Program-Areas/Environmental-Restoration/Contaminated-Groundwater/ER-199519 [accessed 9 April 2018].

U.S. DoD. 2008b. “Unified Facilities Criteria (UFC): Design: In Situ Thermal Remediation.” UFC 3-280-05. Washington, DC: U.S. Department of Defense. https://frtr.gov/costperformance/pdf/remediation/USACE-In_Situ_Thermal_Design.pdf [accessed 9 April 2018].

U.S. DoD. 2016a. “A Low-Impact Delivery System for In Situ Treatment of Sediments Contaminated with Methyl Mercury and Other Hydrophobic Chemicals.” ER-200835. Alexandria, VA: Environmental Security Technology Certification Program (ESTCP). https://www.serdp-estcp.org/content/download/39402/379263/file/ER-200835-CP.pdf [accessed 9 April 2018].

U.S. DoD. 2016b. “Evaluating the Efficacy of a Low-Impact Delivery System for In Situ Treatment of Sediments Contaminated with Methylmercury and Other Hydrophobic Chemicals.” ER-200835. Alexandria, VA: Environmental Security Technology Certification Program (ESTCP). [accessed 9 April 2018].

U.S. DOI (U.S. Department of Interior). 2012. EM’s $500,000 investment in contaminant remediation leads to Hanford site strategy providing $6.35 million in cost savings. [accessed 9 April 2018].

U.S. DOE (U.S. Department of Energy). 2012. “Response Action Report for the 200-PW-1 Operable Unit Soil Vapor Extraction Remediation.” DOE/RL-2014-48 REV 0. Richland, Washington: U.S. Department of Energy. https://pdw.hanford.gov/arpir/index.cfm/viewDoc?accession=0074923H [accessed 9 April 2018].

U.S. EPA (U.S. Environmental Protection Agency). 2005. “Deployment of Phytotechnology in the 317-319 Area at Argonne National Laboratory-East, Innovative Technology Evaluation Report.” EPA/540/R-05/011. Washington, DC: U.S. Environmental Protection Agency. https://cfpub.epa.gov/si/si_public_record_report.cfm?dirEntryId=96194 [accessed 9 April 2018].

U.S. EPA. 2010. “Five Year Review Report: Second Five Year Review Report for Southern California Edison Company, Visalia Pole Yard Superfund Site, Visalia Tulare County, California: Five Year Review.” San Francisco, CA: U.S. Environmental Protection Agency. https://semspub.epa.gov/work/HQ/180372.pdf [accessed 9 April 2018].

U.S. EPA. 2014a. Record of Decision: Lower Duwamish Waterway Superfund Site. Part 3 Responsiveness Summary. https://semspub.epa.gov/work/10/715977.pdf [accessed 9 April 2018].

U.S. EPA. 2014b. Statement of Basis for EPA’s Proposed Remedial Action for the Housatonic River “Rest of River.” https://semspub.epa.gov/work/01/556821.pdf [accessed 9 April 2018].

U.S. EPA. 2017. Methyl tertiary butyl ether (MTBE): overview. https://clu-in.org/contaminantfocus/default.focus/sec/Methyl_Tertiary_Butyl_Ether_(MTBE)/cat/Overview/ [accessed 4 April 2018].

Udell KS. 1998b. Application of in situ thermal remediation technologies for DNAPL removal. In: Water Quality: Remediation and Protection. (Proceedings of the GW ’98 Conference). Herbert M, Kovar K, eds. September 1988, Tübingen, Germany. Oxfordshire, UK: International Association of Hydrological Sciences, 367–374.

University of Arizona SRP Center. 2016. UA SRP negotiates contract renewal with three global mining partners. https://superfund.arizona.edu/highlights/ua-srp-negotiates-contract-renewal-three-global-mining-partners [accessed 9 April 2018].

Volchko Y, Normann J, Rosén L, Karfeldt Fedje K. 2017. Cost-benefit analysis of copper recovery in remediation projects: a case study from Sweden. Sci Total Environ 605-606:300–314, PMID: 28686741, https://doi.org/10.1016/j.scitotenv.2017.06.128.

Wan X, Lei M, Chen T. 2016. Cost-benefit calculation of phytoremediation technology for heavy-metal-contaminated soil. Sci Total Environ 563-564:796–802, PMID: 26765508, https://doi.org/10.1016/j.scitotenv.2015.12.080.