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PRACTICE NOTE

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Ten years later: The progress and future of integrating sustainable principles, practices, and metrics into remediation projects

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Abstract

In 2009, the Sustainable Remediation Forum released a white paper entitled "Integrating sustainable principles, practices, and metrics into remediation projects" (Ellis & Hadley, 2009, *Remediation*, 19, pp. 5–114). Sustainable remediation was a relatively new concept, and the white paper explored a range of approaches on how sustainability could be integrated into traditional remediation projects. This paper revisits the 2009 white paper, providing an overview of the early days of the evolving sustainable remediation practice and an assessment of the progress of sustainable remediation over the last 10 years with a primary focus on the United States. The current state of the sustainable remediation practice includes published literature, current practices and resources, applications, room for improvement, international progress, the virtuous cycle that applying sustainable remediation creates, and the status of the objectives cited in the 2009 white paper. Over the last decade, several sustainable remediation frontiers have emerged that will likely be a focus in advancing the practice. These frontiers include climate change and resiliency, weighting and valuation to help better consolidate different sustainable remediation metrics, programmatic implementation, and better integration of the societal impacts of sustainable remediation. Finally, as was the case for the 2009 white paper, this paper explores how sustainable remediation may evolve over the next 10 years and focuses on the events and drivers that can be significant in the pace of further development of the practice. The events and drivers include transformation impacts, societal influences, and the continued development of new technologies, approaches, and tools by remediation practitioners. The remediation industry has made significant progress in developing the practice of sustainable remediation and has implemented it successfully into hundreds of projects. While progress has been significant, an opportunity exists to implement the tenets of sustainable remediation on many more projects and explore new frontiers to help improve the communication, integration, and derived benefits from implementing sustainable remediation into future remediation projects.

1 | INTRODUCTION

In June 2009, the Sustainable Remediation Forum, Inc. (SURF) published the "Sustainable remediation white paper—Integrating sustainable principles, practices, and metrics into remediation projects" (referred to hereafter as the SURF white paper) (Ellis & Hadley, 2009). SURF, a professional organization, first convened informally in 2006 as a group of remediation professionals interested in bringing sustainability principles and concepts into the remediation industry. SURF incorporated in 2011 as a 501(c)(3) professional nonprofit corporation. Over the last 10 years, sustainable remediation has become increasingly applied to remediate contaminated soil, sediment, and water. Sustainable principles, practices, and metrics have been incorporated into hundreds of remediation projects, and the topic of sustainable remediation has been highlighted in countless publications and has had a visible and meaningful presence in the remediation industry's most revered and highly attended technical conferences.

SURF's mission is to maximize the overall environmental, societal, and economic benefits in the site cleanup process by: (a) advancing the science and application of sustainable remediation, (b) developing best practices, (c) exchanging professional knowledge, and (d) providing education and outreach. SURF prepared this 10-year anniversary edition of its white paper to highlight:

- The early days of sustainable remediation: provides an overview of how sustainable remediation started in the remediation industry and some of the early activities accomplished
- Current state of the practice: highlights a cross section of green and sustainable remediation literature, current practices and resources, applications, areas of improvement, international activities, the concept of the virtuous cycle, and progress in comparison to SURF's 2009 objectives in the white paper
- New frontiers in sustainable remediation: outlines the new boundaries sustainable remediation practitioners have been exploring but not yet commonly practiced, including climate change and resilience, weighting and valuation, programmatic implementation, and societal impacts
- Sustainable remediation in the next 10 years: touches on a broad range of issues and topics that can change the trajectory of how sustainable remediation is implemented in the future and includes some information from the above three topic areas as well as new topics

As SURF's membership is predominantly located in the United States, the focus of this 10-year anniversary edition of the white paper is U.S. centric. Nevertheless, sustainable remediation practitioners in other geographic regions may find common parallels with the material presented herein.

2 | THE EARLY DAYS OF SUSTAINABLE REMEDIATION

This section focuses on the period of time leading up to the publication of the SURF white paper and the initial years after publication. As cited in the white paper, the remediation industry in the United States was born in the late 1970s following a steady stream of highly publicized discoveries of toxic chemicals in landfills, drinking water, and even neighborhoods. Environmental laws were passed at the state and national level, and industry and consultants kept pace by hiring staff, building programs, and initiating cleanups. The remediation industry was off at a sprint before it had learned to crawl. With the public demand for swift and sometimes immediate cleanups, responsible parties and the remediation industry invested heavily in energy-intensive engineered projects, such as groundwater pump-and-treat systems, soil excavation and off-site disposal, and incineration. Similar to other industries, the remediation industry uses energy, consumes raw materials, and otherwise contributes to humankind's environmental footprint.

SURF in the United States was formed in 2006 when a group of remediation professionals banded together to rethink how the remediation industry's behavior, reliance on technology, and consumption of energy impacts on the environment could be improved when looking through the lens of sustainability. SURF members were the first to consolidate broad-based institutional knowledge into an exploration of sustainable remediation drivers, practices, objectives, and case studies (Ellis & Hadley, 2009). The group recognized that there was still much to be learned about sustainable remediation and stated that it was the intent of SURF to identify the right questions in the white paper. In the paper, SURF defined sustainable remediation practices not only as those practices that reduce global impacts (e.g., greenhouse gases), but also those practices that reduce local atmospheric effects, potential impacts on worker and community safety, and/or the consumption of natural energy resources (beyond fuel consumption) that might be attributable to remediation activities. The document focused on remediation industry activities that most directly impact the environment. Although the "triple bottom line" of the environment, the economy, and social interests were discussed in the document, SURF members were mostly concerned with finding scientific and engineering approaches and alternatives that reduced the secondary (largely unaccounted for at the time) impacts of remediation on the environment, specifically:

- Minimize or eliminate energy consumption or the consumption of other natural resources;
- Reduce or eliminate releases to the environment, especially to the air;
- Harness or mimic a natural process;
- Result in the reuse or recycling of land or otherwise undesirable materials; and/or
- Encourage the use of remedial technologies that permanently destroy contaminants.

Societal, technical, economic, and regulatory and legal impediments and barriers to the implementation of sustainable remediation existed in 2009. Some regulators, members of the remediation industry, and the public feared that sustainability would become an excuse for "doing nothing" or that all remediation projects would become some version of the natural attenuation remedy. To some extent, this fear remains today. The different types of tools and difficult-to-validate performance criteria and metrics proposed to assess triple bottom line impacts further inflamed fears and uncertainty about whether sustainable remediation was a worthwhile cause. Finally, the inherent nature of remediation involved a complex interplay between metrics, measurements, and regulations that affected the evaluation in the decision-making process. As a result, SURF members believed it was important for the remediation industry to develop standards and train personnel so that sustainable remediation could be considered in the decision-making process to both achieve positive remediation outcomes and prevent potential misuse.

During this timeframe, practitioners grappled with the definition of sustainable remediation. Some practitioners focused primarily on the environmental component of sustainable remediation. This focus and approach was eventually termed "green remediation." Practitioners who wanted sustainability to focus on all three components of sustainability (i.e., economic, social, and environment) called it "sustainable remediation." When these two different groups came together to work on the Interstate Technology and Regulatory Council (ITRC) project for this topic area, a new term inclusive of both focus areas was adopted—"green and sustainable remediation."

As the concepts and principles of sustainable remediation were discussed at various SURF meetings in the early days, two topics continued to arise:

- Comparing the relative sustainability of a remedy between sites—Life-cycle assessment (LCA) experts suggested that, to make defensible comparisons, the remediation industry needed to identify the fundamental unit of remediation. No consensus was reached on how to best define a unit of remediation.
- Considering remediation worker safety and community impacts (and whether it was appropriate to do so)—Based on actuarial figures and other potential risks, it had become apparent to some SURF members that human health exposure risks were potentially less than the risks associated with actual cleanup (e.g., potential for injury or fatality of remediation workers and impacted community during remediation activities). SURF debated both sides of this position. On one side, the risks (incremental life-time cancer risk of 1 in 1 million from exposure to contaminants) associated with a large excavation and disposal project were juxtaposed against the probability of remediation worker injury or fatality during site cleanup activities. On the other side, an opinion was presented that risk exists when a person goes to work and does their job, and health and safety plans are the mechanism by which risks are reduced for workers.

Although boundaries between remediation stakeholder groups were blurred at times, SURF identified four general groups (site owners, regulatory entities, the public, and industry service providers who develop and implement sustainable solutions) that were involved in remediation projects. As discussions about sustainable remediation ensued, the importance of including representatives of each of these groups in the site remediation planning process was repeatedly emphasized.

Remedy selection regulations in 2009 did not explicitly require consideration of sustainability in the remedial process, but neither did they prohibit it. As a result, sustainability was not widely considered in the process. In some instances when sustainability was incorporated into the process, there was skepticism from regulators, site owners, and practitioners who were unfamiliar with the concept and unsure how it should be incorporated into the established process. At the time, only a few states (Illinois, Minnesota, New York, and California) were promoting the use of greener cleanup concepts.

Since the early days, SURF has continued to expand on the topics explored in its white paper, publishing its "Framework for integrating sustainability into remediation projects" (Holland et al., 2011), "Guidance for performing footprint analyses and life-cycle assessments for the remediation industry" (Favara, Krieger, Boughton, Fisher, & Bhargava, 2011), a compendium of metrics (Butler, Larsen-Hallock, Lewis, Glenn, & Armstead, 2011), and a call to improve the integration of land remediation and reuse (Holland et al., 2013) and groundwater conservation and reuse (SURF, 2013). The publication of this paper is another contribution by SURF to advance the science and application of sustainable remediation and share knowledge. SURF members continue to believe that the true benefit of sustainability is both in guiding remediation professionals to make better decisions, offering a new lens to design remedies to achieve these benefits.

In addition to the works completed by SURF members, other organizations published their views on sustainable remediation. Some of the most recognized works are the U.S. Environmental Protection Agency's (USEPA's) green remediation primer (USEPA, 2008), green remediation strategy (USEPA, 2010), and various best management practice (BMP) fact sheets, and the ITRC's guidance documents for green and sustainable remediation: "Green and sustainable remediation: A practical framework" (ITRC, 2011a) and "Green and sustainable remediation: State of the science and practice" (ITRC, 2011b). These works, as well as many others, provided resources for practitioners when implementing sustainable remediation and serve as the foundation of the current state of the practice.

3 | CURRENT STATE OF THE PRACTICE

Over the last 10 years, sustainability has become one of the many elements considered when developing and making decisions about remedial strategies. The depth of knowledge about sustainable remediation, as a school of thought and remedial strategy in practice, has grown and become more prevalent. Since 2009, the majority of this evolution has focused on the environmental component of sustainability. More recently, sustainable concepts and principles, including the social and economic components, are being integrated earlier in the remediation project life cycle. In the last 10 years, the evolution of sustainable remediation is evidenced by the published works and resources such as frameworks and guidance documents.

3.1 | Literature review

Since 2009, a large collection of sustainable remediation literature has been published in peer-reviewed journals and by international publishing companies. Results from a literature search for "sustainable remediation" and "green remediation" literature are provided in Table 1 (note: a single paper may have referenced both green remediation and sustainable remediation).

It is apparent in the body of sustainable or green remediation literature that the focus has shifted from establishing the practice and spreading general awareness throughout the industry to refining and standardizing the practice. However, that is not to assume that the prevalence of sustainable remediation is such that it no longer requires education and outreach, and recent literature reflects this. The prevalence and awareness of sustainable remediation is now approaching a stage requiring a common language that practitioners, regulators, and stakeholders can speak and reference when considering and/or performing sustainable remediation practices.

A review of available published literature related to sustainable remediation revealed trends in the content of the works. Green and sustainable remediation literature over the last 10 years has focused on the following:

- Identification of the opportunities and challenges associated with incorporating sustainable remediation concepts throughout the remediation project life cycle.
- Discussion and evaluation of methods and tools to quantify or measure the effects of sustainable remediation.
- Development of standard procedures and protocols for evaluating and implementing sustainable remediation.

In 2018, Reddy and Kumar (2018, p. 92) indicated the following challenges and opportunities:

- Presence of false claims (i.e., "greenwashing") of sustainable remediation.
- Lack of financial incentives to adopt sustainable practices that would lead to appropriate strategies and decisions for sustainable remediation implementation.
- Lack of a regulatory mandate to perform a sustainability assessment of potential remedial options before final remedy design and implementation.
- Lack of public awareness about the greater benefits of adopting environmentally sound, economically feasible, and socially conscious approaches during remedy implementation.
- Lack of specialized sustainability assessment tool training for remediation practitioners.
- The need for greater academic focus to develop frameworks for integrating the three components of sustainability in a standardized manner.
- The need for more tangible metrics and tools to assess economic and social impacts and improve indirect impact assessments.
- The need to refine and develop new assessment tools and frameworks to incorporate multicriteria decision analysis so that remedial strategies can be evaluated based on the interests of stakeholders.

Similar to the standardization of evaluating the feasibility of potential remedial alternatives for contaminated sites, standard means in which to effectively and consistently both integrate sustainable practices and thinking early in the project life cycle and evaluate remedial strategies in terms of sustainability is needed. As discussed in "Metrics for integrating sustainability evaluations into remediation projects" (Butler et al., 2011), a common framework needs to be developed and implemented to assess and monitor the sustainability of different remedies. Similar conclusions were drawn in "Progress in sustainable remediation" (Bardos, 2014), in which the need for a comparative sustainability assessment was identified to achieve enhanced decision making. Quantifying the monetary benefits and/or consequences of different remedial strategies in an effort to evaluate their economic sustainability is fairly well defined and agreed upon, although quantifying and/or projecting the economic impacts that a remedial approach may have on the economy of the local community often remains somewhat subjective in nature.

The evolution of footprint tools such as SiteWise™ (U.S. Navy, U.S. Army Corps of Engineers, & Battelle, 2015) and Spreadsheets for Environmental Footprint Analysis (SEFA) (USEPA, 2012a) have aided in the ability of a remediation practitioner to compare site-specific remedies based on a handful of sustainability metrics primarily comprised of chemical emissions, energy and water consumption, and accident risk to site workers. However, methods and tools to comprehensively assess the sustainability of a remedial approach in terms of overall environmental impact (i.e., ecosystem services and habitat enhancement), and quantifying or articulating the social and economic impacts beyond site activities and implementation costs, respectively, of a sustainable remedy are less available and agreed upon (Harclerode et al., 2015). Infrequently, LCA and multicriteria

TABLE 1 Literature search results for sustainable remediation and green remediation

Source	Number of References: Sustainable remediation	Green remediation
John Wiley and Sons	191	84
Environmental Science & Technology	15	18
Science Direct	395	168

decision analysis are used as tools to perform a more comprehensive sustainable remediation assessment (Linkov & Seager, 2011; Hou, Al-Tabbaa, Guthrie, Hellings, & Gu, 2014). The literature supports evidence of continued need and effort to quantify some of the seemingly subjective effects of sustainable remediation using standardized methodologies.

Quantification aside, procedures and protocols for implementing and evaluating sustainability are prevalent in literature published over the last decade. SURF members published "Framework for integrating sustainability into remediation projects" (Holland et al., 2011), which outlined a strategy for remediation practitioners to consider and incorporate sustainability throughout the remediation project life cycle in a forward thinking and consistent manner. Similarly, ASTM International, Inc. (2013) published the "Standard guide for integrating sustainable objectives into cleanup."

Other organizations developed framework and guidance documents focusing primarily on the environmental component of sustainability, including the "Standard guide for greener cleanups" (ASTM International, 2016) and "Green and sustainable remediation: A practical framework" (ITRC, 2011a). Over the years, the U.S. federal government and individual states also have developed guidance documents related to green and sustainable remediation. Furthermore, USEPA issued a memorandum, "Consideration of greener cleanup activities in the superfund cleanup process," to further aid remedial project managers and other stakeholders (USEPA, 2016).

In the effort to standardize the sustainable remediation evaluation and implementation methods, reviews of international means and methods and approaches to sustainable remediation have been completed. In one review, "Comparison of international approaches to sustainable remediation" (Rizzo et al., 2016), different international practices are compared and evaluated to highlight the similarities and differences of developed frameworks. The heart of the frameworks themselves is evaluated, appreciating that differences may be the result of differing cultures and cleanup priorities. Ridsdale and Noble (2016) evaluated the sustainability principles in remediation frameworks to measure and compare the definition of sustainability in the context of remediation projects. Evaluation results indicated that sustainable remediation is defined variably and applied uniquely to specific sociopolitical contexts and that, despite some level of agreement on what sustainable remediation means, there is more room for standardization. This type of review of different frameworks may ultimately help in developing a recognized standard for considering, implementing, and evaluating sustainability within the remediation project life cycle on a national or international level. As true in the development of all standards and guidance documents, allowances must be made and exceptions considered for each specific country, region, and/or project, informed by stakeholders.

As apparent in the literature published over the last decade, sustainable remediation has grown in recognition and has begun to develop a more defined structure. Yet published literature also identifies areas in which the field of sustainable remediation can grow and develop (i.e., in quantifying the effects and standardizing the approach of sustainable remediation as well as establishing a common language/vocabulary among interdisciplinary practitioners). Moreover, remediation practitioners have provided countless presentations on the topic at United States and internationally renowned remediation conferences and meetings. Sustainable remediation case studies are documented and featured as resources so that the practice of sustainable remediation becomes recognizable to others. Thought leaders in the industry have gathered at SURF meetings since 2006 to discuss and debate how sustainable remediation should progress. These meetings have served and continue to serve as a venue for brainstorming and debating sustainable remediation topics and have been the origin of some of the ideas represented in sustainable remediation literature.

3.2 | Current practices and resources

Since the publication of the SURF white paper in 2009, many sustainable remediation guidance documents, frameworks for incorporating sustainable remediation, and tools have been developed. At the time of this publication, many of these resources are publicly available and can be downloaded from the SURF website library (www.sustainableremediation.org). Increasingly, environmental consultants and other companies are developing and using their own tools. Qualitative and quantitative tools have been developed and used by consultants and responsible parties for environmental footprint analysis, BMP selection, and sustainable remediation in general. Although the interest in developing more tools is certainly a positive step, proprietary tools limit the transparency of the methods and application of these tools. A brief overview of some, but by no means all, of publicly available resources that are more commonly used by practitioners is provided below.

Organizations such as the ITRC and SURF have developed documents that provide frameworks and methods for incorporating sustainable remediation into cleanup projects (ASTM International, 2013, 2016; ITRC, 2011a, 2011b). Some of these frameworks, such as ASTM E2893-16, provide a methodology for identifying, prioritizing, selecting, implementing, documenting, and reporting BMPs to enhance green remediation. The ITRC documents provide an overview of the available tools and resources at the time of publication and aim to provide users with planning methods and help them navigate available sustainable remediation information. SURF, the SURF-United Kingdom (SuRF-UK), and SURF Australia/New Zealand (SURF-ANZ) through the Cooperative Research Centre for Contamination Assessment and Remediation of the Environment (CRC CARE) also have developed frameworks (CRC CARE, 2018; Holland et al., 2011; Smith & Nadebaum, 2016; SuRF-UK, 2010) that provide a more holistic approach and discuss methods to incorporate sustainable concepts into remediation projects, assess sustainability metrics, and compare remedial alternatives. A common theme of these frameworks and guidance documents is the need for sustainable remediation practices to be applied and completed in a transparent and consistent manner to allow engagement with stakeholders.

A number of sustainable remediation tools are available and provide support ranging from simple qualitative assessments to complex, cradle-to-grave quantitative metric evaluations. The primary objective of using these tools is to gain a better understanding of the remedy from a net environmental benefit perspective by looking at remediation approaches holistically. As described above, some companies have developed their own proprietary tools for internal use, but many tools are publicly available for free or with a licensing or software fee. Some of the most commonly used environmental footprint tools are SiteWise™, SEFA, and the Sustainable Remediation Tool (SRT), which are all open source (see brief descriptions below). Although these tools can be used throughout the remediation project life cycle, they are best used to help practitioners select a more sustainable remedy when comparing remedial alternatives and identify opportunities to minimize the impact of a single remedy during the remedial design or optimization phases.

- SiteWise™ is a series of Microsoft Excel spreadsheets used to calculate the environmental footprint of remediation activities in terms of common sustainability metrics such as emissions, energy use, worker safety, and waste generation. The emissions factors in SiteWise™ are reflective of the full life cycle of materials and waste; impacts are inclusive of raw material production and management of waste at landfills, even though these activities are conducted offsite. SiteWise™ includes the ability for users to enter information about remedy cost and community impacts so that all three components of sustainability are considered in the assessment.
- SEFA (developed by the USEPA), another environmental footprint calculator based on Microsoft Excel, is a flexible tool used to evaluate alternative remedies, existing remedy designs, or remedies postimplementation. In addition, SEFA is used to estimate a subset of available hazardous air pollutant emissions. Similar to SiteWise™, the SEFA tool follows a life-cycle approach when calculating the environmental footprint of chemicals and materials used in a remedy.
- SRT is similar to these tools and is Microsoft Excel based, but it has an integrated decision-making tool that allows users to weight the different metrics as part of the remedial selection. SRT is also used to estimate the implementation cost of various remediation technologies.

A LCA is a more comprehensive means used by sustainable remediation practitioners so they can better understand the comprehensive environmental impacts (i.e., beyond air emissions related to energy use and material production), of a cleanup. While the philosophy of LCA is somewhat similar to that of Microsoft Excel-based footprinting tools that primarily evaluate the impacts of a limited set of air emissions and energy use, a LCA addresses additional impacts that affect a variety of categories and allows a practitioner to assess if burdens are being transferred from one system to another (e.g., using a treatment reagent that may reduce greenhouse gas emissions but at the expense of increased water use and agricultural runoff). In a LCA, the emissions are consolidated into numerous life-cycle impact categories such as climate change, respiratory impacts, eutrophication, ecotoxicity, human toxicity, natural resource use, and land transformation. The robust impact categories allow users to better identify opportunities to improve the environmental footprint of a cleanup and assess if any optimization activities have an overall benefit or if the optimization results in shifting environmental burdens from one impact category to another. In general, LCA is primarily applied to large projects or cleanup projects that have physiochemical processes or are materially intensive (e.g., large quantities of treatment reagents). The primary barriers remediation practitioners have with performing LCAs are the steep learning curve necessary to become proficient with the software tools and the costs to maintain a commercial software license. However, the idea of open-source LCA is gaining momentum and may allow more practitioners to use LCA, if they are amenable to learning the software. A greater utilization of LCA will result in a better understanding of impacts and how to best minimize or avoid them. Visentinet al. (2019) provide a literature review of publications highlighting LCA applications to remediation projects.

3.3 | Applications

A great variety of sustainable remediation applications have been published and presented. Many publications, technical conference presentations, and publicly available webinars focus on case studies because generally case studies have proven to be the most effective means to convey the benefits of sustainable remediation. The USEPA-hosted website CLU-IN contains the most comprehensive list of green remediation case studies, featuring 35 profiles (https://clu-in.org/greenremediation/profiles). Case studies are also posted on the SURF website. Searching on the Internet is the easiest way to access green and/or sustainable remediation case studies and review the range of applications. Another resource for case studies is conference proceedings; most environmental remediation conferences include a track on sustainable remediation.

3.4 | Room for improvement

Although the field of sustainable remediation has advanced substantially since its inception in the mid-2000s, the practice continues to evolve and areas for improvement exist. For example:

- A lack of understanding of sustainable remediation persists within the regulatory community.
- Further expansion of sustainable remediation into corporate programs has proven difficult, despite several corporate success stories.
- An inability by remediation professionals to demonstrate the value of sustainable remediation.

Each topic is evaluated below.

3.4.1 | Understanding of sustainable remediation within the regulatory community

There continues to be a lack of interest and understanding in the regulatory community relative to sustainable remediation. In part, this lack of interest and understanding is both because few regulations require sustainable remediation and because regulators tend to gravitate to remediation concepts that address regulatory requirements. While some regulatory drivers for greener cleanups exist, these have limited, sparse applications within the federal programs of Superfund, the Resource Conservation and Recovery Act, and the Toxic Substances Control Act. Superfund regulatory drivers differ from region to region, with only two regions having specific requirements (Regions 2 and 9). The requirements in these two regions are limited to selecting environmental BMPs, not necessarily applying the environmental considerations of sustainable remediation. The greener cleanup policies in the other eight regions are more policy oriented with the notion of incorporating greener cleanup concepts into remediation programs as a beneficial practice, but not a requirement. In addition, a total of 10 states (California, Connecticut, Illinois, Massachusetts, Minnesota, New Jersey, New York, Oregon, Wisconsin, and Vermont) have some type of regulation, policy, or guidance related to greener cleanup policies but only Massachusetts, New York, and Vermont have requirements for greener cleanup practices. Of these three states, only New York regulations mention sustainability per se; the others focus solely on green remediation. Therefore, regulators have some impetus to incorporate the environmental considerations of sustainable remediation into state and federal remediation projects, but almost no regulatory drivers to integrate social and economic considerations beyond limited community relations and protecting worker health and safety.

An area of potential improvement is to apply sustainable remediation concepts and principles as part of brownfield redevelopment projects. Similar to sustainable remediation, brownfield redevelopment involves remediating former industrial properties with the explicit purpose to reuse the land in a way that improves the surrounding community. This global concept, initially championed by the USEPA in the early 1990s, promotes cleaning up and reinvesting in industrial properties and includes provisions for establishing risk-based remediation standards so that the protection of human health and the environment is ensured for the future use of the property. The link between brownfield redevelopment and sustainable remediation is illustrated by the USEPA's summary, "Brownfields and sustainability," that focuses on green buildings, green economies, green infrastructure, and smart growth (USEPA, 2006). In this document, the USEPA states: "Although many brownfields redevelopment projects have sustainable elements, opportunities exist to make even greater strides in sustainable brownfields redevelopment" (USEPA, 2006, p. 1). The document exemplifies how brownfield redevelopment projects can offer a mechanism to apply sustainable remediation concepts, especially in the United States where the USEPA may support it.

Over the years, considerable and enthusiastic debate has occurred about regulatory requirements for sustainable remediation. Some industry stakeholders, including some site owners' representatives, believe it would be beneficial to the practice and society as a whole if the regulatory community provided the impetus for a step change in the practice of sustainable remediation. Alternatively, some remediation practitioners believe that, because of the intrinsic value of sustainable remediation, no regulatory requirement is needed. In this scenario, market forces would identify the best applications of sustainable remediation and only those that provide value would be implemented. Regardless of which perspective an individual holds, an opportunity exists to better represent sustainable remediation attributes in site cleanup and increase understanding of its role and benefits among the regulatory community.

3.4.2 | Further expansion of sustainable remediation into corporate programs

Several large corporations provide excellent examples of corporate sustainable remediation programs (see Section 4.3). However, the authors' collective experience is that, despite the corporate sustainable remediation successes illustrated below, other companies have decided against investing in a corporate sustainable remediation program because of the following:

- A lack of regulatory drivers.
- The perception that the effort is not worth the benefits.
- Resource constraints that inhibit implementing and tracking sustainable remediation programs and benefits.

Although many larger companies have some type of corporate sustainability program, sustainability goals often do not include corporate remediation functions for a variety of reasons (e.g., the small scale of remediation projects compared to other company operations, the lack of social or investor pressure to implement sustainable remediation practices). Experience has shown that if remediation practitioners are given the opportunity to demonstrate the value of sustainable remediation, then companies will directly experience the benefits of sustainable remediation. A catch-22 arises when corporate remediation managers have difficulty demonstrating value without an initial investment yet cannot leverage an existing driver (e.g., regulatory requirement) to obtain the investment. Additional outreach, particularly to corporate sustainability managers who may not be familiar with sustainable remediation, may help convince corporations to make the investment in sustainable remediation and, in turn, better understand its value relative to corporate sustainability and other benefits (e.g., cost savings). This topic is further discussed in Section 4.3.

3.4.3 | Demonstration of the value of sustainable remediation

Generally, most remediation professionals are not adept at expressing the value of sustainable remediation. Although sustainable remediation is practiced in some manner by most larger service providers (i.e., consulting firms), a relatively low percentage of remediation professionals overall have studied or practiced sustainable remediation and, therefore, understand and/or can convey its value to nonpractitioners.

This lack of proficiency in demonstrating the value of sustainable remediation is particularly accentuated when addressing the social and economic components of sustainability. While guidance for and an understanding of these components have improved over the last 10 years, many remediation professionals (even those who practice sustainability) continue to grapple with how best to integrate the social and economic value of sustainable remediation into cleanup projects, particularly projects that lack a development aspect (development projects have greater interest from the community and businesses). The sustainable remediation field needs additional granular-level guidance in these areas so that remediation professionals can better demonstrate the value of integrating social and economic considerations into remediation.

The ability to more widely demonstrate the value of sustainable remediation poses a challenge to the leaders of sustainable remediation, who must persevere in conveying the benefits of the practice to the broader remediation community. Meeting this challenge involves demonstrating the value of sustainable remediation through education, case studies, webinars, seminars, community engagement, and articles. Although these steps may have been taken previously and substantial progress has been made over the last 10 years, there is still outreach work to accomplish.

3.5 | International progress in sustainable remediation

Since 2009, the sustainable remediation movement has expanded across the globe. Numerous international SURF organizations exist (United States, Canada, Australia, New Zealand, Netherlands, Italy, Taiwan, Brazil, Japan, Columbia, with further interest in China and Scandinavian countries). The Network for Industrially Co-ordinated Sustainable Land Management in Europe (NICOLE) and the Contaminated Land: Applications in Real Environments (CL:AIRE) organization continue to be a foundation of sustainable remediation efforts in Europe and provide guidance and resources to sustainable remediation practitioners internationally. The international SURF organizations communicate on a quarterly basis to share updates and progress on initiatives. The groups also convene at conferences to share knowledge, work collaboratively, and provide support in the development of newer SURF networks.

In 2016, this network of SURF organizations formed an alliance known as the International Sustainable Remediation Alliance (ISRA). ISRA members aim to link with external global stakeholders and work collaboratively to help promote their work through on-site and on-line global events. ISRA members helped develop the International Standard (International Organization for Standardization (ISO), 2017) that defines sustainable remediation in Section 3.10 as “elimination and/or control of unacceptable risks in a safe and timely manner whilst optimizing the environmental, social and economic value of the work.” More mature SURF organizations are currently evaluating sustainable land management holistically, considering climate change and the community resilience. It is easier to implement more attributes of sustainability into remediation practices in non-U.S. geographies because international regulations are generally more flexible than those in the United States.

All of these international organizations are advancing sustainable remediation within their geographic regions. As referenced above, sustainable remediation needs to appreciate differences in cultures and ways of life. Additionally, different countries have different regulatory requirements.

3.6 | Virtuous cycle

A number of practitioners have noted the phenomena of a virtuous cycle when implementing sustainable remediation. Simply put, when practitioners and stakeholders implement sustainable remediation, they see a number of positive outcomes that make them want to improve and enhance sustainable remediation benefits.

A virtuous cycle, by definition, is series of events that reinforce themselves through a feedback loop with increasingly favorable results. The triggering event, no matter how small, can set off a cycle that has a very large impact, colloquially known as the snowball effect. In the practice of sustainable remediation, the virtuous cycle is often applied to two different processes: data feedback and external influence. These processes can be started at any point in the life cycle of a project, but the earlier a process is implemented the greater impact it can have.

The data feedback virtuous cycle (Figure 1) describes the process of teams using results from sustainability tools such as SiteWise™, SEFA, or LCAs as an additional line of evidence for remedy selection as well as a way to improve the remedy. The process starts with the team using the tool to enter data, calculate results, and generate recommendations. As a team completes the process steps, understanding and acceptance of sustainable remediation increases for both the team and those who receive the results. Recommendations can be used to select sustainable remedial alternatives and improve future remedial alternatives. The overall process increases the team's comfort with and awareness of the tool, leading to more sustainable and innovative remedy designs. Furthermore, by transparently engaging stakeholders (including the community, regulators, and business decision makers), an added level of acceptance for selecting a sustainable solution is gained because stakeholders have “gone on the journey.”

The external influence virtuous cycle (Figure 2) shows how consistent external influence provides motivation to develop and apply sustainable remediation. In the top right quadrant titled “Agency Support” the regulator begins by emphasizing the importance of sustainable remediation and providing a template for how to implement these practices. Teams implementing these approaches are likely to receive positive feedback (e.g., Green Team Awards, federal or state recognition such as the Leading Environmentalism and Forwarding Sustainability Award in USEPA Region 7) (USEPA, 2012b). Sustainable remediation benefits and award acknowledgments are shared in literature and at conferences, which leads to increased awareness that influences other practitioners and industry stakeholders. Service providers may provide training for

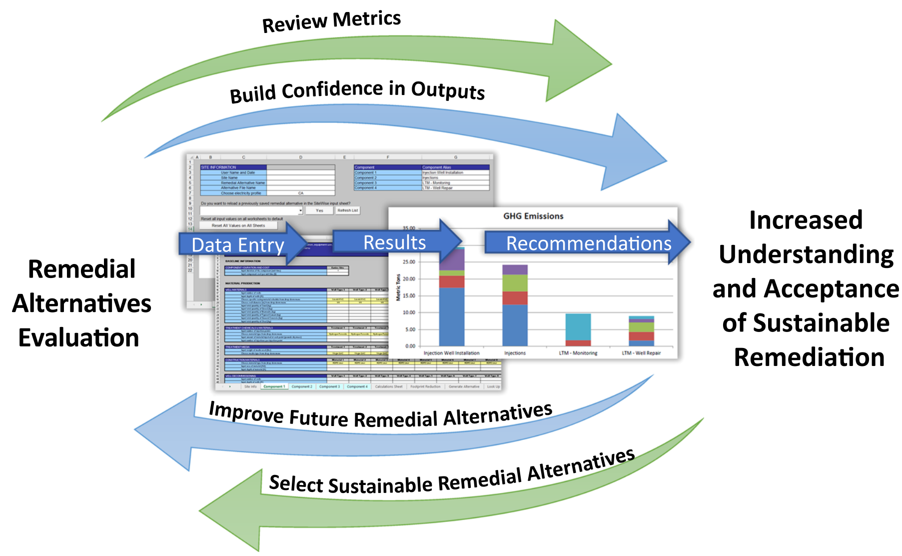

FIGURE 1 Data feedback virtuous cycle [Color figure can be viewed at wileyonlinelibrary.com]

remediation managers and/or endorse the use of footprinting tools or BMPs. Alternatively, the site owner may begin to require increased application of sustainable remediation after learning of the benefits, such as time, cost, and societal implications. The cycle then progresses with members of the initial projects applying their learnings to new projects or later project phases.

These virtuous cycles can be further improved by implementing a bottom-up approach versus the traditional top-down approach to sustainable remediation. As cited by Favara and Gamlin (2017), the traditional top-down approach to integrating sustainability into remediation projects involves first developing and selecting remedial alternatives and then applying sustainable BMPs. In this approach, the selected remedy undergoes conservation analysis, optimization, and minimization and results in a reduced environmental footprint. While the footprint of the selected remedy is improved, the improvement is only a fine tuning of a traditional industry application. Alternatively, the bottom-up approach consists of systems thinking where environmental, social, and economic impacts are taken into consideration as the remediation approach is conceptualized (i.e., before technology selection). The goal is to minimize the footprint with technologies that are inherently sustainable. After the remedy is selected, the practitioner performs the conservation, optimization, and minimization analysis to further reduce the footprints (as is currently completed with the traditional approach). In this way, a new approach to implementing remediation is discovered, leaving room for technology innovation. If sustainability is not a key component of the remediation plan, these impacts are not considered and innovation opportunities are not realized.

3.7 | Revisiting the sustainable remediation vision from the 2009 white paper

SURF's vision in 2009 was for the remediation industry to contribute to planetary sustainability by promoting approaches and practices that take into consideration the long-term effects of remedial action on the environment, stakeholder communities, and economics. Implementation of these approaches and practices was envisioned to result in a foundation that allows more consistent planning and implementation of stakeholder-supported sustainable remediation projects.

To achieve the vision for sustainable remediation, the white paper (Ellis & Hadley, 2009) offered objectives that needed to be achieved. Table 2 provides these objectives along with the current progress in achieving the objectives.

4 | NEW FRONTIERS IN SUSTAINABLE REMEDIATION

In the past 10 years, SURF has successfully augmented the anecdotal evidence for the efficacy of sustainable remediation with data collection, analysis, and transparent reporting. Yet while *green* remediation is increasingly commonplace, truly *sustainable* practices are implemented by organizations with mature remediation and sustainability programs. While much has been accomplished in the last

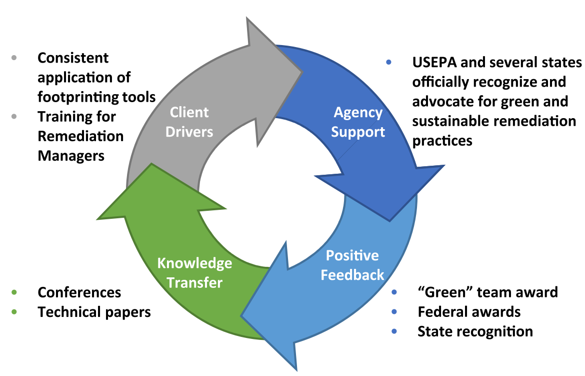

FIGURE 2 External influence virtuous cycle [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 2 Looking at the 2009 sustainable remediation vision with a 2019 lens

Identified objectives to achieve vision for sustainability in SURF white paper	Evaluating progress for objectives identified in 2009
Recognize diverse and emerging drivers for implementing sustainable remediation	A range of potential social, economic, and environmental drivers were identified and were organized around the three components of sustainability. Social: Some site owners have implemented sustainable remediation practices to enhance social responsibility. However, the expected drivers related to nongovernmental organization advocacy and role of public awareness cited in the SURF white paper have not yet come to fruition. Environmental: In the United States, Executive Orders were created (and have since been rolled back), creating a demand for sustainable remediation strategies in federal procurements. More flexible international regulations have mandated the use of sustainable remediation. The expected drivers related to climate-change legislation and a focus on net environmental benefits cited in the white paper have not yet been realized. Economic: Brownfield development incentives have increased in the past decade but the role of sustainable remediation in contributing to this is difficult to correlate. The expected drivers of minimizing liabilities and more transparency in liabilities reporting cited in the white paper have not yet materialized.
Develop technical resources	A number of technical resource development goals were identified (as represented by bold text): **Sustainability framework**: Numerous sustainability frameworks have been developed by technical work groups, national governments, and site owners. They all have common elements but additional elements that make them unique. **Technical and regulatory guidance documents**: A significant amount of technical guidance documents have been developed. In the United States, less regulatory guidance documents are available at the federal and state level, as compared with technical guidance documents. **Sustainability certification program**: a certification program has not been developed, although the "Standard guide for greener cleanups" provides an option for the user to prepare a "self declaration" of compliance with the standard (ASTM International, 2016). **Pilot studies and research**: Numerous pilot studies have been implemented, ranging from testing different tools to implementing different sustainable technologies. Significant research has occurred, as evidenced by journal publications (see Section 3.1 and Table 1). **Lessons learned and case studies**: Numerous case studies and lessons learned have been presented at conferences, published in journals, and posted on different websites (e.g., SURF, USEPA-hosted CLU-IN). **Education**: Significant training has occurred through numerous technical webinars and conference workshops and within different organizations. Sustainable remediation is being introduced in education curriculums and textbooks. **Technical stewardship**: Different international SURF chapters, regulatory entities, site owners, and service providers provide joint stewardship of the practice. No single entity, however, has the primary charge of responsible stewardship. **Sustainability metrics**: Most current metrics are those related to energy usage (and associated emissions), material use, waste production, and water use. Social and economic metrics are mostly absent to this day (aside from safety statistics and project costs). As was the case in 2009, the basket of metrics currently used are unbalanced as they mostly focused on the environmental component of sustainability. **Policy and guidance development**: The USEPA and some U.S. state programs have provided policy guidance on implementing green remediation, mostly in terms of recommendations of inclusion but stopping short of mandating requirements.
Use valuation properly	As stated in the 2009 white paper, "The challenges of bringing valuation principles and practices to the remediation industry are not insignificant. There has traditionally been great reluctance among environmentalists, community stakeholders, elected officials, and regulators to discuss, much less accept, if it is appropriate…" (SURF, 2009, p. 75). This statement largely holds true today. Also, site owners are concerned that monetizing the impacts of remediation project emissions may make them vulnerable to additional enforcement actions.
Respond to market and government forces driving sustainability	A number of market and government forces that could promote sustainable remediation were identified in the 2009 white paper. However, those previously identified in 2009, as well as new ones, have not increased sustainable remediation implementation. Most market and government forces focus on projects of much larger scale than even the largest cleanup projects.
Prepare for carbon trading and emissions credits	This market has yet to materialize in the U.S. Carbon trading and emissions credits are a highly partisan issue that ebbs and flows with changing government leadership.

(Continues)

TABLE 2 (Continued)

Identified objectives to achieve vision for sustainability in SURF white paper	Evaluating progress for objectives identified in 2009
Adapt to sites of different scale	A three-tier system to assess sustainability was envisioned in the 2009 white paper. Today, a three-tier system is generally accepted with a slight modification of the one offered in 2009. Tier 1 is applicable to smaller sites and includes the implementation of BMPs. Tier 2 is used for more complex sites where footprint tools may be applied and Tier 3 is used for large and complex sites where a LCA may be incorporated.

Abbreviations: LCA, life-cycle assessment; SURF, Sustainable Remediation Forum, Inc.; USEPA, U.S. Environmental Protection Agency.

decade, in some respects, the industry continues to be limited in vision and creativity when applying the concept of sustainability itself and understanding how its application can benefit the services and functions of our government to protect human health and the environment. Bringing creative ideas to fruition will be the key to progressing from green remediation to sustainable remediation. Several new frontiers in sustainable remediation are addressed below.

4.1 | Climate change/extreme weather and resilience

As technology and innovation advance globally, scientific research around the world has revealed that the impacts of these advances are changing our climate. Building resilience into our innovations and technological advances will help us prepare for the uncertainty and risk associated with climate change impacts.

Decades of research, including the recent "Fourth national climate assessment, Volume II: Impacts, risks, and adaptation in the United States" (U.S. Global Change Research Program (U.S. GCRP), 2018), document the global reality of impacts from more powerful and frequent storms, heavy rainfall, heat waves, wildfires, and more frequent and longer droughts. Rising sea levels, declining snowpack, long-term stress on water availability, declining groundwater levels, acidification, and rising temperatures represent further threats to ecosystems and communities. These realities highlight the importance of researching the long-term sustainability of cleanup actions at contaminated sites that could be affected by extreme weather and climate change.

Since early 2016, SURF members have been organizing knowledge exchanges to examine (a) the impacts of climate change and extreme weather events on hazardous waste sites and (b) how these impacts can be mitigated and how value can be created for communities. Through these exchanges, the participating sustainable remediation practitioners concluded that climate change and extreme weather events can undermine the effectiveness of the approved site remediation by altering exposure pathways; influencing the fate and transport of contaminants; altering organism sensitivity; and impacting long-term operations, management, and stewardship of remediation sites. When climate change impacts are not considered, major investments in remediation, containment, and waste management infrastructure are at significant risk. During these exchanges, practitioners also emphasized the importance of considering social vulnerability to climate change. When social vulnerability is included in the sustainable assessment of a long-term remedy, populations that may experience disproportionate climate change impacts are considered. Failure to consider these populations and individuals could compromise remediation and adaptation strategies and result in significant environmental and human health risks.

SURF recommends incorporating climate change resiliency into sustainable remediation and building on resources and regulatory drivers from state, national, and international organizations. Climate change factors should be assessed to plan for projected impacts, and resilience plans should be developed and include aspects beyond site boundaries (e.g., energy availability). In addition, vulnerability assessments that benefit and build on established hazardous waste management law, policy, and practices should be performed.

Resilient remediation can also help expedite cleanup and development, decrease public health risks, and create jobs, parks, wetlands, and resilient energy (Maco et al., 2018). Resilient remediation and redevelopment can help achieve goals for sustainable land management, climate action, clean energy use, and sustainable cities as well.

4.2 | Weighting and valuation

Currently, practitioners evaluate a number of different variables to ascertain which remediation options may be more sustainable than others. Weighting can be used to show how different metrics may have more "weight" in a decision than other metrics. Valuation converts metrics into more relevant descriptions that are easier to understand for different audiences. Valuation can be nonmarket based (e.g., ecosystem services) or market based (e.g., monetization, where a dollar value is assigned to specific emissions, such as the cost to society of particulate matter emissions). This evaluation often results in an analysis that provides narratives of the different sustainability attributes which, in turn, leads to a subjective conclusion as to the relative strengths and weaknesses of a sustainability option. For example, weighting or valuation can be used to assess a reduction in greenhouse gas emissions to mitigate climate change impacts versus a reduction in ozone and particulate matter to not exacerbate poor air quality. As stated in the 2009 white paper, SURF has been in search of a sustainability unit that can be used to better compare sustainability metrics so a more direct comparison can be made.

Within other areas of the environmental field, weighting has been used to normalize or quantify attributes with different values. For example, within the remediation field, different carcinogen concentrations are weighted during a risk assessment to determine the total incremental life-time cancer risk for a combination of different carcinogens in a particular media. Similarly, within the field of LCA, several different impact assessment methods provide weighting to individual impact categories, so the overall environmental impacts of remedial strategies can be compared directly using endpoint assessments. Bare et al. (2000) summarize the benefits and limitations of endpoint LCAs. Multicriteria decision analysis is one approach that can be used to compare different sustainability attributes; however, it is limited because establishing criteria and weighting are often defined for a specific project, and, thus, not transferrable. As referenced in Section 3.2, there are a number of different sustainability frameworks and numerous metrics among the frameworks. The variation among frameworks and metrics, as well as unique site-specific characteristics, pose a challenge to developing one harmonized weighting factor reference for all criteria.

One potential solution is to use monetized factors to represent some of the impacts of a remedy. Harclerode et al. (2016) proposed using the social cost to society of different emissions and energy use. In the publication, the monetized social costs of nitrogen oxides, sulfur oxides, particulate matter, and carbon dioxide were assigned to emissions and the social cost of energy was assigned to energy consumption to develop an overall "costs borne by society" metric to compare two different cleanup options. There are two primary challenges with this approach. First, the social costs for emissions and energy varies by country and region, which has been partially addressed by recent studies. For example, Muller and Mendelsohn (2010) mapped marginal damages of emissions for each U.S. county based on locations of source emissions and associated air quality. Second, there may be more certainty for some social costs than others. For example, some site owners may be reluctant to share potential societal costs because of the uncertainty in how the costs may be interpreted. However, comparing options using social costs, when properly qualified, may help put some environmental impacts into context. There will always be a number of project attributes that cannot by monetized, but for those that can be, social costs may make the evaluation and communication of results more meaningful.

To progress the use of economic valuation methods to aid in remediation decision making, the approach needs to encompass a cost-benefit analysis framework that places the beneficial value of remediation in the context of improved soil and water quality, habitat and ecosystem services, and quality of life needs to be quantified alongside the costs of emissions and resource consumption. This type of framework has been embraced by the stormwater management industry to determine the value of green infrastructure installation compared with gray stormwater infrastructure. In addition, the Center for Neighborhood Technology's (CNT) Value of Green Infrastructure Framework evaluates economic, environmental, and social benefits in terms of water, energy, air quality, climate change, urban heat island, community livability, habitat improvement, and public education (CNT, 2011). The project to develop this framework was partially funded by the USEPA Office of Water and Watersheds. Obviously not all green infrastructure valuation metrics are applicable to remediation, however, these metrics can be used to expand upon the remediation economic valuation methodology. For instance, green infrastructure valuation frameworks assign emissions to electricity and natural gas costs, as opposed to social cost emission metrics. Reductions in ozone and particulate matter emissions are valued in terms of avoided air pollution health effects and associated cost savings using the USEPA's environmental Benefits Mapping and Analysis Program—Community Edition tool (USEPA, 2019) and other similar tools.

Literature on the valuation of ecosystem services is plentiful. In 2017, the USEPA developed a conceptual process for considering ecosystem services during cleanup activities that incorporates quantification of relevant ecosystem services endpoints (USEPA, 2017). Ecosystem services evaluation tools referenced in the report are primarily geographic information system (GIS) based. Further research is needed to integrate economic valuation methodologies into USEPA's conceptual process for cleanup to monetize benefits from ecosystem restoration.

Lastly, contingent valuation methods can be employed to engage stakeholders to determine the value of nonmarket resources, such as the impact of contamination on quality of life improvements. Evaluating sustainability metrics that represent quality of life and other community improvements can also be successfully achieved without monetization. However, employing these contingent valuation metrics often requires decision- science tools to help weigh and prioritize metrics.

4.3 | Programmatic sustainable remediation

Since the early 2000s, several government policies, international agreements, and agency and corporate initiatives have spurred the advancement of sustainable remediation. In the United States, Executive Orders signed by Presidents George W. Bush and Barack Obama in 2007 (Executive Order No. 13423), 2009 (Executive Order No. 13514), and 2015 (Executive Order No. 13693) have provided incrementally advanced protocols for achieving sustainability in government agency and corporate programs. The requirements of these Executive Orders were reflected in policies set forth by the U.S. Department of Defense and implemented throughout the supply chain. Remediation practitioners began to see contract requirements for green and sustainable remediation practices and requests for contractors to support achievement of broader agency or company goals in support of broader climate change, energy reduction, and sustainability initiatives. While these Executive Orders were revoked in 2018 (Executive Order No. 13834), the contract requirements and programmatic shifts they spurred have largely remained intact.

The National Research Council (NRC) also encouraged the inclusion of sustainability considerations in decision-making processes. The 2011 *Sustainability and the U.S. EPA*, also known as the "Green Book" (NRC, 2011), presents a sustainability framework recommending the USEPA consider the three components of sustainability in decision making. In 2014, at the request of the

USEPA and as a follow-up to the Green Book, the NRC published *Sustainability concepts in decision making: Tools and approaches for the U.S. Environmental Protection Agency* (NRC, 2014) to examine how to apply scientific tools and approaches to incorporate into sustainability assessments. Specifically, the NRC recommended that "[f]or every major decision, EPA should incorporate a strategy with the goal of assessing the three dimensions of sustainability (economic, social, and environmental) in an integrated manner" and "apply tools and approaches in a manner best suited to the type of problem being addressed" (NRC, 2014, p. 6). In the context of Superfund, the NRC recommended including the broad consideration of possible effects of remediation alternatives and referenced the use of LCA and the potential for natural systems to advance remediation.

This shift toward including sustainability in decision making has also been reflected in the emergence of federal and state agency sustainable remediation programs in the United States and proliferation of sustainable remediation groups internationally. Many corporations have acknowledged that human activities are contributing to global climate change, while facing significant public and shareholder pressure to operate with environmental, social, and fiscal responsibility. To this end, many organizations, spanning a wide range of industries, have established short- and long-term sustainability goals, including emission reduction targets and waste minimization. Depending on the size of an organization's remediation portfolio or the intensity of the remediation technologies employed, the environmental impacts of remediation may be small when compared to the organization's overall footprint. Yet, the ways in which an organization manages its environmental liabilities will also affect the communities in which it operates and, in the case of expensive, multiyear cleanups, influence aspects of the local or regional economy (e.g., jobs, tax revenue). Thus, it is increasingly important to consider all aspects of remediation, especially for large sites.

Organizational sustainable remediation programs vary in many aspects. Some organizations have established program requirements for applying sustainable remediation practices, while others have evaluated sustainability or applied BMPs in an ad-hoc fashion. Quantification and tracking of sustainability metrics may be valuable in some contexts but can also be difficult to track consistently across a large program. In cases where data collection and reporting are inconsistent, there is diminishing value in generating the information. As such, some companies have opted to forgo quantifying metrics, especially for smaller sites, where BMPs may provide a known benefit to a project.

Finally, the three components of sustainability is reflected among many remediation programs, though the balance of focus between the three components shifts based on the needs of the project and the priority of the organization. In the last 10 years, SURF meetings have served as an industry water cooler for organizations to share best practices and lessons learned as green or sustainable remediation programs have developed. Some of these organizations have included (in alphabetical order):

- The Boeing Company (Exhibit 1)
- DuPont
- ExxonMobil
- Ford Motor Company
- Norfolk Southern Railroad Company (Exhibit 2)
- Pacific Gas and Electric
- Shell
- U.S. Department of Navy (Exhibit 3)

In October 2018, sustainable remediation practitioners assembled at the Association of Environmental Health and Sciences Foundation (AEHS) 34th Annual International Conference on Soils, Sediments, Water, and Energy in Amherst, Massachusetts. In a panel titled "Organizational drivers for sustainable remediation", panelists[1] discussed some of the lessons learned from implementing sustainable remediation in their organizations. Among these:

- Exchange knowledge: sharing information about sustainable remediation, both internal and external to the organization is critical to gain understanding, acceptance, and adoption

Exhibit 1 The Boeing Company's sustainable remediation guidelines

The Boeing Company is committed to identifying cleanup project opportunities that use natural resources and energy efficiently, reduce negative impacts to the environment, minimize or eliminate pollution at its source, reduce waste to the greatest extent possible and stay abreast of policy, technology and industry standards associated with sustainable practices. This concept of sustainable remediation can be defined as a remedy or combination of remedies whose net benefit on human health and the environment is maximized through the judicious use of resources. Sustainable Remediation incorporates sustainable environmental practices into remediation of contaminated sites to increase the environmental, economic and social benefits of a cleanup so that remediation work can be performed in a way that (a) incorporates options to minimize the environmental footprint of remedy implementation; (b) reduces demand on the environment and natural resources during cleanup; (c) integrates sustainable practices throughout the life cycle of a remediation project; and (d) achieves remedial action goals and complies with environmental regulations. We developed Boeing's Sustainable Remediation Guidelines predicated upon information presented in the 2009 SURF white paper (emphasizing a Triple Bottom Line approach) and modeled around EPA's Green Remediation Core Elements. In 2010, we rolled out the Boeing Sustainable Remediation Program during our annual All Hands Meeting, also known as "Remediation Fest"

Exhibit 2 Norfolk Southern Railway Company's corporate sustainable remediation program

In 2016, Norfolk Southern Railway Company developed a Corporate Sustainable Remediation Program. The company recognizes that the use of sustainable remediation approaches throughout the remediation project lifecycle is likely to reduce impacts to the surrounding communities, minimize resource consumption, and reduce overall program costs. The objectives of the program are to:

(1) Implement the program across the company's entire portfolio of remediation sites.

(2) Use a tiered approach that matches the complexity of the sustainable remediation assessment with the size and complexity of the project.

(3) Provide sustainable remediation guidance to all consultants and require implementation at all sites at the appropriate tier.

(4) Roll up the quantified metrics at year-end to demonstrate progress and allow for a quantitative summary of the program's impact on the company's overall sustainability program.

As part of the company's tiered approach, sustainable remediation assessments have included combinations of sustainable remediation BMPs, quantitative remedial alternative evaluations in terms of sustainable remediation metrics, and subcontractor evaluations of sustainability performance.

Exhibit 3 U.S. Department of the Navy Green and sustainable remediation policy and guidance*

*Per the U.S. Department of Navy Environmental Restoration Program, the Navy is responsible for identifying and cleaning up contamination from hazardous substances, pollutants, and contaminants at both Navy and Marine Corps installations. The Navy is the lead agency for these CERCLA sites and works in partnership with the USEPA and state regulators to remediate the sites and ensure all federal and state requirements are met. Green and sustainable remediation principles and practices are being integrated into the Navy's existing optimization program. The "Policy for Optimizing Remedial and Removal Actions at All DON [Department of Navy] Environmental Restoration Program Sites states that "opportunities to improve performance and to evaluate green and sustainable remediation (GSR) practices shall be considered and implemented throughout all phases of remediation regardless of the regulatory framework under which cleanup may occur." (*U.S. Department of Navy, 2012a*). The policy requires optimization and green and sustainable remediation evaluations at key times during the CERCLA process, recommends relevant BMPs to be employed throughout the project lifecycle, and identifies metrics (e.g., energy consumption, greenhouse gas emissions, criteria pollutant emissions, water impacts, ecological impacts, resource consumption, worker safety, community impacts) to be included in evaluations. Guidance was developed to provide Navy remedial project managers RPMs and consultants with a clear approach to incorporating green and sustainable remediation considerations into the current remediation process (*U.S. Department of Navy, 2012b*).*

** This information was accessed on the Internet on July 5, 2019.*

- Seek opportunities for collaboration: seeking opportunities for synergy and collaboration (e.g., using waste by-product generated during operations in remediation)
- Recognize value: identifying remediation sites that may provide opportunities for jobs, investment, and societal assets to eliminate the perception that sites are merely a liability and that remediating sites sustainably is just an added cost
- Change outlook: fully integrating sustainability concepts into the remediation program, environmental strategy, and organizational culture versus adding concepts on an ad-hoc basis

As cited above, a number of organizations have integrated sustainable remediation into their operations. However, the vast majority of responsible parties do not have a program for implementing sustainability. There is an opportunity for those organizations who do not have sustainable remediation programs to learn from those who have implemented them so they can achieve consistent benefits across their remediation portfolios.

Panelists: Nick Garson, The Boeing Company; James K. Henderson, Corteva (formerly DuPont); Scott Pittenger, Norfolk Southern Corporation; and Thomas Potter, Massachusetts Department of Environmental Protection. Session Chairs: Paul Hadley, SURF, and Jake Torrens, Haley & Aldrich, Inc.

4.4 | Societal impacts

In 2009, SURF acknowledged social component of sustainability as important to consider to achieve sustainable outcomes from cleanup projects (Holland et al., 2011). Since then, many practitioners have come to the realization that the social component of sustainable remediation is not well defined nor operationalized (Harclerode et al., 2015; Hou, Guthrie, & Rigby, 2016). There is often confusion on the role of stakeholder engagement and which social indicators and social methodology(ies) to use to perform a technically sound sustainability assessment. In addition, there is often confusion about the definition of stakeholder engagement and how to operationalize it within the context of the social component of sustainable remediation. Over the past 5 years, progress has been made toward addressing these knowledge gaps.

Social indicators, in the context of sustainable remediation, are metrics that define potential socioeconomic-cultural impacts (costs) or benefits that result from a cleanup action and associated site activities (e.g., investigation and redevelopment) (Harclerode et al., 2015). These metrics are well defined in the literature and commonly used in environmental projects that do not involve remediation (United Nations, Department of Economic and Social Affairs, 2007), and those that do (ASTM International, 2013; Bardos, Lazar, & Willenbrock, 2009). The SURF Social Technical Initiative published "Integrating the social dimension in remediation decision-making: State of the practice and way forward" (Harclerode et al., 2015), which identified the following 10 main societal impact categories:

1. Health and safety
2. Economic vitality
3. Stakeholder collaboration
4. Benefits community at large
5. Alleviate undesirable community impact
6. Social justice
7. Value of ecosystem services and natural resources capital
8. Risk-based land management and remedial solutions
9. Regional global societal impacts
10. Contributions to local and regional sustainability policies and initiatives

Social methodology simply means tools and processes used to identify and evaluate social indicators (Limb & Dwyer, 2001; Neuman, 2012). When performing a sustainability assessment, social indicators are semiqualitatively or quantitatively evaluated at each stage of a remediation project's life cycle (i.e., investigation, alternative analysis, design, remedial action, and redevelopment). Social impact assessment techniques applicable to a remediation project (Harclerode et al., 2015), include but are not limited to:

- Rating and scoring system evaluations
- Social Sustainability Evaluation Matrix
- Envision™ rating system
- Enhanced cost-benefit analysis
- Multicriteria decision analysis

Stakeholder engagement is a separate and distinct process from performing a social impact assessment and is a component of evaluating the social component of sustainable remediation (Bond, Morrison-Saunders, & Howitt, 2013; Gibson, 2006; Pope, Annandale & Morrison-Saunders, 2004; Pope, Bond, Hugé, & Morrison-Saunders, 2017; Sinclair & Diduck, 2009). In the context of sustainable remediation, the objective of stakeholder engagement is to identify project-specific stakeholder needs and values to aid in selecting sustainability metrics and assessment methods, as well as in planning and performing public outreach, community involvement, and risk communication. Identifying stakeholder values and needs can be referred to as a stakeholder assessment. While integrating a stakeholder assessment into site activities and decision making can be performed in tandem with a social impact assessment, conducting a social metric evaluation is not stakeholder assessment nor does performing stakeholder engagement result in a robust social impact evaluation.

Over the last several years, considerable discussions pertaining to the role of stakeholder engagement in sustainable remediation have emerged during international conferences and panels, (SustRem 2014; SustRem 2016; SustRem 2018; USEPA Brownfields 2017) and research papers (Alexandrescu et al., 2018; Alexandrescu, Rizzo, Pizzol, Critto, & Marcomini, 2016; Cappuyns, 2016; Harclerode et al., 2015; Hou et al., 2016; Nathanail, Gillett, McCaffrey, Nathanail, & Ogden, 2016; Ridsdale & Noble, 2016). As part of these discussions, it is evident that early, meaningful stakeholder engagement is a vital component of the social component evaluation process, and early engagement helps shape the process of sustainability indicator selection (Cundy et al., 2013; Ridsdale & Noble, 2016). Several resources are available to sustainable remediation practitioners that guide performance of stakeholder engagement in community involvement and risk communication (USEPA, 2006, 2018), with even fewer resources that guide engagement in social indicator and impact methodology selection (Apitz et al., 2018; Harclerode et al., 2015; Nathanail et al., 2016).

Furthermore, performance of early stakeholder engagement to identify their needs and values for integration into a sustainability assessment is limited. Rather, early stakeholder engagement is more commonly performed in scenarios in which the community is either currently or will be significantly negatively impacted by the presence of contamination and/or site activities. Under these scenarios, stakeholders, in particular the community, are often outraged, which has likely resulted in the skepticism that early stakeholder engagement is only used in large, complex projects with potential societal impacts and uncertain outcomes. Furthermore, a perception has formulated that early stakeholder engagement may result in public backlash and/or a demand to perform above and beyond typical cleanup activities. Thus, remediation practitioners are faced with a systematic barrier to performing early, meaningful engagement to aid in development and performance of sustainable remediation. This barrier is especially disheartening when stakeholder engagement is a core element to the sustainable remediation process (Alexandrescu et al., 2016; Cappuyns, 2016; Harclerode et al., 2015; Nathanail et al., 2016; Ridsdale & Noble, 2016).

To overcome this barrier, it is essential to define the purpose and process of stakeholder engagement early in the project life cycle (Exhibit 4). Defining the site-specific purpose of engagement in the context of sustainable remediation is an often-neglected step. Often, practitioners think of stakeholder engagement as a reactionary purpose and to settle conflict and dissent. In reality, stakeholder engagement can be used to maximize stakeholder benefits from site investigation and risk management activities. For example, the site-specific stakeholder engagement purpose could be to identify social metrics to aid in the selection of ex situ or in situ treatment. These social metrics can then be used to design a sustainable remedy that minimizes detrimental impacts and maximizes beneficial impacts to the community.

A conceptual stakeholder assessment roadmap (see Figure 3) allows remediation practitioners to continue advancing the sustainability assessment process and integrating stakeholder engagement early in the project life cycle. The purpose of the roadmap is to provide a simplified framework to determine the site-specific role of stakeholder engagement, the purpose, and aid in engagement planning. As shown in Figure 3, the process of stakeholder engagement should be a means of partnership and information exchange.

Upon reflection of the past 10 years of sustainable remediation science, lessons learned, and research collaboration, the following lessons learned are offered to help practitioners perform successful, meaningful stakeholder engagement throughout the project life cycle.

- Invest time early in the project to identify regulatory, business, and community stakeholders.
- Include an engagement facilitator/technical expert as part of the project team.
- Formulate partnerships with "local champions" or representatives of public stakeholder groups.
- Consider engagement early in the project life cycle.
- Develop an engagement strategy with a participatory design lens.

While stakeholder engagement may result in upfront costs, it will likely save significant costs during project implementation. For example, stakeholder input on social metrics representative of site end-use can help avoid unwarranted remedial actions, such as removing contaminants to the appropriate zoning requirement (Ridsdale & Noble, 2016). Early engagement may avoid costly delays due to litigation, public descent, or a smear campaign on the responsible parties, site owners, or governments. There are various methodological approaches that are affordable, such as surveys, interviews, online information, and a dedicated telephone line for questions to aid in early engagement and determine if more comprehensive engagement is required. Each method used can be a transparent tool to then communicate back to the community and include as an engagement record in site documentation. Lastly, early engagement may lead to a more cost-efficient and sustainable risk management strategy which can provide maximum benefit to communities (Harclerode et al., 2016). Success stories are highlighted by the USEPA Targeted Brownfields Assessments and Region 7 Leading Environmentalism and Forwarding Sustainability Awards. For example, early engagement of the community at the Chemical Commodities, Inc. Superfund site resulted in a remedy that facilitated a pollinator habitat garden that serves as a sanctuary for monarch butterflies, neighborhood walking trails, and can used by the community to host pollinator educational events. Chemical oxidation treatment to address contaminated groundwater and the operation of vapor mitigation systems to address contaminated air in residences are ongoing (USEPA, 2012b).

Exhibit 4 **Purpose and process for stakeholder engagement**

The purpose of stakeholder engagement is dependent on the context and scale of the project, on each stakeholder's needs and values (in particular the community), and future use. While defining the purpose, practitioners should evaluate the potential drivers, barriers, and beneficial outcomes in conducting stakeholder engagement. A common misconception is that each procedural aspect of stakeholder engagement must be the same and be used for each and every site. Inevitably this idea of using stakeholder engagement only for large complex sites, leads to arguments that smaller sites do not meet the requirements for conducting stakeholder engagement. Not all stakeholder engagement operations are created equal, nor are projects. The exercise of defining the site-specific purpose is to determine the scale of engagement needed, if at all, in a transparent manner. Additionally, when the purpose is defined upfront, the team can identify potential conflicts and individualize responses. For example, early deliberation can avoid extra and unnecessary steps (i.e., conducting public engagement when consultation, information sharing is enough). If the site is complex, then the purpose of that engagement will change and become more robust. Another example is when remediation and redevelopment is community or government driven, the level of engagement changes as well as the tools and methodology.

After defining the purpose on what the project team wants to achieve with stakeholder engagement, the process of "how-to" and methodology of stakeholder engagement follows. Defining the stakeholder engagement process entails identifying the methods and materials used to perform stakeholder assessment and achieve the desired purpose. These methods include, but are not limited to, those listed under social impact assessment, as well as:

- *Social network analysis*
- *Audience assessment and actor mapping*
- *Design charrettes*
- *Interviews, surveys and focus groups*
- *Public meetings*
- *Web-based platforms and forums*

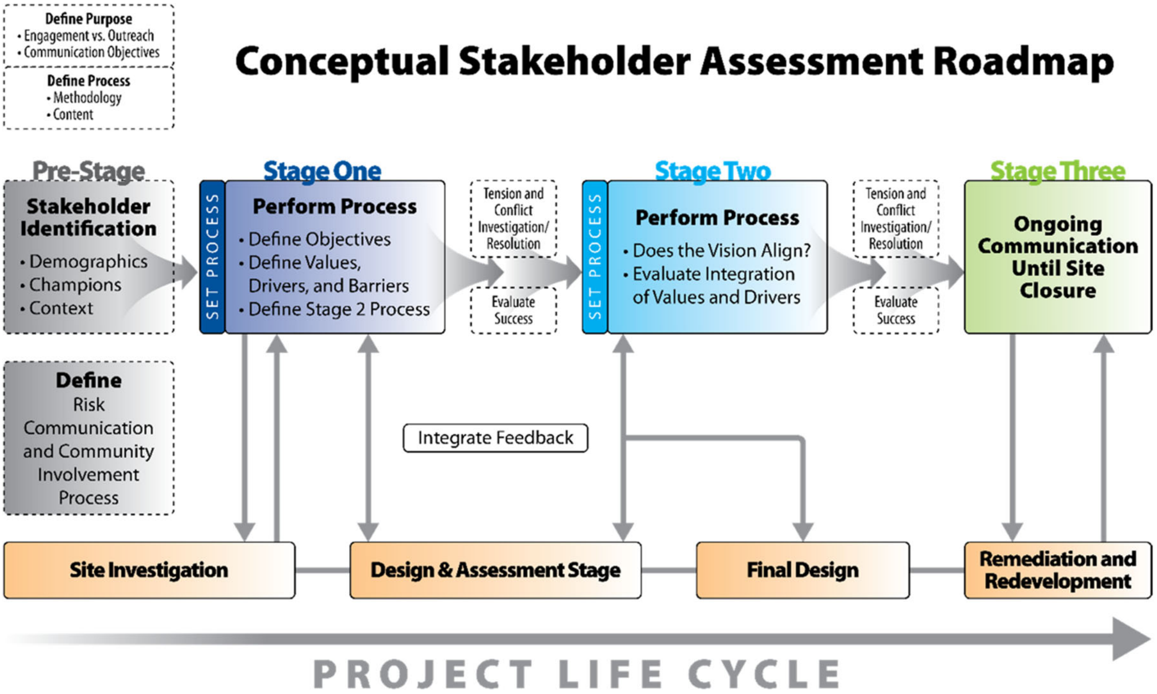

FIGURE 3 Conceptual stakeholder assessment roadmap (Ridsdale & Harclerode, 2019) [Color figure can be viewed at wileyonlinelibrary.com]

5 | SUSTAINABLE REMEDIATION IN THE NEXT 10 YEARS

This section provides a longer-term view of how sustainable remediation may evolve over the next 10 years and the drivers that may facilitate this evolution. Three types of future activities could change how sustainable remediation may be implemented in the future: (a) transformational changes, (b) societal influences, and (c) the continued progression of the practice. These three topics and the likely elements that would contribute to change are listed in the third column of Table 3 and described in more detail below.

5.1 | Transformational changes

Here, transformational changes are considered disruptive and create an immediate and urgent demand for more integration of sustainable

TABLE 3 Accomplishments to date, current challenges, and emerging frontiers, and the next 10 years

2009–2019 accomplishments	2019	2019–2029
Framework development		
Guidance development	***Current challenges***	***Transformational changes***
Tool development	Varying and/or incorrect perceptions	Climate change/extreme weather and resilience
Peer-reviewed literature	Lack of practitioner and site owner awareness	Emerging contaminants
Technical webinars and presentations	Limited corporate program integration	Big data and machine learning
Case studies	Ability to convey value and benefits	***Societal influences***
U.S. states and international geographies engagement	Lack of engagement of social and economic scientists	Social pressures and citizen awareness
Assessments and integration into projects	***New frontiers***	The governments we elect
	Climate change/extreme weather and resilience	Political and business drivers
	Weighting and valuation	Intergenerational impacts
	Programmatic sustainable remediation	***Progression of the practice***
	Societal impacts	Interdisciplinary engagement and education
		Technology and tools
		Adaptive management

remediation. Transformational changes include climate change and resiliency (which includes adaptation), emerging contaminants and big data and machine learning.

5.1.1 | Climate change/extreme weather and resilience

Climate change and resilience was presented in Section 4.1. While it is generally recognized that extreme weather events are increasing in intensity and frequency, most planning for potential flooding still refers to dated historical information (e.g., 100-year storm events) and does not consider precipitation increases. The same is true for increased potential fire risks. Most remediation projects in fire-prone areas do not address the potential threat of fires. Generally, the increased frequency of severe weather events is not yet thought to increase the probability of an event at a specific location such that additional remedy expenditures or planning is warranted. This thinking arises from the misperception that extreme weather impacts are generally more widespread than repeated at a specific location on a consistent basis. Without regulatory or governmental requirements, only further increases of frequency and intensity of flooding and fire will gain the attention of site owners and practitioners who currently ignore the potential impacts of future extreme weather.

How will the U.S. remediation industry respond to this challenge? There are two possible paths the industry may take:

1. Without a regulatory requirement, the consideration of climate change and extreme weather event impacts in remediation projects will continue to be voluntary; its prominence in remediation will only increase as the frequency and severity of extreme weather events increase. For example, site owners that have experienced remedy failure or negative impacts to remedies due to extreme weather will likely consider remedies that are more resilient to extreme weather events or develop adaptation plans to respond to these conditions.
2. Regulatory, permitting, and governmental entities may require site owners to consider extreme weather impacts on remedies, particularly on a local scale. Considerations could range from developing contingency plans (i.e., what to do in response to an extreme weather event) to integrating adaptation plans (i.e., managing future climate risk) into remediation plans.

The effects of climate change also create both risks and opportunities within site remediation which should be considered during remedial design and long-term planning (O'Connell & Hou, 2015). Some work in this area has been started. For example, the USEPA developed the "Climate change adaptation plan" (USEPA, 2014) and specific fact sheets. A new ITRC workgroup has been launched entitled "Green and Sustainable Remediation with resiliency to extreme weather events and wildfires" and will undoubtedly address these risks and opportunities.

5.1.2 | Emerging contaminants

One of the greatest challenges facing the remediation industry is how to effectively and sustainably remediate emerging contaminants, particularly perfluoroalkyl and polyfluoroalkyl substances (PFAS). These substances are composed of increasingly complex number of industrial compounds that degrade in the environment to complex and challenging daughter products. PFAS are more difficult to treat using current traditional remediation technologies; the most practical solutions include groundwater extraction with treatment using ion exchange or activated carbon. This method requires disposal or regeneration of the treatment media, resulting in significant environmental footprints. In addition, these treatment media are used with pump-and-treat technology, which is generally considered to be one of the least sustainable technologies due to its inefficiency in mass removal over time and inability to achieve cleanup objectives, high energy usage, and water usage. New treatment technologies are being developed, such as in situ immobilization or new chemical/biological methods, to address these contaminants. If these approaches use technologies that are not currently used in the remediation industry, a LCA of the technologies will be important to evaluate the full impacts of these approaches. LCA should also be performed on amendment, resin, and other treatment media considered for remediation to determine high environmental impacts within the supply chain that may be addressed with sustainable BMPs. Other considerations, such as social and economic impacts, and net environmental benefit analysis should also be leveraged to assure that new technologies do not contribute to unintended social, economic, and environmental impacts. The ITRC PFAS Technical Guidance includes sustainable remediation considerations for treatment technologies currently under consideration and in research and development (ITRC, 2018).

Another aspect of sustainable remediation that plays an integral role in managing emerging contaminants is stakeholder engagement, often in the form of community involvement and/or risk communication. Early, meaningful engagement with the public and other site stakeholders assists regulatory agencies and site owners in identifying community needs, values, and concerns. These social factors are a form of site sustainability objectives that can inform interim and long-term risk management decisions that best serve the community and impacted stakeholders. Revisiting the social component of sustainable remediation, stakeholder engagement tools and methods, as well developing a communication plan and community-based performance metrics can help implement and track the success of sustainable risk management approaches. The ITRC is currently preparing a risk communication plan toolkit to support practitioners in developing a comprehensive engagement strategy for environmental hazards of emerging concern.

In addition to PFAS, other contaminants such as 1,4-dioxane, nanoparticles, and pharmaceuticals also pose remediation challenges. Undoubtedly, additional contaminants will also emerge over the next 10 years. As remedies for current and future emerging contaminants are considered, integrating sustainable remediation in technology development will provide better solutions for society.

5.1.3 | Big data and machine learning

The remediation industry is continuously learning and implementing better data management. Through the decades, most decision-making organizations have transitioned from paper-based data to spreadsheets to databases and then to geospatial databases that are able to provide data visualization. The limitations with these systems are as follows:

- Geospatial data systems are implemented in a variety of ways by different organizations and people within the same organization.
- Individuals are not using the functionality of the geospatial databases to their full potential, and often relying on geospatial database experts to query the data rather than do it themselves.
- Geospatial databases are focused on a single site or facility.

Over the next decade, these database concepts will be more frequently used by engineers and scientists to improve site-specific data interpretation and result in better remedy decisions. For example, recent industry conferences have addressed virtual reality, three-dimensional physical models, and four-dimensional virtual models. Big organizations use databases to share data with multiple levels of decision makers. GIS databases are also starting to be used to share data transparently with regulators, third-party reviewers, and the public.

Along with these improvements, the internet of things will become an increasingly greater contributor to data. Subsurface sensors will become more sophisticated and allow practitioners to improve the quantity and quality of real-time data to monitor the pace of natural attenuation or impacts of remediation (e.g., changes in geochemistry and contaminant concentrations). These increased data will provide a feedback loop that will improve the understanding of remediation system performance and highlight when additional optimization is needed.

Despite the progress to date, many data collecting organizations continue to maintain field and laboratory data separately, making it difficult for decision makers to access all of the data electronically. The continued increased use of field data input devices will result in better integration of these data.

As the quality and quantity of site data increases, remediation practitioners will begin to use machine-learning techniques to identify trends and correlations that may further help decision makers improve the quality and confidence of their decisions. As the use of these techniques becomes more commonplace, practitioners will apply the practice to larger datasets to identify trends and correlations across a larger body of data to determine how to improve cleanup outcomes. As artificial intelligence (AI) becomes more prolific in the coming decade, it can be used to help identify and optimize remediation approaches and limitations with specific technologies. For example, AI will likely be used to evaluate databases to identify and determine which technologies can be effectively applied to a site. The determination will be based on site geology, chemistry, and biology, and the time to achieve different cleanup objectives may be predicted through stochastic results.

All of these improvements will help advance decisions at all steps in the remediation process—evaluation, design, and monitoring—leading to more optimized remedial outcomes that achieve objectives using less material and energy yet decrease the time until those objectives are achieved while still being protective of human health and the environment.

5.2 | Societal influences

Societal influences, both directly and indirectly remediation focused, may drive greater integration of sustainable remediation because of views on how remediation is performed and how it can be more sustainable. Societal influences include social pressures and citizen awareness and the governments we elect.

5.2.1 | Social pressures and citizen awareness

While most remediation industry stakeholders have heard of sustainable remediation, there is significant variance in the understanding of the concepts (Ridsdale & Noble, 2016; Rizzo et al., 2016). Additionally, these concepts are not familiar to communities and other stakeholders. Unlike nongovernmental organizations (NGOs) and investment firms that pressure industry for more sustainable processes and products, remediation organizations have not faced these pressures. Therefore, there is minimal social and decision-making pressure to consider and integrate sustainable remediation explicitly.

Stakeholders do not typically use the term "sustainable remediation," but instead request specific resilient remedies and impact minimization of select sustainability components (e.g., energy use, transportation through a community, local air emissions and climate change mitigation) during site cleanup activities. The future pace of these requests will be directly related to the increased intensity and frequency of extreme weather events or citizen awareness of local pollution issues and transportation challenges. For example, continued decreasing water table elevations and societal use of water may pressure site owners to increase the pace of their groundwater remedies to restore aquifers to beneficial uses or limit groundwater withdrawal and use more in situ remedies.

5.2.2 | The governments we elect

The governments we elect have an indirect though significant role in how sustainable remediation is implemented. Sustainable remediation is far too small an issue to be a platform issue in any election, but the implementation of sustainable remediation ebbs and flows with other more prominent environmental issues. Under the Obama administration, the United States saw numerous incentives and initiatives related to sustainability. The Trump administration has rolled back many incentives. While none of these incentives or rollbacks were directly focused on sustainable remediation, advances in sustainability topics (and resources dedicated to them) with a larger scope (e.g., greener energy, public education and awareness, clean air, climate change) can, and have successfully, trickled down to the remediation industry.

5.2.3 | Political and business drivers

By most industry size measures, the environmental remediation business is small with an estimated $42.8 billion in global revenues and $13 billion in the United States in 2015 (Environmental Business International, Inc., 2017). Thus, the remediation industry does not garner a lot of attention from politicians or NGOs compared with other industries. Most of the political and business impacts to the remediation business in the next 10 years will occur as a result of other business drivers. For example, a company that makes a top-down commitment to sustainability may request its remediation units to comply with corporate objectives. However, anecdotal information indicates that some global corporations consider their remediation activities too small to count in their data tracking activities (e.g., water usage, energy usage, greenhouse gas emissions). Likewise, unless a national "green plan" is adopted in the United States, it is unlikely that regulations will be written to specifically require the implementation of sustainable remediation practices. In the last decade, 10 U.S. states developed some sort of guidance or recognition for sustainable remediation but, as stated in Section 3.4.1, only three states (New York, Massachusetts, and Vermont) have some aspect of sustainable remediation as a regulatory requirement. Therefore, it is unlikely that political and business drivers will focus on sustainable remediation specifically. Rather, sustainable remediation will be impacted by the ebbs and flows of how sustainability—in general—is viewed, becoming more focused on aspects valued by corporate leadership and government.

If society (partially as a result of the governments we elect) increases its priority on sustainability (of which climate change perceptions can be a significant component), political and business organizations will place more pressure on the remediation industry to develop and select sustainable remedies.

5.2.4 | Intergenerational impacts

In the US, many remediation sites are contaminated with a complex mixture of contaminants and will require years (i.e., decades and, in some cases, centuries) of remedy operation, maintenance, and monitoring. The optimal solution for a specific remedy is based on the assumed conditions (e.g., time of remediation, appropriate valuation of money, impacts on future generations, planning for extreme weather) considered in the remediation plan. As these conditions change, the optimized solution changes.

For example, a solution based on 30 years of operations may be considered optimized for the assumed conditions during the project planning phase but could have deleterious impacts to future generations in the longer term. In these cases, decision makers must better understand how the decisions they make today impact future generations. For example, when calculating the net present value (NPV) of a remedy, it is not uncommon for practitioners to use a 7% discount factor and 30 years of operation. This approach reduces the value of future dollars to a small fraction of current (e.g., at year 30, only 13% of base-year dollars is represented), which, in turn, undervalues the needs of future generations to manage the remedy.

Other intergenerational impacts include long-term emissions from operations, the use of natural resources for continued remediation system operation, long-term containment of wastes in landfills, and the delay in being able to return the site to beneficial use because of ongoing remediation activities.

5.3 | Progression of the practice

The natural progression of the practice of sustainable remediation will continue to create new technologies, tools, and approaches in how sustainable remediation is implemented and will likely evolve from the three areas discussed below.

5.3.1 | Interdisciplinary engagement and education

When sustainable remediation became a new practice around 2006, the primary focus was on better understanding the environmental footprint of a cleanup. Most remediation practitioners focused the environmental component of sustainability based on their industry experience and education. It is becoming more apparent that the application of the social and economic components of sustainability are not advancing in sustainable remediation at a similar pace as the environmental component because of the limited technical resources and lack of practitioners with academic backgrounds. Some remediation industry stakeholders rationalize that the social and economic components of sustainability are less important and have not advanced as quickly because they are already addressed in the regulatory process (i.e., social components are typically addressed in the community involvement process and costs are always considered in the decision).

With the global focus on the importance of sustainability primarily through the lens of sustainable development, academic programs have and will continue to integrate sustainability education into their core curriculums. Numerous universities now offer various degrees in sustainability. Core education curriculums like chemistry and engineering are integrating sustainable education topics such as green chemistry and LCA. While these topics will be helpful in creating awareness about how sustainability can be implemented, they often do not leverage the experience of the social and economic sciences, especially at the undergraduate level. Engineering and science curriculums will need to better address sustainability and should offer more training in the social and economic components of sustainability. Students will need to understand all three components of sustainability, regardless of their field. Over the past 10 years, graduate environmental management programs that encompass a holistic, triple bottom line approach to environmental solutions, including a focus on contaminant remediation, have been established. Examples include the Environmental Science and Management Program at Montclair State University (New Jersey) and the Sustainable Management Program at Stevens Institute of Technology (New Jersey) (Montclair State University, 2018; Stevens Institute of Technology, 2019).

For individuals who have completed their education, the remediation industry and companies that work in the industry will have to train them to meet the demands of more sophisticated sustainable solutions. More industry guidance like the ASTM International's "Standard guide for integrating sustainable objectives in cleanup" (ASTM International, 2013) and the information presented in Section 4.4 on societal impacts can help educate practitioners and site owners.

To increase the application of the economic component of sustainability, interdisciplinary integration is needed with the financial/economic community. Investors and lending institutions sometimes drive more environmental investigation than regulators. For example, investment firms consider climate change resiliency in market analyses for valuation exercises. As discussed in October 2018 during a brownfields session at the 34th Annual International Conference on Soils, Sediments, Water, and Energy, remediation practitioners would be well served to integrate with real estate/market analysis experts to help facilitate an understanding of the return on investment for investing in cleanup.

There is also an opportunity to create better synergies with biologists who focus on improved ecosystems and natural treatment systems and who can bring more diversity of thought to sustainable solutions. Academic programs can provide additional LCA training (beyond a few lectures on the topic) for engineers so students are versed in the science and better understand the sustainability impact tradeoffs of using different technologies, materials, and processes. Also, training in decision science can better equip junior practitioners on how to facilitate the decision-making process to mitigate and address competing objectives and associated tradeoffs with greater certainty and transparency.

Although most academic and training programs are rooted in the concept of a 20th century world, recent graduates have been more exposed to sustainability-focused curriculum. More understanding and training on sustainability, climate change, and resiliency will prepare practitioners to meet the challenges of the 21st century. The synergy that will evolve from greater interdisciplinary involvement in the remediation industry can lead to new and sustainable solutions that have not yet been conceived.

5.3.2 | Technology and tools

Natural treatment systems, such as constructed wetlands (Kassenga, Pardue, Blair, & Ferraro, 2003) phytoremediation (Legault et al., 2017), and in situ bioreactors (Gamlin, Cox, & Castor, 2019) using locally available materials, and the progress in understanding microbiology hold great promise for contaminated site remediation. Natural treatment systems leverage the power of nature and decrease emphasis on intensive engineered elements. The environmental footprints of these projects are typically lower than traditional remedial measures (Favara & Gamlin, 2017) and also less expensive, while still mitigating unacceptable risks. The benefits of these systems are their general reliance on minimal energy and their low operations and maintenance requirements. Various configurations for these technologies exist, and limitations are based on contaminants, physical site features, and time constraints. As successful outcomes of natural treatment systems increase and perceptions of sustainable remediation improve, the uptake and implementation of these remedies will increase.

LCA is an excellent tool for assessing numerous impact categories of an engineered remedy (e.g., greenhouse gas emissions, acidification, resource depletion, energy use, respiratory impacts). As stated previously, few sustainable remediation practitioners use LCA because of its expense and steep learning curve. However, as young scientists and engineers who have been exposed to LCA are entering the remediation workforce and open LCA formats that use public domain tools and datasets are gaining in popularity, the accessibility and usability of LCA may increase. With an increase in LCA use, more sustainable remedies will be able to be developed. The NRC report recommended more use of LCA so there could be a better understanding of how actions affect systems (NRC, 2014).

BMPs are increasingly being leveraged as a valuable component of remediation planning. A number of BMP resources are available; however, these resources have created an overwhelming amount of individual BMPs. A more concise and better organized library of BMPs, with the addition of more social and economic considerations, will improve BMP applications in remediation projects and lead to more sustainable projects.

5.3.3 | Adaptive management

The USEPA is reinvigorating the concept of adaptive management to increase the rate of cleanup and address the increasing uncertainties. The concept of adaptive management is not new and has been used in the environmental remediation industry for decades and termed "observational approach," and "trial and error," among others. The USEPA has identified six Superfund sites to implement sustainable pilot studies in 2019. The results of these pilot studies may provide additional insights about how adaptive management can be implemented to address the remediation of complex sites and possibly the impacts of extreme weather events. From a sustainable remediation perspective, adaptive management can shine a light on how to assess the potential impacts of extreme weather and climate change in existing or planned remedies and help determine the need for resiliency plans that outline how to monitor remedies and respond to such events. The sustainability performance of these remedies can also be incorporated in adaptive management plans.

5.4 | Potential interrelationship changes (or "the ripple effect")

The above-described future progression of sustainable remediation is interrelated in that changes that occur to progress in one area of practice can influence another. Some of these interrelationships are presented in Figure 4. For example, if a government administration wants to make progress on climate change, sweeping regulations or incentives may occur across different industries to achieve sustainability. The incentive for progress may result from current conditions, some uptick in intensification of extreme weather impacts, or voters' demand to address climate change. While it is unlikely that these sweeping changes would specifically focus on the remediation industry, interrelationship changes could result in more sustainable remedies. Social activism can also trigger this same demand for more sustainable remedies, and this activism can be triggered by concerns for climate change and emerging contaminants.

6 | SUMMARY AND CONCLUSIONS

Many advances have occurred in the sustainable remediation field in the past 10 years. Similar to when SURF issued its white paper in 2009, a number of opportunities and challenges face the integration of sustainability principles and practices into remediation projects. Table 3 provides a summary of past accomplishments, current challenges, and emerging frontiers. In addition, Table 3 provides a forecast of what the next 10 years may hold for sustainable remediation.

The greatest successes in sustainable remediation over the past 10 years have been the development of different frameworks, tools, guidance, literature, and application of green and sustainable remediation concepts and principles at hundreds of project sites. The concept of sustainable remediation has also spread geographically, with a number of U.S. states and all 10 USEPA regions adopting some guidance or policy on green or sustainable remediation. These concepts have also proliferated across the globe to different countries.

Most sustainable remediation practitioners and site owners agree that integrating sustainability concepts and practices into remediation projects has value. Consensus among these same practitioners is that many remediation practitioners and industry stakeholders have varying and incorrect perceptions of the practice. While some organizations have developed corporate guidance for implementing sustainable remediation, most have not—and, without this guidance, well-intentioned sustainable remediation efforts will likely fall short of expectations. Although the technical development of the practice has grown significantly in the last 10 years, the focus has been primarily on the environmental components of sustainability, leaving social and economic considerations underrepresented. Furthermore, use of sustainable remediation concepts has been reserved primarily for large sites or pilot projects rather than implemented portfolio-wide by corporate entities.

These limitations associated with sustainable remediation implementation are beginning to be addressed. Emerging frontiers in the practice are addressing new and important issues such as societal impacts; meaningful stakeholder engagement; climate change and resilience; and weighting, and valuation. Incremental growth in the

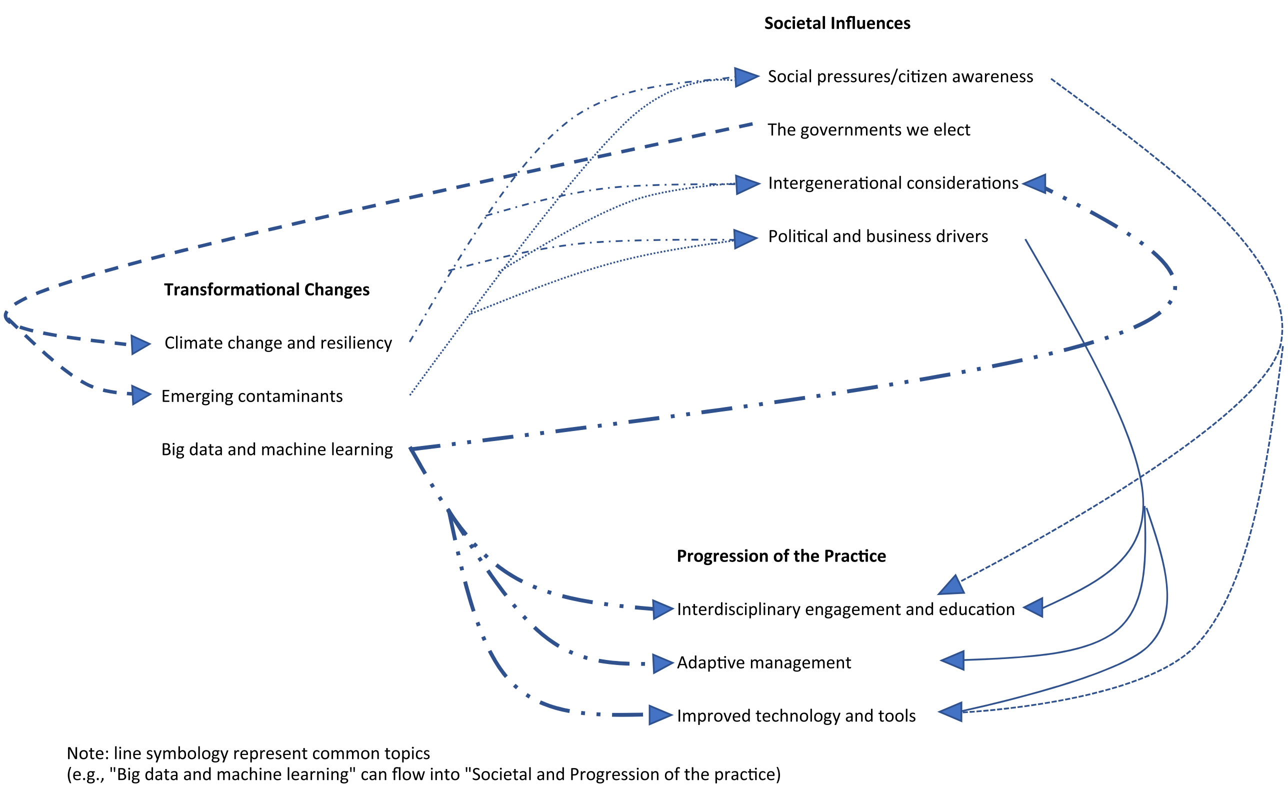

FIGURE 4 Influence diagram of the next 10 years of sustainable remediation [Color figure can be viewed at wileyonlinelibrary.com]

use of sustainable remediation practices can be achieved with new thought leadership, additional publicly available tools, the use of sustainable remediation as an engine to develop new remediation technologies, the integration of disciplines from all three components of sustainability, and the use of adaptive management. Additionally, SURF organizations around the globe will continue to advocate for sustainable remediation by better articulating the value and benefits to site owners and stakeholders.

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