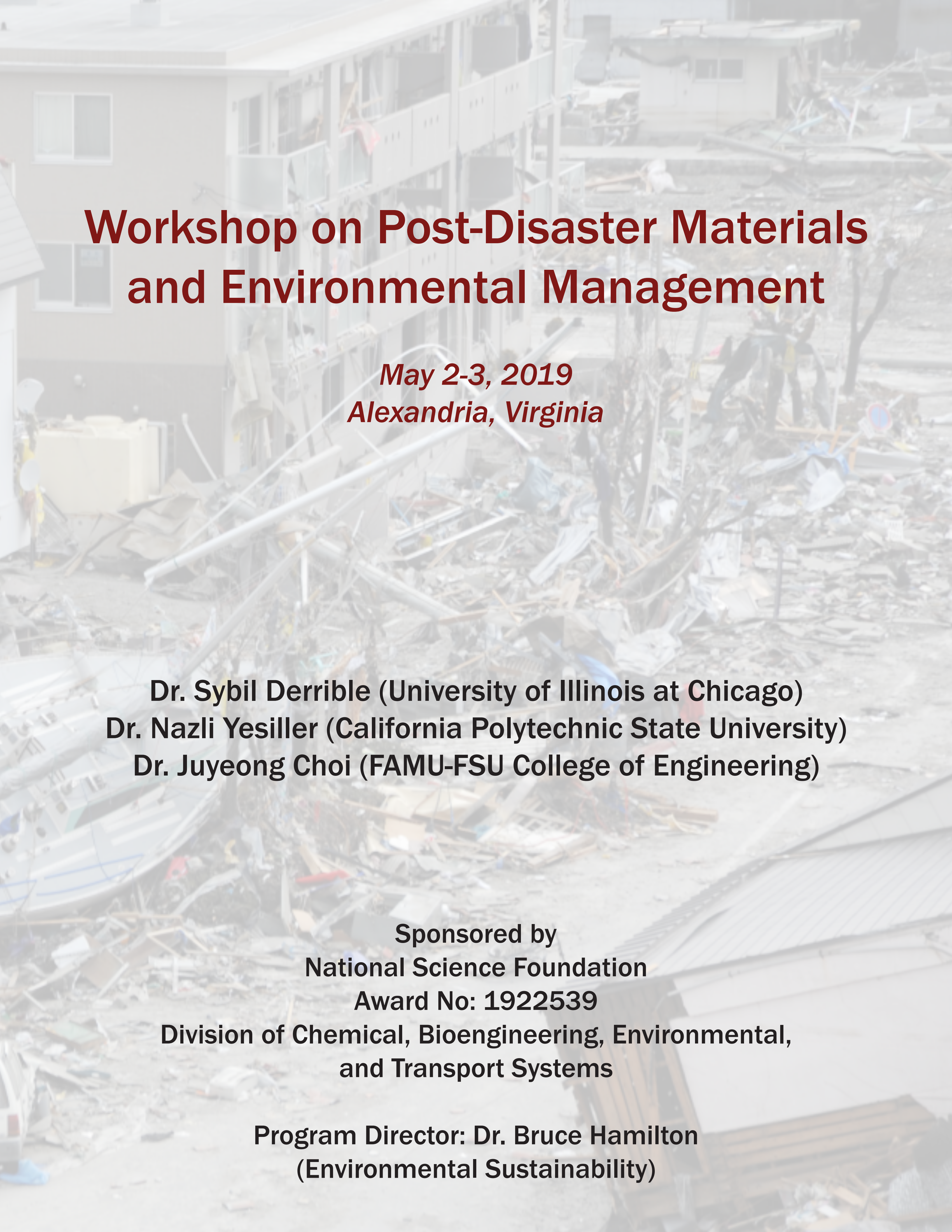

Workshop on Post-Disaster Materials and Environmental Management

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INTRODUCTION

Millions of tons of debris and waste are generated due to natural and anthropogenic disasters on an annual basis in the United States (U.S.) as well as other parts of the world. The main causes of disaster events include storms/hurricanes, fires/wildfires, earthquakes, tsunamis, volcanic eruptions, and explosions. In 2018 alone, there were 8 hurricanes in the Atlantic region and over 8000 fires in California. High hurricane winds and wildfires directly cause destruction, while high precipitation from hurricanes and following fire events cause flooding, mudslides, landslides, rockfall, and debris flows.

The occurrence, magnitude, and particularly damage and destruction from disasters have been increasing due to increases in population (Najafi et al. 2013), climate change (Oh 2010), controlled and uncontrolled urbanization, deforestation, soil erosion (Sudmeier-Rieux and Ash 2009), inadequate and aging infrastructure (Cutts et al. 2017), and also due to significant alterations of the natural environment (Sudmeier-Rieux and Ash 2009). The increasing trends are expected to continue in the foreseeable future due to lack of effective measures available to significantly reduce the occurrence of and resulting impacts from major disaster events. Disasters affect both rural and urban areas with more significant implications for urban centers due to the prevalence of human activity and the built environment (McDaniels et al. 2015; Oh et al. 2013). The composition of disaster debris and waste varies as a function of the type of disaster (e.g., earthquake, storm, and wildfire), geographic location, population density, building structure, and socioeconomic setting (EPA 2008). In general, disaster events generate significant amounts of debris similar to construction and demolition (C&D) waste in populated areas and high amounts of natural materials and organic matter in rural areas and less developed locations (Brown 2012). Hazardous materials enter the waste stream from various sources in variable types and amounts as a function of specific source such as residential, commercial, institutional, industrial, and agricultural sources (Yesiller 2012). Inert wastes as well as hazardous materials pose human health and environmental risks including impacts on soil, groundwater, and air.

The management of debris and waste in the aftermath of major disasters is complicated by the priority for search and rescue efforts and the constraints associated with available disposal, treatment, recycling, or reuse infrastructure; access to waste management facilities; transport of waste; environmental hazards; and financial responsibility and ownership-related legal and ethical issues (Yesiller 2012; Brown and Milke 2016). The most significant issue is the sheer magnitude of the debris and waste materials generated (Kim et al. 2018). Moreover, the highly heterogeneous nature of waste and debris including mixed materials (composition, size, shape), presence of hazardous and toxic constituents, and widely variable moisture contents, complicate the proper management of these materials (Brown and Milke 2016). These problems are further exacerbated by requirements for rapid response and restoration of basic lifelines that necessitate fast removal of debris confounding sustainable management practices including recycling, beneficial reuse, waste-to-energy-conversion, and optimal disposal.

While significant research has been conducted on disaster resilience ranging from development of tools, models, and guidelines with special emphasis on infrastructure resilience across different phases of the disaster management cycle (i.e., mitigation, preparedness, response, and recovery phases) (e.g., Bristow and Brumbelow 2012; Chang 2003; Choi and Hastak 2018; Deshmukh and Hastak 2014; Kocatepe et al. 2017) including pre- and post-disaster community resilience (e.g., Miles 2014; Lam et al. 2016) and hazard mitigation (e.g., Chang 2003; Espada et al. 2015; Oh et al. 2010); little work, in particular in the U.S., has focused on post-disaster materials and environmental management for debris and waste. California, for example, has extensive preparedness and mitigation plans (2018 State of California Hazard Mitigation Plan, 1088p.); however, post-disaster debris and waste management is typically included in broad generalized terms with only tenuous references to state solid waste laws and regulations. Similar observations apply to guidance documents from other states that are highly susceptible to major disaster events such as Louisiana (2014 State of Louisiana Hazard Mitigation Plan), North Carolina (2018 State of North Carolina Hazard Mitigation Plan), and Texas (2018 State of Texas Hazard Mitigation Plan). Furthermore, individual states typically have their own policies related to management of debris and waste. However, as seen in past disaster events, the individual state policies are often inconsistent with post-disaster recovery approaches of the U.S. Federal Emergency Management Agency (FEMA) such that the states cannot fully pursue their own policies to manage post-disaster debris and waste (e.g., State of California–1994 Northridge earthquake, State of Louisiana–2005 hurricane Katrina) (Brown and Milke 2016). In an effort to minimize the conflict between federal regulations and local regulatory requirements, the U.S. Environmental Protection Agency (EPA) published the “Planning for Natural Disaster Debris” guidance in 2008 with a revision provided in 2019. In particular, the recently revised report documents federal regulations and recommendations that are intended for local governments for development of regional debris management plans in advance, highlighting the importance of pre-incident debris management planning using past disaster debris management cases. Furthermore, in addition to local governments, the report strongly urges engagement of the whole community (i.e., private, nonprofit, community, and other stakeholders) in debris management planning to maximize communities’ capacities to handle large quantities of debris (e.g., developing and implementing segregation strategies at a community level and building end markets for potential debris streams).

Technical or educational research investigations, research and development activities, and overall research output related to disaster debris and waste are limited in the United States. In line with limited research activity, the available analytical and modeling tools for estimating physical damage and economic losses (e.g., the HAZUS-MH software developed by FEMA and a debris estimating model developed by USACE) are focused on identifying the number of impacted buildings (in some cases additional infrastructure components) and assigning monetary amounts to the expected damage and losses (FEMA 2010). Tools typically are not available for management of materials generated in the aftermath of a disaster event. For example, HAZUS-MH uses demographic and geographic data to estimate the post-disaster debris composition and amount (FEMA 2013). However, this tool does not provide the information essential for planning and management of disaster waste including geographical spread of disaster debris, areal extent of the waste, access to waste materials, removal and delivery of wastes, segregation and recycling, or temporary storage and final disposal at appropriate facilities. Limited research and knowledgebase on post-disaster debris and waste impedes sustainable management and valorization of the post-disaster materials through reuse, recycling, and waste-to-energy applications.

Therefore, the objective of the proposed workshop was to bring together experts from academia and from public and private institutions across the United States to identify critical research questions with respect to the sustainable management and environmental impacts of the debris and waste generated by disasters, with a focus on debris reuse and recycling. The workshop was proposed by a uniquely qualified cross-disciplinary group of organizers with complementary expertise. The workshop, for the first time, provided a broad forum for discussion of disaster debris and waste management issues with an interdisciplinary group of participants. Overall, the workshop enabled the identification of important research questions that need to be addressed as well as create an initial network of partners who will collaborate to pursue the research initiatives identified during the workshop.

WORKSHOP SUMMARY

Workshop Participants

The workshop had a total of 36 participants that consisted of a diverse group of individuals specifically selected by the PIs (Table 1). The essential attributes of the participants were established as demonstrated expertise and/or interest in workshop topics through theoretical, experimental, or modeling research investigations, publications, oversight of management activities, development of new interventions, leadership in interdisciplinary studies, and specifically direct and central involvement in post-disaster recovery and waste and debris management activities during recent disaster events.

Table 1 – Workshop Participants

Name	Affiliation	Expertise
Academic		
Tarek Abichou	Civil and Env. Eng. FAMU-FSU College of Eng.	Waste management, geotechnical/ geoenvironmental eng, landfill design, coastal resiliency, landfill emissions
Akram Alshawabkeh	Civil and Env. Eng. Northeastern University	Geoenvironmental eng, geoenv restoration, environmental health
Weslynne Ashton	Stuart School of Business Illinois Institute of Technology	Industrial ecology, circular economy, sustainability and resilience of socio-ecological systems
Callie Babbitt	Golisano Inst. of Sustainability Rochester Institute of Technology	Sustainable waste systems (food waste, e-waste, batteries), industrial ecology
Kira Baltutis	Urban Planning University of Illinois at Chicago	Urban planning
Lawrence Bank	Civil Engineering City College of New York	Recycling and reuse of materials, engineering and architectural design
Yong Kwon Cho	Civil and Env. Eng. Georgia Institute of Technology	Automation and robotics for damage detection and disaster relief activities
Juyeong Choi	Civil and Env. Eng. FAMU-FSU College of Eng.	Infrastructure system-of-systems, community resilience, demolition planning
Christian Claudel	Civil, Architectural, and Env. Eng. Univ. of Texas-Austin	Control systems, traffic control, UAVs
Sybil Derrible	Civil and Materials Eng. University of Illinois at Chicago	Urban engineering, smart, sustainable, resilient cities
Ozlem Ergun	Mechanical and Industrial Eng. Northeastern University	Infrastructure/network recovery, debris clearance, removal and disposal operations, supply chain resilience
Arvin Farid	Civil Eng. Boise State University	Geotechnical, geoenvironmental, and electrical engineering and geophysics
Bruce Hamilton	Environmental Sustainability National Science Foundation	Environmental sustainability
Jose Holguin-Veras	Civil and Env. Eng. Rensselaer Polytechnic Institute	Disaster response logistics, sustainable freight transport
Pinar Keskinocak	Industrial and Systems Eng. Georgia Institute of Technology	Debris management, resource allocation, scheduling, network design, network

		recovery
Yongcheol Lee	Construction Management Louisiana State University	Disaster damage identification, recovery, and risk analysis
Derek Manheim	Global Waste Research Inst. Cal Poly State University	Biochemical engineering, biotechnology, numerical and systems modeling, environmental microbiology
Nikolai Maximenko	Intnl. Pacific Research Center University of Hawaii	Debris tracking and modeling in the ocean, pathways and impacts of marine debris from disasters and general sources
Priscilla Nelson	Mining Eng. Colorado School of Mines	Geotechnical, structural, infrastructure, resilient systems, geological eng
Terri Norton	Civil and Env. Eng. Bucknell University	Structural (dynamics, vulnerability), debris management, disaster recovery and reconstruction, debris characterization
Krishna Reddy	Civil and Materials Eng. University of Illinois at Chicago	Environmental remediation, waste management, landfill engineering, resilient and sustainable geoengineering
Maya Trotz	Civil and Env. Eng. University of South Florida	Community engagement/education, stormwater/water quality/source protection
Adam Yeeles	Nature Climate Change	Environmental/social risk assessment, public policy, science communications
Nazli Yesiller	Global Waste Research Inst. Cal Poly State University	Geotechnical/geoenvironmental eng, disaster waste mng, containment systems, landfill eng
Public and Private Organizations		
Nicole Boothman-Shepard	AECOM	Resilience and recovery management
Suzanne Boxman	EPA	Sustainable materials management, resource recovery, systems thinking
Laurent Corroyer	World Bank	
Melissa Kaps	EPA	Waste/debris management-related planning and preparation for disasters
Ken Lewis	Waste Management	
Wessel Mindermann	CalRecycle	Disaster debris management, landfill engineering, landfill remediation
John Morton	World Bank	Sustainable solid waste management in world countries
Hiroshi Ogawa	Kajima Corporation Tokyo, Japan	Disaster debris and waste management, landfill engineering, waste-to-energy
Holly Pelt	FEMA	Coordination, consultation, and compliance with environmental laws
Kristina Torres	EPA	Sustainable materials management policy
Christopher Vaughan	FEMA	Geospatial information, disaster management
FEMA Tour		
Liz Jackson Carol Mintz	FEMA	National Response Coordination Center

The PIs engaged participants with varied backgrounds and demographics The participants consist of academic and non-academic contributors. The academic contributors constituted

67% of the participants with the remaining 33% from non-academic institutions. The backgrounds of the participants represent technical and non-technical fields and also include policymaking in line with the complex and interdisciplinary topic of the workshop. The academic participants were from R1 research, primarily undergraduate, and historically black colleges and universities institutions. The non-academic participants were selected from regulatory agencies at federal and state level and large consultancy organizations as well as the waste management industry. The non-U.S. participant was from a large construction, consultancy, and research and development company from Japan with practical expertise in collection, storage, separation, recycling and reuse, and disposal of the large quantities of hazardous and non-hazardous waste materials and debris that resulted from the 2011 great east Japan earthquake. Approximately 45% of the participants were from underrepresented groups. The total number of participants, the relative contributions of academic and non-academic participants, the backgrounds and expertise of the participants, and the relative proportion of participants from underrepresented groups met and exceeded the levels targeted in the original proposal and thus achieved the workshop participant goals set forth in the proposal. A group photo of the participants is provided in Appendix A.

Workshop Activities

Day 1 of the workshop included a set of activities, presentations, a guided tour FEMA's National Response Coordination Center (NRCC), and a networking dinner. Day 2 included short activities and time to write up the knowledge generated during the workshop. The workshop agenda is presented in Table 2. An online file sharing platform has been used extensively by the PIs starting with the proposal preparation stage. The online platform was used for making arrangements for the workshop after funding was received by the PIs; informing participants of necessary arrangements pre-workshop; generating and collecting ideas and organizing recommendations and preparing materials summarizing workshop results during the workshop; and sharing various workshop materials such as presentations and reports during all stages.

Table 2 – Workshop Agenda

Day 1 (05/02/2019)	
8:30 – 9:00	Arrival and breakfast
9:00 – 9:30	General introduction and participant introduction
9:30 – 9:50	Disaster scenarios and initial brainstorming of relevant focus areas
Time	**Item**
9:50 – 10:10	Talk 1: Nicole Boothman-Shepard (AECOM)
10:10 – 10:30	Talk 2: Wes Mindermann (CalRecycle)
10:30 – 10:40	Brainstorming of relevant focus areas

10:40 – 10:50	Break + Vote
10:50 – 11:00	Forming teams
11:00 – 12:00	Team activity: identification of specific challenges that require scientific research
12:00 – 1:00	Lunch Talk 3: Holly Pelt (FEMA) Talk 4: Suzanne Boxman and Melissa Kaps (EPA)
1:00 – 2:00	Team activity: identification of important research questions and of research methods to solve research questions
2:00 – 2:15	Preliminary reports from teams
2:15 – 2:30	Walk to bus
2:30 – 3:15	Transportation to FEMA
3:15 – 5:00	FEMA's National Response Coordination Center (NRCC) tour
5:00 – 6:00	Transportation back to hotel
6:00 – 6:30	Break
6:30 – 8:00	Networking dinner at A La Lucia (315 Madison St, Alexandria, VA 22314) – 2-min walk
Day 2 (05/03/2019)	
8:00 – 8:30	Arrival and breakfast
8:30 – 9:30	Talk 5: Hiroshi Ogawa (Kajima Corp.)
9:30 – 10:30	Teams: research needs and future work for research on post-disaster materials and environmental management
10:30 – 10:50	Break
10:50 – 11:35	Team activity: write up and next steps (led by team captain)
11:35 – 11:50	Report from teams
11:50 – 12:30	General participant discussion
12:30 – 1:00	Lunch
1:00	End of workshop

The PIs developed a comprehensive plan of activities that followed a well-defined and structured sequence: (1) problem identification during disaster events, (2) research question identification, and (3) research solution identification. The main activity scheduled for Day 1 was collaborative work on disaster events for all participants of the workshop and identification of the main problems that may arise, identification of the approaches and tools to study these problems, and devising potential solutions to these problems. The disaster events were viewed mainly from the perspective of post-disaster materials and environmental management with an emphasis on reuse and recycling of the post-disaster materials.

The collaborative work was initially facilitated by the talk presented by Nicole Boothman-Shepard, Vice-President of Resilience + Recovery at AECOM. The presentation provided data and analysis related to hurricanes as well as sea-level rise events that have impacted Florida, particularly the areas in and around Miami in the past as well as included predictive scenarios for future events. The immediately following second presentation by Wes Mindermann (Engineering Support Branch Chief under Waste Permitting, Compliance and Mitigation Division, CalRecycle) related to disaster debris and waste management operations in the aftermath of the major fires in California in 2018. The participants were asked to fill in a Brainstorming Board available online during the talks to provide ideas towards identifying critical issues related to disaster materials management. Open discussion was held subsequent to the two talks to identify the main critical issues related to environmental management of disaster waste materials. The varied ideas and suggestions provided by the participants were then organized by the PIs during a break and four topics are identified for further detailed discussion and development during the workshop. Next, the participants were asked to select a topic based on their interests and background and four teams were established to work on the identified topics during the remainder of the workshop. The breakout team sessions started on Day 1 and continued through Day 2. Preliminary reports from the four teams were presented prior to the tour on Day 1 of the workshop.

Day 1 activities also included two additional talks, one presented by a participant from FEMA and one presented by two participants from EPA. In addition, the workshop group toured the National Response Coordination Center (NRCC) at the FEMA Headquarters in Washington DC. The tour included in-depth coverage of the pre-disaster event tracking activities of FEMA, actions during disaster events, and post-disaster activities. The tour also identified the different groups of FEMA with different backgrounds and expertise that work on a given event as well as potential participants from other federal agencies. In particular, the major role of NRCC to coordinate with disaster-affected regions and provide overall federal support over different stages of disaster management activities is highlighted. The tour described NRCC's support functions and processes including emergency management coordination, planning, and resource deployment. In direct relation to the focus of the workshop, the tour indicated that relatively low emphasis is placed on sustainable management of post-disaster materials and this is not yet an area of priority for FEMA even though this is the main U.S. federal agency charged with the coordination of federal assistance activities during major disaster events.

Day 2 started with a talk by Hiroshi Ogawa from Kajima Corporation (remote presentation from Japan) that focused on management of a large quantity of disaster wastes generated during the great east Japan earthquake in 2011. The presentation generated high interest and was followed by active discussion (details of all of the talks are provided in the next section). Further collaborative work was conducted next during team breakout sessions. The team reports were finalized at the end of the breakout sessions and the reports from each of the four teams were presented to all of the participants. The workshop ended with a final group discussion.

Workshop Talks

The workshop included a total of five talks by participants from two private corporations, two federal agencies, and one state agency. The slides of all of the talks are archived at https://drive.google.com/drive/folders/1reJSPRRL1ANxKoPGv2zxu6uzILmyhq7L together with the informational presentations provided by the workshop organizers. The first talk was provided by Nicole Boothman-Shepard from AECOM and consisted of two parts. The first part provided vignettes from varied disaster events that had occurred at different locations across the U.S. The presentation identified major issues associated with the aftermath of the various events including types and amounts of waste and debris, timelines for removal, potential hazards, and in a few cases examples of separation and reuse. The second part consisted of specific disaster scenarios for Miami metro area for hurricane events. The analysis included estimates for debris types and amounts for present day and also future predictions.

The second talk was provided by Wes Mindermann from CalRecycle. The presentation focused on fire disasters and included data related to the amount of debris generated, duration of collection, and associated costs. Detailed information was provided on types of materials as well as landfilling and recycling rates for an example event from 2018 (i.e., Camp Fire). The presentation also included results of analysis from two studies conducted to characterize wildfire debris.

The third talk was provided by Holly Pelt from FEMA. She provided an overview of FEMA's debris response activities. Information was provided on types of debris and methods of disposal. Examples were included related to temporary storage and recycling operations. Hazardous materials that are commonly encountered in the debris were described. Coverage also was provided related to relevant environmental laws and considerations.

The fourth talk was provided jointly by two participants from EPA, Suzanne Boxman and Melissa Kaps. The talk focused on planning activities for natural disaster debris management and included description of guidance documents available from EPA and an online waste management planning tool. A recent document entitled "Planning for Natural Disaster Debris" published in 2019 was highlighted in the presentation. Older documents related to sustainable materials management also were included.

The fifth talk was provided remotely by Hiroshi Ogawa from Kajima Corporation in Tokyo, Japan. This presentation had the longest duration of all of the talks included in the workshop and was followed by a long discussion session with involvement of a large number of the workshop participants. The presentation at first provided background information on the great east Japan earthquake of 2011 and the associated tsunami including amount and types of waste and debris generated. Difficulties associated with characterization (physical and chemical) were identified. Next, a project that was conducted to manage approximately 10% (3 million tonnes) of the total amount of debris generated was described. The comprehensive project included extensive characterization of the debris and waste mass including physical and engineering properties as well as for presence of toxic components. The waste materials were screened, sorted, reduced in size, cleaned-up, and assessed for reuse and recycling. The project resulted in reuse and recycling of 82% of the debris and waste materials. The project was conducted entirely at temporary facilities set up for the sole purpose of the management of the disaster debris and disassembled subsequent to the debris management operations.

The talks collectively informed the discussions held at the workshop providing background and examples of debris and waste management operations. The information provided related to recent events and included the latest technological developments and best management practices available at the current time. While examples of sustainable environmental management of the post-disaster materials were provided, disposal of these materials in landfills is commonplace in the U.S. and reuse and recycling rates are relatively low. Various factors influence the management of these materials and technical and non-technical barriers are present for valorization of the post-disaster debris and wastes.

Workshop Themes and Teams

After the first two talks and group discussion on the morning of Day 1, four distinct themes were identified for detailed work during the remainder of the workshop. These themes were: pre- and post-disaster debris characterization and inventory; recycling/reuse planning and optimization; technology development (for improving recycling/reuse, handling, and monitoring of disaster materials); and business models and market development. The workshop participants were asked to select a theme, and four teams were formed corresponding to the four themes. Interactive team breakout sessions were held multiple times throughout the remainder of the workshop. The PIs prepared a template prior to the workshop to i) facilitate discussions during the individual breakout sessions, ii) provide a framework for identifying and addressing the significant components targeted to be covered during team discussions, and iii) ensure that the teams generated complete reports during the workshop eliminating the need for post-workshop team report preparation. The template is provided below and was made available through the online file share platform during the workshop.

Team Report Template

Focus Area Title

Summary:
[Use bullet points and short sentences. The summary should be between 150 to 300 words. Include text on context around focus area, typical challenges, intended outcomes, research questions, research methods, future work.]

Team members: [list of team member names]

A. General Context and Relevance of the Focus Area

[In general, why is this focus area relevant to post-disaster materials and environmental management? Emphasize why the focus area is important to help specific agencies/institutions and the broader society.]

B. Focus Area Challenges and Intended Outcomes

[Using bullet points, list specific challenges relating the focus area to the workshop theme of post-disaster materials and environmental management. Moreover, list the intended outcomes (i.e., what are the objectives) of addressing these challenges and include both a discussion of the outcomes for specific agencies/institutions and the broader society.]

C. Research Questions and Methods

[Using bullet points, list specific research questions to address the challenges listed in section B, and list the research methods that are appropriate to addresses these questions. You can categorize the research questions in subtopics if needed. Be broad but try to rank the five most important research questions.]

D. Research Needs and Future Work

[List the research needs and the future work for the questions listed in section C. Do you need more data, new NSF programs, more collaboration with agencies, etc.?]

E. Actionable Research

[If addressed, list how research questions from section C would be implemented and who would use the results.]

Team 1 focused on pre- and post-disaster debris characterization and inventory. The main research questions and needs identified are related to technology innovation for fast and effective pre- and post-disaster debris characterization, debris data analysis, debris planning and management, and human behavior across a disaster time frame (i.e., pre- and post-disaster phases). The main outcomes from the Team 1 report were (i) need for better information on debris characterization, (ii) identification of material characteristics required by various sectors for recycling/reuse planning, (iii) update of building codes to incorporate recycled materials, (iv) increased community engagement (i.e., spanning from hazard identification to improved storage of the hazardous materials and use of greener products), and (v) better coordination of datasets relevant to debris characterization and inventory for the purpose of decision making.

Team 2 focused on effective planning for and optimization of disaster debris recycling and reuse. The most critical research needs are identified as: developing a dynamic lifecycle analysis framework to understand the fate of disaster debris from cradle to grave, preferably cradle to cradle, and projecting these findings to predict the impact of future events; extrapolating findings to different disaster events/demographics, and integrating findings into future sustainable disaster debris management practices; thoroughly and quantitatively understanding solid waste debris transport and fate before, during, and after disaster events through implementation of technology-enabled tracking efforts; developing materials performance standards for improved recycling and reuse efforts for debris management through focused laboratory testing of sampled materials; developing a framework to assess the extent of contamination of disaster debris materials (including, physical, chemical, and biological components or properties) through incorporation of quantitative risk management approaches; identifying, further developing, and standardizing new or existing technologies for treatment and waste volume reduction through a comprehensive literature review, laboratory, and pilot scale testing; and lastly reviewing and investigating potential opportunities for on-site, decentralized energy extraction and recovery to supplement energy demands of the disaster affected communities and offset the energy demands of the overall recycling/reuse efforts. The main outcomes from the report by Team 2 include (i) a flexible planning framework to optimize recycling and reuse that can be implemented everywhere and anytime (i.e., before, during, or after a disaster), (ii) a debris quality assurance and remediation plan to satisfy public perceptions and confidence in performance and safety of these materials, and (iii) robust end-markets and intended uses for products of debris recycling and reuse that will be identified and initiated.

Team 3 focused on technology development for improved recycling/reuse, handling, and monitoring. The team identified key technology gaps and main research needs as better image recognition algorithms for accurate classification of types and condition of debris, condition of buildings, and inspection of infrastructure; advanced processes for reuse and recycling of debris for construction and fabrication of engineered materials; and more energy efficient, faster, and cheaper processes for treatment of post-disaster materials including debris and wastes as well as large quantities of water associated with high water content disaster debris. New technologies developed would aid in short and long-term recovery following a disaster. The new methods would focus on improving construction methods and materials to minimize debris generation; quickly assess the types of debris generated by a disaster; automate the recovery process to minimize human exposure; and improve the efficiency, reduce the cost, and maximize the value of reused/recycled materials. The main outcomes from the report by Team 3 include (i) technology development for automated assessment of debris quantities and characteristics, (ii) systems and methods for better sorting, separation, and processing of debris materials for use as incoming material streams for various reuse applications and recycling operations, and (iii) incorporating technological developments for entire lifecycle of debris management to reduce debris generation, increase reuse and recycling, decrease direct disposal, and promote waste-to-energy applications.

Team 4 focused on business models and market development. The team identified that the short event duration and current mechanisms for disaster assistance focus on taking the debris to proper facilities, often for storage and disposal, but do not encourage businesses or assist the market in alternative ways to steer the debris for longer-term or more sustainable uses. The main research needs are in access to accurate and detailed information on materials generated / debris accounting to estimate available materials; recovery and separation of these materials; delivering the materials to appropriate markets; product/building design for end of life reuse from different disasters; new/innovative markets for recycled/reused/upcycled post-disaster materials; and incentivizing for market development; and information needs to market matching mechanism. The main outcomes of research in this area would include (i) developing best practices for planning (to be used by local governments and other government agencies), (ii) development of a business community (e.g., chambers, market development agencies, and small business administration) that understands the potential market value of debris materials, and (iii) communications/learning for local recyclers and businesses to be able to react to disasters.

Detailed individual team reports are provided in Appendix B. Various commonalities were identified in the reports prepared by the four teams as illustrated in Figure 1. These common threads as well as distinct points are summarized in the next sections under research needs and recommendations.

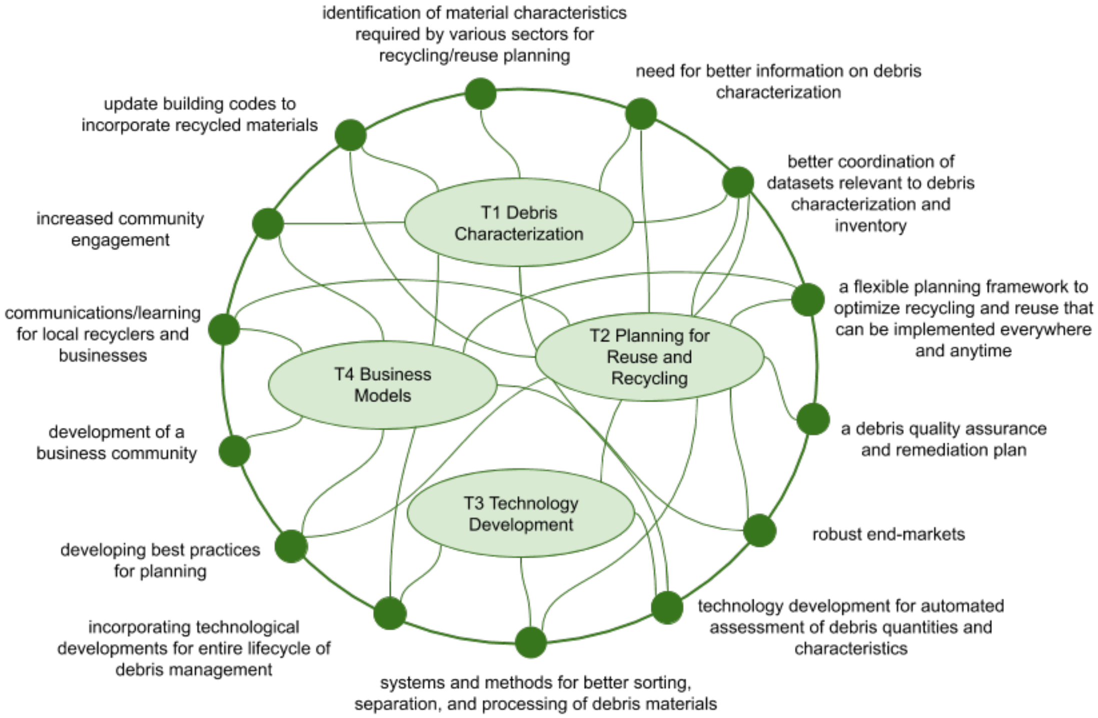


Figure 1 — Commonalities Identified across Four Team Reports

RESEARCH GAPS AND NEEDS

The main research gaps and needs identified based on the activities and discussions at the workshop are grouped under six categories: (i) development of debris management inventories, (ii) collection of post-disaster debris management data, (iii) characterization of post-disaster debris, (iv) development of a generalizable framework for pre- and post-disaster debris planning, (v) development of advanced technologies, and (vi) development of post-disaster recycling markets.

Development of debris management inventories

Foreknowledge of disaster materials (quantity, composition, and characteristics of disaster debris is required for effective pre-disaster debris management planning. Such information can facilitate community engagement in reducing debris sources and development of pre- and post-disaster recycling/reuse plans. Analysis of data collected from diverse data sources at various levels (e.g., community, county, and state) is required to develop comprehensive databases. A debris management inventory that narrows down and houses all the relevant information facilitates sustainable debris management planning. In this regard, the specific research needs identified during the workshop are:

- Identification and integration of diverse databases and community inputs associated with disaster materials planning and management
- Quantitative analyses of relationships between pre-disaster efforts and debris source reduction
- Quantitative analyses of relationships between pre-disaster efforts and debris reuse/recycling efforts

Collection of post-disaster debris management data

There is a lack of tools for post-disaster debris management and planning because of the lack of post-disaster data. Insufficient understanding of post-disaster debris impedes not only development of debris estimation and planning methods, but also validation of existing approaches. Considering that reuse and recycling of disaster debris is constrained by post-disaster operational conditions (e.g., lack of resources), collection of post-disaster debris data is critical for development of pre-disaster planning. Disaster materials are seldom qualified for reuse and recycling at the current time. The research needs identified during the workshop are:

- Data on post-disaster materials including debris and waste as well as liquid and gas phase releases
- Understanding of post-disaster operations of a debris management system (e.g., infrastructure interdependencies, operation efficiency, and other constraints)
- Evaluation data on disaster material properties and behavior for reuse applications and recycling operations
- Data and analysis on recyclable/reusable debris quality assurance to satisfy public perceptions and build confidence in performance
- Data and analysis on measurable indicators or metrics of reuse/recycling success such as landfill space saved or carbon dioxide equivalents saved in management to show the value of resiliency
- Evaluation of effective planning/pre-planning to define the waste streams

- Data on transportation of debris materials and associated energy consumption
- Debris field tests for the purpose of validation
- Identification of potentially toxic and hazardous materials in debris

Development of generalizable frameworks for pre- and post-disaster planning

The commonality of research needs across the workshop teams is the lack of generalizable frameworks or methods to be applied to regional post-disaster planning. Limited pre-disaster planning tools are available to facilitate recycling and reuse planning of disaster materials, yet, these do not sufficiently reflect regional factors and guide a diverse range of debris stakeholders (e.g., debris contractors, community members, material recovery facilities, and government agencies) during lifecycle of disaster management. Furthermore, methods important for sustainable debris planning (e.g., debris tracking and data collection methods) are missing in current literature and practices. Additional research needs identified are:

- A model for prioritization of material recovery options based on both characteristics and on economic, environmental, and social constraints.
- Design of collection and sorting processes to maximize reuse of debris
- A model to inform the community of how to sort residential debris
- A dynamic life cycle analysis framework to optimize a plan for recycling and reuse of disaster materials
- A regulatory framework to guide policies for incentivizing/promoting recycling and reuse, pre-contracting, and market development before disasters
- Methods for debris tracking during/after disasters
- Design of structures and infrastructure systems for reduced debris and waste generation
- Integration of elements of recycling, reuse and energy recovery into prediction, preparation, response, and recovery of disaster debris

Characterization of post-disaster debris

The lack of proper understanding of characteristics of post-disaster debris/waste is identified as the main impediment to pursuing sustainability in disaster debris management. Specifically, information on characteristics of various types of disaster materials that may be influenced by various factors (e.g., disaster type and climate change) is important to make regional plans for recycling and reuse. Prediction of location, type, and quantity of materials is also essential to planning debris logistics resources. In addition, determination of engineering properties of post-disaster materials is required for reuse in civil engineering applications. The research needs identified during the workshop are:

- Characterization of various types of post-disaster materials generated by different disaster events such as hurricanes, earthquakes, floods, landslides, fires, etc.
- Characterization as a function of local climatic and geological conditions.
- Climate change impacts on magnitude and frequency of disaster events and resulting debris
- Accurate prediction of debris location
- Accurate prediction of debris and waste types and quantities
- Determination of physical, mechanical, hydraulic, chemical, and biological characteristics of post-disaster materials
- Establishing engineering properties and behavior of post-disaster materials for reuse in construction

- Energy content and waste-to- / debris-to-energy applications for post-disaster materials
- Estimation of future waste streams including emerging materials/contaminants such as e-waste, biologic/biomechanical media, nanomaterials, and PFAS contaminants

Development of advanced technologies

Technology development was highlighted by multiple teams at the workshop. The main areas that require technological advances include tracking of debris operations, management of debris information, and testing and analysis of debris materials. Detailed needs for advanced technologies identified during the workshop are:

- Development of post-disaster characterization techniques (in terms of physical, mechanical, chemical, and bilogical properties) for debris and waste
- Development of energy efficient debris operations techniques
- Development of technologies for economical recovery/recycling processes
- Development of repair techniques for buildings that are damaged
- Development of sustainable construction materials that have a high potential for post-disaster recycling/reuse
- Development of a knowledge management system to transfer lessons learned from disaster incidents and improve debris management operations
- Fast assessment/update of debris flow models for processing
- Development of multi-sensor based classification (vision, gas contaminants/liquid contaminants)
- Development of communication systems for automated/robotic systems
- Automated separation of recyclable debris streams
- Automated identification and management of hazardous and toxic materials in debris
- Development of artificial intelligence assisted/based decision-making systems (separation, type of treatment)
- Development of technologies for on-site/mobile/temporary/as-needed recycling in the field
- Development of technologies for tracking debris after/during disasters

Development of post-disaster recycling markets

The lack of recycling markets is often a major impediment to pursuing sustainability in debris management and planning. In the U.S., recycling markets are not highly developed due to relatively insufficient demand compared to new materials and economical constraints. To address this issue, participants identified needs for understanding market matching mechanisms, discovering new markets for recycled materials and developing funding mechanisms to justify otherwise costly recycling/reuse options for disaster materials.

- Market discovery for recycled/reused materials
- Understanding of market matching mechanisms
- Information needs for market matching mechanisms
- Comparisons between developing/developed, low/high income, island/continental, cultural/behavioral differences
- Development of strategies for long-term funding assistance for businesses and markets to assist with post-disaster materials management

RECOMMENDATIONS

Recommendations are provided for future research investigations based on the activities and discussions held at the workshop:

- Develop pre-disaster identification systems for building materials/infrastructure components for estimation of type and quantity of debris.
- Develop pre-disaster identification systems for building materials/infrastructure components for automated post-disaster sorting for improved reuse and recycling.
- Develop novel computational techniques and models—leveraging novel data mining capabilities—to estimate potential future debris quantities.
- Develop aerial measurement techniques to identify geographic location and extent of debris masses.
- Develop aerial measurement techniques to estimate debris and waste mass or volume.
- Investigate techniques and methods for physical, mechanical, chemical, biological separation of debris and wastes.
- Investigate techniques and methods for physical, mechanical, chemical, biological treatment of debris and wastes.
- Develop sensor technologies for identifying hazardous and toxic materials in debris.
- Identify reuse/recycling potential of debris streams from different disaster events.
- Identify significant engineering properties for reuse/recycling of debris streams from different disaster events.
- Investigate reuse/recycling of post-disaster materials for constructing next generation of disaster prevention infrastructure such as levees, sea walls, landslide/rockfall protection structures.
- Develop systematic approaches for generating post-disaster debris management logistics practices (e.g., the location of and access to materials recovery facilities).
- Develop systematic approaches for generating post-disaster debris management practices for matching the materials generated with market needs.
- Develop a standardized framework for collecting the data associated with disaster debris management.
- Develop a debris management repository to provide an integrated data source and facilitate analyses for sustainable debris management and planning.
- Develop community-driven approaches to pre- and post-disaster planning of sustainable disaster management.

In addition to recommendations for future research, the workshop also highlighted the importance of wide engagement of stakeholders for better sustainable management of disaster materials.

The following collaborative activities between academia and industry are required.

- Examination of disaster materials in accordance with specifications for recycling and reuse required by the recycling industry.
- Development and application of standardized contaminant identification and decontamination procedures for broad use in practice.

- Investigation of new sorting technologies available from recycling industry for application to disaster debris management.
- Investigation of potential technologies from other industries (e.g., mining) for sorting and processing debris with better energy efficiency.

State and federal government agencies are important stakeholders for pre- and post-disaster debris planning and management. The recommended collaborative activities between academia and government agencies are identified as:

- Tracking and sharing of operational data for post-disaster materials.
- Application of new decision-making tools such dynamic LCA models.
- Modification and improvement of the current debris estimation and modeling efforts.
- Identification of regulatory and operational barriers to recycling and reuse efforts.
- Study of the impact of debris-related policies on community perceptions on recycling and reuse of debris.
- Development of best practices for sustainable management operations.

Furthermore, the workshop participants recommend the establishment of funding mechanisms to bring together interdisciplinary researchers and diverse stakeholders. Potential funding mechanisms through NSF are identified as:

- NSF RFP targeting post-disaster sustainable debris management incorporating the use of knowledge of diverse academic communities as convergence research spaces.
- NSF RCN co-sponsored with agencies such as EPA and FEMA for post-disaster debris management to connect diverse perspectives and experiences across the U.S. and globally.
- NSF RAPID supporting collection of post-disaster data on disaster materials that can be employed by interdisciplinary researchers for investigating environmental sustainability.
- NSF EAGER supporting the establishment of an Extreme Events Reconnaissance (EER) organization to respond to disaster events with respect to post-disaster debris management, reuse, and recycling.
- NSF ERC on post-disaster debris management to connect diverse experiences across the U.S. and globally leading to innovations and implementable industry advances.

CONCLUSIONS

The Post-Disaster Materials and Environmental Management workshop brought together a diverse group of attendees with high participation of underrepresented groups and representing academia, industry, and state and federal government agencies from across the United States. The participants were exposed to real-world disaster debris problems presented by industry and state and federal government agency participants including a remote presentation by an industry expert in Japan. Workshop time was set aside for open discussion among all participants and also significant time was devoted to discussions in teams established early on to discuss specific themes in detail and provide detailed recommendations. In addition, a tour of FEMA was also included in the workshop. A a result, the workshop participants, through these well-planned and specifically structured activities, identified critical research questions and needs related to the management and environmental impacts of the large quantities and wide varieties of debris and waste generated by disasters set forth as the main goal of the workshop. The diversity of the workshop participants allowed for comprehensive assessment of the complex interdisciplinary topic of the workshop. The intellectual merit and broader impacts of the workshop and the main pathways for distribution of the outcomes of the workshop are further described below.

Main Products

The workshop resulted in: i) identification of main research gaps and needs related to the workshop topic, ii) development of recommendations for research and development to provide solutions to the complicated issues associated with disaster debris and waste management, and iii) a research agenda that includes potential funding agencies and specific funding mechanisms. In addition, the workshop fostered development of a broad network of experts connected through the workshop activities as well as smaller collaborative groups that has organically grown through the interactions of the participants at the workshop. The workshop organizers have knowledge of multiple groups of participants (formed at the workshop) already working on varied research initiatives directly related to the research topic at the time of the writing of this report less than two months after the workshop. Furthermore, publications are underway based on the activities at the workshop as described below in the Dissemination section.

Dissemination

The workshop results are disseminated through various pathways. A journal editorial was published by one of the workshop participants (Babbitt 2019) related to potential contributions of green technology research to disaster debris management highlighting the need for interdisciplinary solutions. The workshop organizers are developing multiple publications based on the workshop results including forum papers in the *ASCE Journal of Management in Engineering* and in *Resources, Conservation and Recycling*, and a review article for Nature-Climate Change. A special issue on the topic of post-disaster materials and environmental management may be organized as well. Moreover, several workshop participants expressed plans to include some of the lessons learned from the workshop in research and teaching materials. PI Choi plans to incorporate the findings from the workshop into his graduate course “Infrastructure System-of-Systems Analysis” in Fall 2019. In this course, graduate students will learn how to design interactions between different but interdependent systems in the context of disaster debris management and propose recommendations. Disaster debris reuse in civil engineering applications is incorporated into the activities of ASTM committee D18 on Soil and Rock by PI Yesiller (vice chair/incoming first vice-chair of the committee and chair of sub-committee D18.14 on Geotechnics of Sustainable Construction) for potential standardization applications.

APPENDIX A
WORKSHOP PHOTOS/PARTICIPANTS

Photo of Participants at Workshop Hotel

Photo of Participants at FEMA during the Tour

APPENDIX B
WORKSHOP TEAM REPORTS

Team 1

Characterization and Inventory of Post-Disaster Debris

Summary:

Debris characterization and inventory provide important information for improved management and reuse of materials post-disaster. Such rich information about disaster materials requires research in multiple areas (i.e., including technology innovation, debris data analysis, debris planning and management, and human behaviors) across a disaster time frame (i.e., pre- and post-disaster phases).

Intended outcomes are (i) the increase in information on debris characterization, (ii) identification of characterization parameters needed by various sectors for recycling/reuse planning, (iii) update of building codes to incorporate recycled materials, (iv) increased community engagement (i.e., spanning from hazard identification to improved storage of those hazardous materials and use of greener products) and (v) better coordination of datasets relevant to debris characterization and inventory for the purpose of decision making.

Team members: Terri Norton (Lead), Arvin Farid, Holly Peltz, Callie Babbitt (co-Lead), Juyeong Choi, Chris Vaughan, Tarek Abichou, Kristina Torres, Maya Trotz

A. General Context and Relevance of the Focus Area

This focus area is on debris characterization and inventory. The more and the better resolved data you have on the community (e.g., behaviors potentially affecting disaster materials) and sources and characteristics of debris (e.g., spatial location, and physical and chemical properties), the more effective recycling strategies can be developed.

We plan to characterize disaster materials in the following aspects: (i) the types of debris, (ii) material condition, (iii) properties relevant to the reuse/recycling, and (iv) logistics related information (e.g., the location of materials recovery facilities). The characterization of disaster materials can lead to other research areas (such as the site determination of debris facilities and development of recycling/reuse markets).

B. Focus Area Challenges and Intended Outcomes

The occurrence of natural disasters is on the rise. These events can damage lots of infrastructure, buildings and other built environments, and create large quantities of debris that often overwhelm a local waste disposal system. Better understanding of the debris makeup can facilitate planning of material recovery, which will help to relieve the burden on local landfills.

The barriers to pursuing sustainability in disaster debris planning include (i) limited time to collect and process materials, (ii) limited data necessary to make a decision, (iii) lack of stakeholder coordination, (iv) limited post-disaster resources (labor and money) for collection, disposal, sorting, and recycling, (v) limited spaces for temporary staging areas, and (vi) lack of robust debris estimation models.

C. Research Questions and Methods

Research Questions:

- What are planning and tools required to integrate diverse databases and community inputs with respect to debris and types of potential disasters, for better recycling planning?
    - Material pathways (or logistics) planning and disaster estimation/prediction models
        - Matching up forward and reverse supply chains
        - Predicting volume of outflows with respect to capacity of recycling markets (i.e., demand)
- What is the impact of different climates and disasters on waste generation? How would this impact the existing technologies? (i.e., identification of a technology to accommodate changing demands for debris management).
- What types of technologies are needed to characterize the physical, chemical and mechanical properties?
    - Onsite management: real-time scanning, imaging methods, and remote sensing
    - Through experimental testing: strength, reliability, and quality testing
- What specifications and building codes are needed to be revised or improved for better recycling/reuse of non-virgin materials? Is it possible that the code can recommend how and when it is possible to reuse disaster debris (C&D, sediments and vegetative debris) and other solid waste?
    - How to affect the current building stock that was designed by earlier building codes?
    - What census data are required to inform the code regulations?
    - How to handle hazardous materials issues (e.g., asbestos) through regulations?
    - We can characterize LULC (land use and land cover) datasets for vegetative debris. But, how can we utilize the datasets for better management of vegetative debris?
    - What protocol is required for better recycling planning? And how to develop it?
    - What is the timeframe for when disaster material processes can be done? (E.g., specific timeframe when materials can be used?)
    - How to design structures and systems that can produce less waste?

- What are the approaches to diverting mixed waste that include hazardous materials from landfills?

    - What are the possible ways to immobilize or reduce the effects of the contaminates such that the debris can be reused?
    - How to segregate, stabilize, and/or use materials to remediate or sequester hazardous materials?
- How do you prioritize material recovery options based on material characteristics and other economic, environmental, and social properties?
- How can you plan the collection and sorting process to maximize the reuse of the debris? What preparation is needed to inform the community of how to sort residential debris?
    - What is the best contract language and terms to debris contractors? What incentives drive better sorting and collection?
    - How to integrate the lessons learned from communities that have done it well into pre-disaster debris planning in such a way to facilitate the sorting process?
    - What is the current messaging for hurricane season? What are the communication mechanisms that will work in a post-hurricane situation? How can they be leveraged in the context of debris planning and management?

Research Methods:

- Use mitigation incentives to influence design of new and existing buildings (e.g., FEMA Building Sciences)
    - U.S. Green Building Council (USGBC) may consider the implementation of this approach
- What types of research on building stock are needed?
    - What "future debris" is likely generated in a post-disaster situation?
    - How to predict disaster materials?
    - How to engage community members in collecting and analyzing the required information (i.e., through citizen science)?
- Data acquisition and management
- Monitoring of disaster debris (during and after a disaster, and in real time).
- Convergence research
- How can characterization findings feed back into specifications (e.g., DOT specifications for concrete) in a way to facilitate recycling of disaster materials?

D. Research Needs and Future Work

Question	Research Need	Future Work
What are effective planning and decision tools that integrate diverse databases and community inputs with respect to debris and types of potential disasters?	● Prediction of potential debris generated and debris size, based on disaster type (through the capture of institutional	● Coordination and collaboration between different agencies and communities

	knowledge) ● Development of methodologies to identify, collect, validate and aggregate data sources that is compatible with multiple users (mixed methods [i.e. citizen science] and machine learning) ● Modeling methods or scenario analysis to forecast the effectiveness of plans on recycling/reuse of debris ● Data management plan and maintenance of tool to capture updated information	to insure that the findings are implementable and usable.
What types of technologies are needed to characterize the physical, chemical and mechanical properties?	● Technologies to quickly and accurately characterize materials ● Accessible/low cost technologies operable under limited energy and connectivity conditions, (e.g., real-time scanning, imaging methods, remote sensing [AI]) ● Experimental testing of mechanical properties	● Better understanding of existing technologies (what are the gaps?) ● Better and more holistic understanding of material properties
What specifications and building codes are needed for non-virgin materials? What are the approaches for	● Understanding of how debris waste can be reused post-disaster	● Development of a code to recommend how and when it is feasible to consider

reusing mixed waste that even includes hazardous materials?	- Understanding of debris performance with respect to existing code requirements - How to immobilize post-disaster hazardous materials	the reuse/recycling of disaster debris (C&D, sediments, vegetative) and other solid waste
How do you prioritize material recovery options based on both characteristics and on other economic, environmental, and social properties?	- Collection uniform and harmonized data (i.e., identifying where data sources are) - How to predict the volumes of debris and length of sorting time? - Cost-benefit analysis and incentives for efficiency	- Development of a decision making tool to facilitate recycling plans for post-disaster waste and debris - Review of EPA i-waste model for pre-populating debris streams and volumes and of HAZUS-MH for debris predictions)
How can you design the collection and sorting process to maximize the reuse of the debris? What preparation is needed to inform the community of how to sort residential debris?	- Understanding of existing C&D facilities and what modifications can be made to deal with disaster debris - What types of localized/community based sorting and characterization facilities will increase reuse potential - Deconstruction practices to be considered in the design phase to enhance the recyclability of C&D materials	- Develop practices to respond to disaster debris needs (what crew changes, truck needs) - Verify that deconstruction concept can increase the amount of material able to be recycled and facilitate the post-disaster sorting process - Study on the effect of the community engagement on debris management and source reduction
What is impact of different climates and disasters on the waste generated? How would this impact the	- Coming up with a technology that is well suited for disaster waste.	- Collection of data from different types of disasters to demonstrate if this

existing technologies?		technology is useful

E. Actionable Research

How to implement research questions?

A key need is funding mechanisms to bring together interdisciplinary researchers and relevant stakeholders. These mechanisms might include

- NSF RFP targeting sustainable debris management post disaster that pilots the use of knowledge of diverse academic communities as convergence research spaces.
- NSF RCN co-sponsored with agencies like US EPA and FEMA for debris management post disaster to connect diverse perspectives and experiences across the nation/world.
- NSF ERC on debris management post disaster to connect diverse experiences across the nation/world and lead to innovations and commercializable industry advances

Who would use results and how to disseminate the findings (to technical and non-technical audiences)?

End users and methods to disseminate:

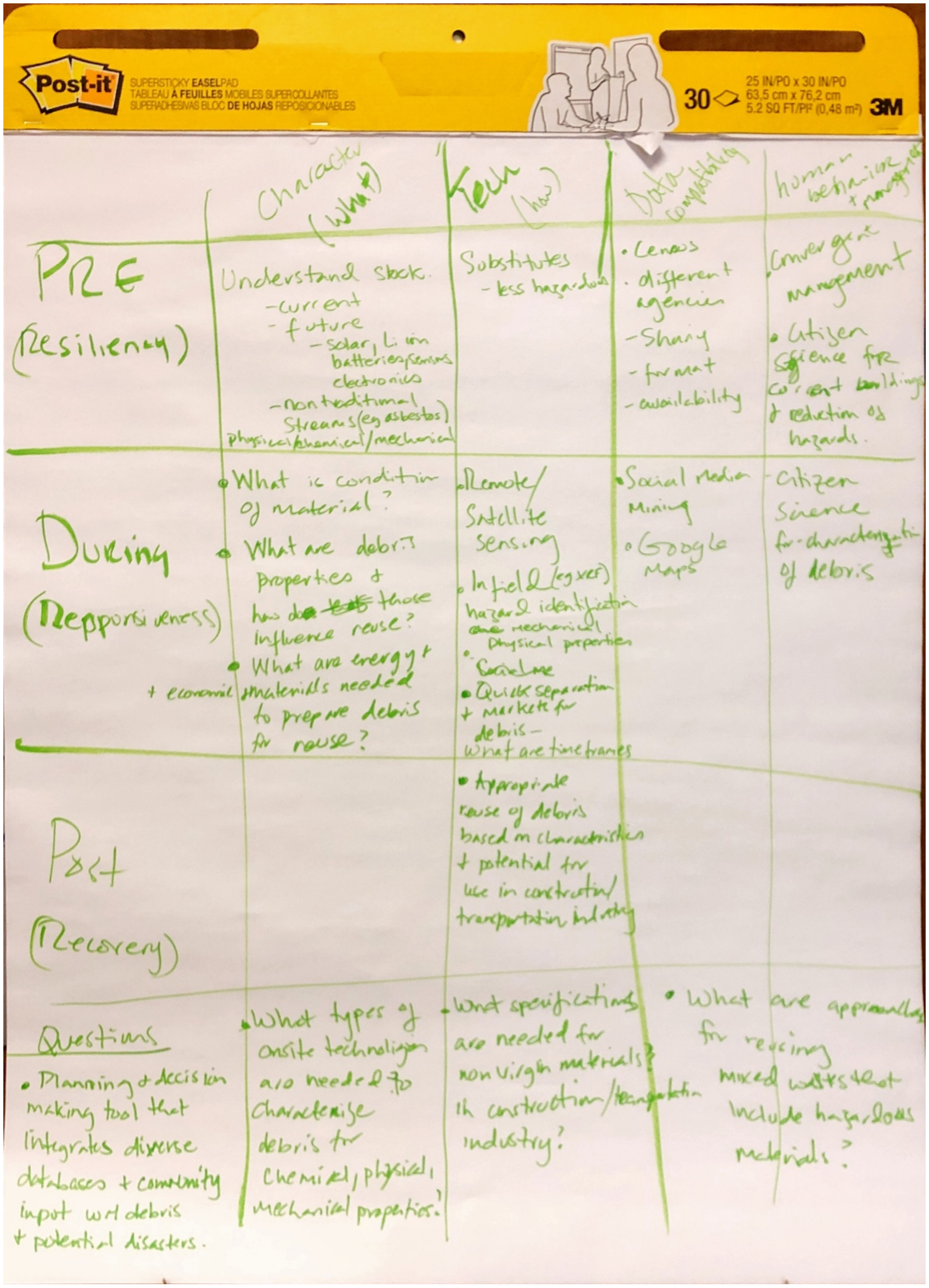
- Disaster management agencies coordinate to address debris in a more sustainable manner. Coordination methods include dissemination through workshops, shared online resources, and assignment of potential separate seat for debris on FEMA's response coordination center.
- Local Communities, especially those in disaster zones, who can be better prepared to characterize debris during emergency, pre- and post-disaster recovery, and who can be better engaged in reducing hazards in community, and with post-disaster sorting and recycling processes. Dissemination methods include community meetings, use of community space as convergence research space, and integration with FEMA hazard mitigation planning approach.
- Business Community, including potential markets for reused, recovered, and recycled materials, technology firms including those who produce equipment for rapidly identifying and characterizing debris materials, those who produce equipment for recycling, and startups innovating in this field.
- Research Community, which includes not only engineering but also broader fields including social science and behavior, informatics and data science, and basic sciences. Each of these domains plays a key role in developing databases and novel models for characterizing debris for reuse and in engaging relevant stakeholders mentioned above.

Multiple methods are required to disseminate translational findings to these stakeholders, including

- Workshops connecting researchers with local, state, and federal actors

- Direct engagement, interviews, and surveys, particularly emphasizing stakeholders with institutional and practical knowledge about debris management in disaster response
- Public science communication
- Policy briefs
- Industry / trade organizations
- Academic papers, presentations, and patents
- Virtual clearinghouse of compiled data

Appendix:



	Character (what)	Tech (how)	Data compatibility	human behavior + management
PRE (Resiliency)	Understand stock. -current -future -solar, Li ion batteries, sensors electronics -non traditional streams (eg asbestos) physical/chemical/mechanical	Substitutes - less hazardous	• Census • different agencies -Sharing -format -availability	Convergent management • Citizen science for current buildings & reduction of hazards.
During (Responsiveness)	• What is condition of material? • What are debris properties & how do ~~tests~~ those influence reuse? • What are energy + + economic materials needed to prepare debris for reuse?	• Remote/Satellite sensing • In field (eg XRF) hazard identification ~~and~~ mechanical physical properties • Social me • Quick separation + markets for debris — What are timeframes	• Social Media Mining • Google Maps	-Citizen Science for characterization of debris
Post (Recovery)		• Appropriate reuse of debris based on characteristics + potential for use in construction/transportation industry		
Questions • Planning & decision making tool that integrates diverse databases + community input w/ debris + potential disasters.	• What types of onsite technologies are needed to characterise debris for chemical, physical, mechanical properties?	• What specifications are needed for non virgin materials in construction/transportation industry?	• What are approaches for recycling mixed wastes that include hazardous materials?	

Team 2

Effective Planning for and Optimization of Disaster Debris Recycling and Reuse

Summary:

This focus group has identified several important research needs and methods regarding how to improve and optimize **planning efforts** for disaster debris **recycling and reuse.** We believe the most critical research needs are to:

1. Develop a dynamic lifecycle analysis framework to understand the fate of disaster debris from cradle to grave, but preferably cradle to cradle, and to project these findings to predict the impact of future events, extrapolate findings to different disaster events/demographics, and integrate findings into future sustainable disaster debris management practices,
2. Thoroughly and quantitatively understand solid waste debris transport and fate before, during, and after disaster events through implementation of technology-enabled tracking efforts,
3. Develop materials performance standards for improved recycling and reuse efforts of debris through focused laboratory testing of sampled materials,
4. Determine a framework to assess the extent of contamination of disaster debris materials (including, physical, chemical, and biological components or properties) through incorporation of quantitative risk management approaches,
5. Identify, further develop, and standardize new or existing technologies for treatment and waste volume reduction through a comprehensive literature review, laboratory, and pilot scale testing,
6. Review and investigate potential opportunities for on-site, decentralized energy extraction and recovery to supplement energy demands of the disaster affected communities and offset the energy demands of the overall recycling/reuse efforts.

The following items are major intended outcomes of this proposed research:

1. A flexible planning framework to optimize recycling and reuse that can be implemented everywhere and anytime (i.e., before, during, or after a disaster),
2. A debris quality assurance and remediation plan to satisfy public perceptions and confidence in performance and safety of these materials,
3. Robust end-markets and intended uses for products of debris recycling and reuse that will be identified and initiated.

We have identified several opportunities to collaborate with outside agencies and regulatory authorities to field validate these research results and to improve future disaster debris management practices. The research results are expected to be actionable, in that regulatory authorities and outside agencies will directly benefit from the acquired results

Team members: Nicole Boothman-Shepard, Laurent Corroyer, Sybil Derrible, Bruce Hamilton, Jose Holguin-Veras, Melissa Kaps, Derek Manheim (team captain), and Nikolai Maximenko

A. General Context and Relevance of the Focus Area

The general context identified for the focus area on Effective Planning for and Optimization of Disaster Debris Recycling and Reuse are:

- Emerging waste-streams (e-waste), LEED movements, logistics and supply chains (liability): any idea will depend on a distribution systems (where is sorting conducted?)
- Chaotic environment: people place other needs (survival instincts) ahead of issues with debris management, sustainable management in the response (including with donations),
- Prediction, preparation, response, recovery of all disaster debris needs to include elements of recycling/reuse/energy recovery
- Planning must be tailored to geographic characteristics of disaster locations
- Socio-economic differences, aesthetic issues related to reuse / recycling – people do not want to buy something if it is not "new" or equally pleasing as a new product
- Life cycle assessment and procedures: two different footprints of a product whether ended in a disaster or not – think of EPA WARM model with an option to estimate the impact of product ended in a disaster.
- Discarding of plastic water bottles and other plastic products present substantial challenges at disaster sites
- Consider liquid wastes (mud, soils subject to contamination) in addition to solid wastes, pre assessment of materials to use for building (source prevention) in disaster prone regions

Some of the issues identified related to the contex are:

- Issues with pests (termites) and vectors during recycling efforts
- Issues with energy generation, extraction, develop a pilot a model or other environments
    - Debris streams, have to consider the (dynamic) LCA results, putrescible wastes, coming up with a general framework for assessment
    - Assess future space in landfill environments – transformation of wastes may be important (energy conversion can help facilitate this)
- Issues with contractors attitudes and perceptions with recycling and reuse efforts
- Waste audits of the disasters, vegetative debris is well characterized, other C&D not characterized as well – FEMA (white goods – appliances), vegetative, household wastes (non-hazardous), E-waste, C&D wastes (FEMA project worksheets)

B. Focus Area Challenges and Intended Outcomes

The intended outcomes related to this focus area are as follows:

- A flexible plan to optimize recycling and reuse that can be implemented everywhere
- Debris quality assurance to satisfy public perceptions, confidence in performance
- Robust end markets for end products of debris recycling identified and cooperated with
- Measurable indicators or metrics of reuse / recycling success such landfill space saved or carbon dioxide equivalents saved in management to show the value of resiliency
- Models to estimate expected catastrophic results from future disasters to enhance pre-disaster preparedness (i.e., impacts on buildings and the environment)
- A plan or guidelines to limit the arrival of unnecessary materials into disaster sites and how to best recycle these materials (e.g., recycling of unwanted donated clothes)

- Procedures to formally integrate local efforts from the community before, during, and after a disaster (e.g., manual labor to sort the debris)
- A plan on energy extraction and recovery to stabilize the local community and also contribute to volume reduction of waste materials
- Development of improved technologies for onsite treatment (decentralized, mobile, and efficient) and incorporate energy extraction

C. Research Questions and Methods

Critical research questions ranked from most important to least:

1. Can we develop a dynamic life cycle analysis framework to better optimize for recycling and reuse of disaster materials and adapt it to different locations?
2. Is there a standard method that can be developed for debris tracking after/during disasters?
3. What are some materials performance standards for reuse or recycling, as indicated from industry?
4. How contaminated is too contaminated for waste debris (water saturation, physical, biological, and chemical components)? We need a better way to assess this issue. (4)
5. What are effective strategies to decontaminate that are efficient, cost-efficient, and localized?
6. What types of energy extraction and recovery systems can be put into place? What should they consider to be more efficient? Where should the energy be transmitted (on-site, locally)? How much energy is required for transportation of debris materials?

Important research questions (unranked):

- Would it make a difference if debris teams had a dedicated resource person with technical experience to promote reuse and recycling at the disaster site?
- How can we better decipher this debris information from satellite observations?
- What are the right incentives to increase recycling efforts during disasters (how to convince people that this is important – a perception issue)?
- Pre-disaster efforts, correlation between source reduction and cost/environmental impact savings?
- Can we match the supply of generated waste materials with needs of the community and supplement their requirements?
- Can we redesign the disaster response procedures (mobile homes and water availability) to be more sustainable and recycling/reuse friendly?
- Can we learn from small events to project to future disasters?
- What existing laws/regulations are stopping us for doing what is right (political barriers) with debris recycling and reuse?
- Can region-wide centralized facilities be established that are responsible for longer term recycling efforts?
- How important is it to inspect industries before, during, and after the disaster events?

Potential research methods and approaches to address the questions listed above:

- Debris tracking and monitoring – observe directly in the field: how does the debris arrive from the field, how fast does it arrive from the field, where should it be sorted, assessment of business practice changes, development of a global market.

    - GPS trackers in each debris stream, compare with what was reported
- Dynamic LCA Methods – monitor landfills, changes in capacity, emissions, leachate generation with and without disaster events (analyze existing data to inform efforts like LIDAR, remote sensing, contractor interviews)
    - Surveying the demographics of the areas, knowing the supply chains (how to transport and arrange things)
    - FEMA worksheets, pre-assessment
    - Verification and validation of the results
- Materials standards for reuse – Samples could be collected directly from the field and tested in the lab for strength and performance.
    - Documenting the waste materials generated at the site, contractor interviews, GIS, debris characterization directly performed at the site (standardized methods)
- Assessment of debris contamination and remediation approaches
    - Literature review of potential contaminant sources and remediation approaches
    - Apply quantitative chemical and microbial risk assessment approaches to determine the appropriate levels of contamination for human and environmental health
    - Take samples and perform lab characterization of treatment methods include biological, physical-chemical, and some combination of these methods
- Energy extraction and recovery efforts
    - Identify the routes to effectively harness energy from disaster debris
    - Perform lab and pilot scales studies to assess the efficacy of these energy extraction efforts
    - Assess the need for implementing these technologies in practice, where can they be most effective (what type of disaster event, geography, demographics, etc.)
    - Acceptable degree of contamination for environmentally friendly energy conversion to take place

D. Research Needs and Future Work

Some of the research needs and future work for this focus area are:

- Collaboration with local organizations and public institutions at all level of governments to address some of the questions listed above, perhaps in coordination with FEMA for debris tracking for example.
- Collaboration with outside agencies (standards agencies like ASTM, etc.) are needed to determine relevant standards for materials performance and to identify possible decontamination procedures and whether co-locating energy extraction/recovery efforts is warranted
- In the planning we need to consider emerging waste streams and trends of the future, including how the composition of the waste stream is changing. For example, food wastes (15% of the waste stream) and E-wastes (20% +) will likely compose much of the future waste stream.
- Assess trends in emerging materials and chemicals for improved recycling and reuse practices

E. Actionable Research/User-inspired research

Research that can be connected with implementation needs:

- Engineering properties must be up to specifications for recycling – needs to do XYZ to be compliant with codes and standards – partnerships with industry and academia will likely be very reciprocal and dependent on one another
- Applying a standardized decontamination identification procedure for use in practice
- Monitoring and handling of the solid waste debris materials
- Applying decision making tools, such as the dynamic LCA, in practice (integrating with FEMA efforts), further modifying and calibrating the modelling efforts using real world data
- Identifying regulatory and operational bottlenecks that prevent recycling and reuse efforts
- Programs for incentivizing local communities to enhance debris recycling perceptions/efforts and study how local people recycle and reuse debris as opposed to designated contractors

Team 3

Technology Development (Improved Recycling/Reuse, Handling, and Monitoring)

Summary:

New technologies could be developed to aid in short and long-term recovery following a disaster. The new methods would focus on i) improving construction methods and materials to minimize debris generation, ii) quickly assess the types of debris generated by a disaster, iii) automate the recovery process to minimize human exposure, and iv) improve the efficiency, reduce the cost, and maximize the value of reused/recycled materials.

Key technology gaps include i) better image recognition algorithms for accurate classification of debris types and condition, building condition, and infrastructure inspection, ii) advanced processes for construction, recycling, and fabrication of engineered materials from debris, and iii) more energy efficient, fast, and cheap processes for water/debris treatment.

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A. General Context and Relevance of the Focus Area

Most of the discussion here focuses on developed countries. In developing countries the types of debris may be very different.

Debris cleanup following a disaster is a slow, expensive, and dangerous process. Opportunities exist to improve this process through the use of better materials, construction methods and processes, and standards that would lead to a reduced quantity of debris. There are also opportunities in improving automation to better estimate the amounts of debris following a disaster, and automatically sort and classify different types of debris.

Once the debris are sorted, these need to be recycled, reused in some manner. Better materials and construction processes could improve the recyclability of the debris, and new, energy efficient and water efficient methods could be used to generate engineered materials on site to create value.

B. Focus Area Challenges and Intended Outcomes

Pre disaster

- RFID-like tags for building materials for automated sorting

Post disaster

In-field automated sorting of debris, in real time (conveyor-belt type)
Automatic detection of hazards (chemical/biohazard, asbestos, mechanical (sharp, fall…), nuclear)

- Automated sorting of hazardous materials
- Soil decontamination
- Sorting materials by quality (for recycling/reuse)
- Structural made land
- Prediction of debris location
- On-site grinding (extract steel, fibers)
- New technologies to recycle in the field (wood, concrete)
- Multi-sensor based classification (vision, air contaminants/water contaminants)
- Communication systems for automated/robotic systems
- Fast assessment/update of the debris flow model for processing

- Validation requires realistic debris/field test
- AI assisted/based decision making (separation, type of treatment)

C. Research Questions and Methods

Sensing/robotics

- How can we know enough (in the field) about the debris to be confident on the durability of the reused/recycled materials made from these?
- How can we set up a scalable (economically) environment of self-healing automated robots given the communication/energy challenges post disaster?
- How can we quickly inspect underground infrastructure (pipes)?
- How can we design technology to automatically separate different debris streams?
- How can we design technology to automatically separate hazardous waste?
- How can we design technology to automatically decontaminate sites?

Efficiency/environmental impacts

- How can we minimize landfill use?
- How can we increase reuse over recycling?
- How can we make crushing more energy efficient?
- How can we better manage particulates and dust?
- How can technology make the recovery/recycling process cheaper (e.g., shingles)?
- How can we develop new repair strategies for buildings that are damaged to minimize debris generation?
- How can we design portable units for energy generation from biowaste/organic materials?

Planning

- How to incorporate and anticipate change of debris over time and geographical area?
- How can we construct local protection structures from debris (see level rise, landslides, etc.)?
- How can we create concrete that sequester CO_2?
- How can we incorporate lessons learned in construction and design?

D. Research Needs and Future Work

We need better construction methods, materials to minimize waste generation (for example the design of better electrical systems that resist a flood). We also need to anticipate the future shifts in debris types caused by new construction methods or materials.

What limits us from improving the reuse/recycling rates. We need to develop technology that will maximize reuse/recycling, and need to influence designs, construction methods to improve the recyclability of debris.

We need to create new usable materials from debris (sorting, detection of quality of material, washing processes). We need new innovative applications of these materials (both for temporary and permanent use). We also need to reuse geotechnical materials beneficial manners (e.g., engineered fill)

We need cheap, energy efficient (sustainable) ways to clean debris and water on site, for example using chemical or bio-based technologies.

We need a fast-deployable power grid that would provide the power required to clean up debris.

We need to remove people from exposure to contaminants, and need more automation. The research needs are in automated sorting, automated detection of the quality of sorted materials, and automated detection of hazardous waste.

We need better image classification algorithms to assist with debris sorting and characterization.

We need better automated ways of assessing structural health of standing buildings to avoid unnecessary generation of debris. More generally we need better automated inspection technologies for both above and underground structures.

We need a better way to assess the quantity, type and the level of hazard of debris that are generated during an event. These include better data analytics, automation (drones and ground based robots), sensors (lidars, SARs), and better inference from early debris collection.

We need better technologies (accelerated, more energy efficient, cheap) for dewatering/drying operations.

Technology from related agencies

We need to investigate the use of new sorting technologies from recycling industries for debris sorting.

We need to investigate the use of new technologies from other industries (mining) to better separate debris and crush debris with better energy efficiency.

We need the participation of DoD/DARPA on debris processes used following battles.

We need the participation of State DOTs/USDOE to understand the issues associated with underground infrastructure.

E. Actionable Research

If the proposed questions are addressed, we can

- Reduce the time required to clean up debris
- Improve the recycling rates
- Design for post disaster reuse
- Reduce the economical cost/energy cost associated with debris cleanup and water treatment, conservation of resources
- Reduce exposure/accidents associated with recovery
- Rebuild faster using on-site engineered materials
- Repair infrastructure in-situ to speed up recovery
- Improve sustainability and resilience by constructing permanent structures from debris, that would address the problem (landslide, flood), or enhance the value of pre-disaster land

Team 4

Business Models and Market Development

Summary:
The often unpredictable nature of disasters and the focus on urgent removal of debris in the interest of protecting human life and health are not conducive to the management of these materials in accordance with the desired waste management hierarchy (i.e., recycling and reusing to the greatest extent practicable) by the recycling and waste disposal industries. The short event duration and current mechanisms for disaster assistance focuses on the taking the debris to proper facilities, often for storage and disposal, but does not encourage businesses or assist the market in alternative ways to steer the debris for longer-term or more sustainable uses.

Team members
Weslynne Ashton - business models
Adam Yeeles - financing adaptation, economic incentives risk mitigation
Wes Mindermann - debris removal, if there is no money/no plan it's hard to make things happen
Ken Lewis - landfills, get ahead of curve, models for diversion to reduce materials to landfill, business incentives - materials as valuable
Pinar Keskinocak - government incentives for separation and recycling
Suzie Boxman - sustainable materials management, deconstruction, incentives
Larry Bank - reuse of infrastructure, circular economy; small business, new technology
John Morton - waste management - post-disaster, conflict zones

A. General Context and Relevance of the Focus Area

- In general, if there is no money/no plan it's hard to make things happen beyond sending all debris to landfill.
- Current debris management efforts focus on disposal, it uses valuable and/or limited landfill capacity.
- No **long-term** funding assistance makes it difficult for businesses and markets to assist with material management.
- Strategies that emphasize long-term and local debris management will result in more sustained economic benefits to the affected community.
- Effective planning will make communities more resilient and able to respond with less assistance.
- FEMA had a pilot program of incentives for debris collected from federally declared disasters, where if you could keep any money generated from its sale - what can we learn from such programs?
- Interest to agencies
    - FEMA - can revenue streams from debris management offset recovery costs/payouts that they are asked to make?

    - EPA - effective management of disaster debris aligns with sustainable materials management portfolio
    - Local governments - protect citizens' health
    - Citizens - short term employment opportunities in debris management can help citizens and local economies to recover

B. Focus Area Challenges and Intended Outcomes

- Economies of scale
- Lack of planning regarding utilization of recycled material prior to disasters
- Inventory of materials, planning capacity for recycling, logistics - getting materials to where they can be reused
- Lack of government incentives for sustainable debris reuse/recycling
- No or unstable market for materials - different types, demand
- Money right now is in acceptance, hauling, storage of debris materials
- Concrete - can find reuses within a decade, but storage for that long can be challenge if more attractive uses for the land where it's stored appear
- Tree debris—potentially valuable resource for lumber and paper industries and small businesses such as carpentry and furniture production
- If recycling systems don't normally operate profitability under normal circumstances, how can we expect disaster waste recycling to be profitable?
- Challenges for reuse/recycling
    - Material quality, storage, transportation, separation, no market, political resistance/lack of coordination

C. Research Questions and Methods

GENERAL PROBLEM: moving debris from a disaster to a market (several intermediate markets):

- What materials?
- How can it be recovered, separated?
- How can it be taken to market?

What are the industries that would be involved in an end-to-end market? (e.g., wood - debris removal, storage, recyclers, grinders, particle board, etc.)

- Economic value
    - What is value of different types of material, under different disaster scenarios, who can use these materials, what does it cost to get it to them – economic valuation of materials
    - What types of facilities are needed for storing different types of materials and putting them back into use
    - What are the market failures specific to post-disaster debris removal?
    - Are there regional approaches to create economies of scale for recovery/reuse and recycling?

    - How to address the post-disaster labor markets to leverage for recovery/removal? Considering formal vs informal labor.
    - What is the funding model to facilitate resource recovery market in the long term?

- Policies/incentives
    - Normal markets don't work well in post-disaster scenarios – how do markets change after disasters, how might we change logistics/operations to respond to new market dynamics, or what interventions can be made to market to enable normal operation
    - What types of policies from local to federal levels can effectively incentivize materials recycling, e.g., separation, buying disaster waste vs. new concrete/wood
    - How to incentivize long-term management of debris materials (e.g., fly by night contractors hired by those looking for cheapest option and paid upfront but then abandon sites)

- Future/out of box
    - If there was no money for disaster debris management how would debris reuse/recycling happen; product/building design for end of life reuse/different disasters
    - What is the business model for 100% recyclable/resilient buildings, rating systems, how to prepare/treat materials?
    - What can you do incentivize/change behavior to accept recovery/separation and waste disposal centers?
    - How do you monetize the costs of siting new landfill?
    - How can debris removal be optimized to facilitate post-disaster business?
    - How do we change the paradigm to think about upcycling, because the recycling business is already a difficult market?
    - What type of information do you need to facilitate a business agent/marketplace matching platform?

D. Research Needs and Future Work

- Debris accounting to estimate potential materials
- Evaluation of effective planning/pre-planning to understand the waste stream
- Compilation of regulatory framework incentivizing/prohibiting recycle and reuse, pre-contracting, and market development before disasters
- Market discovery for recycled/reused materials
- Information needs to market matching mechanism
- Comparisons between developing/developed, low/high income, island/continental, cultural/behavioral differences

E. Actionable Research

- Developing best practices for planning (use by local governments, other government agencies).
- Business community (e.g., Chamber, Market Development agencies, Small Business Administration) to understand the potential market value of debris materials.
- Communications/learning for recyclers, businesses to be able to react to disasters.

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