Introduction
The Fukushima nuclear disaster triggered by the magnitude 9.0 Great East Japan Earthquake and tsunami on March 11, 2011, reminded the world that nuclear power plant accidents like the Chernobyl and Three Mile Island disasters can still occur. Cascading electrical systems failures resulted in a massive expulsion of stored radioactive hazards, including varying concentrations of strontium, cesium, plutonium, americium, iodine isotopes, and radioactive noble gases to the environment (International Atomic Energy Agency [IAEA], 2011a; National Diet of Japan, 2012; Physicians for Social Responsibility [PSR], 2011; Stohl et al., 2012). Foods, agricultural animals, and fish were restricted from shipping in many prefectures, though many Japanese affected by the radiation stated that they did not understand the risk as communicated by the Japanese government (National Diet of Japan, 2012). The disaster is not over; highly radioactive waters are discharging into the Pacific Ocean continuously, and “ice wall” mitigation technologies are faltering (Tokyo Electric Power Company, 2014a). Over 120,000 people remain evacuated from their homes and live with fear of radiation (Sase & Ojino, 2014). Some will never return home (Reconstruction Agency of Japan, 2014). The radiological impact upon environmental health is not certain. Four years from the disaster start, the risk to environmental health continues and the disaster is ongoing.

Therefore, we sought an understanding of the risk of radiation from the Fukushima nuclear disaster to environmental health and to learn how that risk was communicated to the public. Further, we aimed to gain an understanding of the Fukushima Dai-ichi nuclear power plant preparedness and response challenges that led to the Fukushima nuclear disaster and the associated risk to environmental health. We studied the Fukushima nuclear disaster and its effect upon environmental health through an all-hazards lens. We analyzed the known risk of radiation to environmental health, the factors that led to its release, and concepts of environmental health end fate as relational to disaster planning. We cross-examined whether the Fukushima nuclear disaster would apply to disaster planning, risk communication, and consequence management rubrics in other countries including the U.S. This article attempts to clarify disaster planning challenges to all-hazards identification and vulnerability analysis processes. It also discusses how our research led us to understand the risk to environmental health by distinguishing man-
made hazards and vulnerability factors from a natural disaster trigger event.

**Methods**

We conducted a literature review of publications germane to the Fukushima nuclear disaster including the following subject matter: national and international nuclear industry standards; the site operator, Tokyo Electric Power Company (TEPCO); international and American nuclear associations; Fukushima nuclear disaster scientific papers; and reports referencing the Chernobyl nuclear disaster and nuclear accidents at other sites in the world.

**Research Questions**

1) How did the natural disaster trigger event, man-made hazards, and vulnerability factors impact risk assessment and communication capacity and heighten the risk to environmental health?

2) What do the environmental health implications of the Fukushima nuclear disaster add to all-hazards planning and response capacity opportunity, including concepts of environmental end fate, in and outside Japan?

From an all-hazards/CBRNE (chemical, biological, radiological, nuclear, and explosive) preparedness perspective, we sought to understand and differentiate the hazards existing at the Fukushima Dai-ichi nuclear power plant at the time of the Great East Japan Earthquake and tsunami. We intended to explore the application of that knowledge to disaster planning processes in and outside Japan, including the U.S., to prevent the risk of radiation to environmental health, defined as air, water, soil, and environmental media (Bisesi, Long, London, Hester Harvey, & Enriquez Collins, 2013).

**Results**

Our analysis of the Fukushima nuclear disaster found that risk to environmental health profoundly associates with disaster trigger events, man-made hazards, vulnerability factors, and level of preparedness and adequacy of response. The Fukushima nuclear disaster provides insight into the risk of man-made hazards and nuclear plant vulnerabilities.

**Disaster Trigger Event**

The Fukushima nuclear disaster was triggered by linked natural disasters, both of which were probabilistically analyzed according to geographic and geological metrics by Japanese risk assessment authorities (National Diet of Japan, 2012). TEPCO estimated that the probability of natural disasters (earthquake, tsunami) exceeding plant design safety margins would be low (National Diet of Japan, 2012). Likewise, the International Atomic Energy Agency (IAEA) considered a nuclear release a low probability event prior to the Fukushima nuclear disaster (IAEA, 2010). The March 11, 2011, Great East Japan Earthquake and tsunami exceeded estimations, however.

Other international preparedness perspectives such as the Hyogo Framework, which is hailed as the lead international disaster driver, are natural-disaster focused (Maurice, 2013). The Hyogo Framework, predominantly focused on external disaster events (Maurice, 2013), has led to response, or event-based planning paradigms. Other international sources warned that secondary technological and infrastructure failure events can be initiated by a natural disaster trigger event, causing secondary hazards release as its consequence (Cruz, Steinberg, Arellano, Nordviuk, & Pisanon, 2004; United Nations, 2005).

The Fukushima nuclear disaster stands apart from the Chernobyl and Three Mile Island nuclear disasters: it involved the first-ever reactor core melt (three separate core reactor meltdowns) triggered by a natural disaster. The man-made Chernobyl and Three Mile Island disasters remind the world that Fukushima nuclear disaster-like scenarios can be caused by intentional (e.g., terrorism), accidental, and natural disasters.

**Vulnerability Factors**

Specific vulnerability factors heightened the risk of man-made hazards stored at the Fukushima Dai-ichi nuclear power plant early in the disaster event horizon: multi-unit reactor configuration, spent nuclear fuel pools, risk assessment and communication, and incident command system execution.

**Multi-Unit Reactor Configuration**

The near proximity of six nuclear reactor units caused one to directly affect the others, compounding the severity of systems failures and response difficulty (U.S. Nuclear Regulatory Commission [NRC], 2011, 2014). The radiological complexities of the multi-unit reactor configuration and the adjacent spent nuclear fuel pools exceeded the capacity of the on-site sampling equipment placed by the U.S. Nuclear Regulatory Commission (NRC) after the disaster (NRC, 2011). The vulnerability density design configuration also directly impacted reactor unit #3, which contained an additional plutonium content. NRC later ordered U.S. licensees to “modernize monitoring equipment to insure multi-unit site monitoring capability” as a result of the lessons learned from the Fukushima nuclear disaster (NRC, 2011).

**Spent Nuclear Fuel**

The open-water storage vessels containing thermally hot, high-level radioactive spent nuclear fuel were of particular concern early in the event. Spent nuclear fuel is not stored within the fortified containment units that safeguard reactor fuel release. Spent nuclear fuel, the “most hazardous of all man-made wastes,” must be managed for 200,000 years, essentially “forever,” due to the lack of disposal options presently challenging the U.S. and other nations (PSR, 2011; Rosenbaum, 2014; Taebi & Klosterman, 2008). Dependent upon constant cooling processes that require complex and integrated electrical systems to maintain safe cooling temperatures, spent nuclear fuel pools lost mechanical cooling capacity at the Fukushima Dai-ichi nuclear power plant for over three weeks. IAEA records show that power was restored at least partially to all nuclear reactor units and spent nuclear fuel pools on April 3, 2011 (IAEA, 2011b). Spent nuclear fuel is capable of killing a human within minutes in near-direct contact (PSR, 2011).

Spent nuclear fuel rod assemblies, which contain hundreds of rods, must be stored in carefully spaced containers to prevent a spontaneous nuclear reaction. Spent nuclear fuel in Japan, as well as in the U.S., is stored such that coolant loss would cause immediate safety concerns and the resulting spontaneous fires could result in a contamination zone as large as 188 square miles (Alvarez, 2011). The March 14, 2011, IAEA Fukushima Nuclear Accident Update Log, published on their Web site immediately after the Fukushima nuclear disaster, described the first appearance of burning spent nuclear fuel and stated that radiation was being released “directly into the atmosphere (IAEA,
employees manifested in response delays, causing further deterioration of nuclear fuel cooling processes (NRC, 2014a).

**Man-Made Hazards**

National and international nuclear oversight agencies provide focus for nuclear site safety programs in general. The IAEA lists three primary nuclear plant safety functions: prevention of criticality, removal of fuel heat, and the mitigation of radioactive releases (IAEA, 2011d). The Japan Atomic Energy Agency (JAEC) lists six primary risk considerations regarding nuclear power generation: nuclear fuel cycling, treatment and disposal of waste, proliferation, terrorism, and accidents (JAEC, 2009). Population vulnerabilities from underevaluated factors associated with disasters, however, such as agency governance capacity and the role of public health in defining disaster risks, remain undefined in disaster planning processes internationally (Maurice, 2013).

**Japan**

The National Diet of Japan report on the Fukushima nuclear disaster contained the following language, “although triggered by these catastrophic events, the subsequent accident at the Fukushima Dai-ichi nuclear power plant cannot be regarded as a natural disaster. It was a profoundly man-made disaster—that could and should have been foreseen and prevented. And its effects could have been mitigated by a more effective human response (National Diet of Japan, 2012).” According to Japanese occupational safety experts, Japan had no regulations on the disposal of radiation outside the controlled areas of the Fukushima Dai-ichi nuclear power plant (Yasui, 2013), leading to inadequate consideration for radiation environmental health end fate. The National Diet of Japan report also stated that TEPCO had no “countermeasures” in place for a severe accident (National Diet of Japan, 2012).

**United States**

In the U.S., all-hazards preparedness was originally driven by pre-1996 Federal Emergency Management Agency (FEMA) Civil Preparedness Guides (Bokman, 2003). After the terrorist attacks on September 11, 2001, disaster planning emphasis shifted towards terrorism (Bokman, 2003). Site-specific hazard analysis is now emphasized (Pandemic and All-Hazards Preparedness Reauthorization Act [PAHPRA], 2013). All-hazards readiness is defined by being prepared for chemical, biological, radiological, and nuclear threats, whether naturally occurring, unintentional, or deliberate (including man-made acts of terrorism) (PAHPRA, 2013). Therefore, man-made hazards can be exacerbated unintentionally (by accident), by intention (such as an attack on a power grid), and by a natural disaster trigger event. U.S. regulations do not adequately address a natural disaster-triggered hazardous material release, however, and fail to require preemptive evaluation and planning (Cruz et al., 2004).

The terms risk and hazard should not be interchangeable (Royal Society of Chemistry, 2013), though it is agreed that hazards create the risk of a disaster (Bolz, Dudonis, & Schulz, 2005). Both terms are tied to probabilistic notions associated with the severity of a disaster event impact (Royal Society of Chemistry, 2013). A broad spectrum of terms are used by FEMA, the Department of Homeland Security, NRC, presidential directives, and other sources to describe a disaster: risk event, significant event, extreme event, catastrophic event, incident, incident of national significance, risk and threat and hazard, all-risk, all-hazard, natural hazard, technological hazard, natural disaster, and natural and technological disaster (NA-TEK).

According to the 2012 National Academy report on disaster resilience, gaps exist in all phases of disaster “preparedness, response, recovery, mitigation, and adaption, as well as research, planning, and community assistance (National Academies, 2012).” Additionally, U.S. emergency responders, overwhelmed by natural disaster, may fail in response to secondary hazards released in the case of NA-TEK disasters by a natural disaster trigger (Cruz et al., 2004). Occupational Safety and Health Administration (OSHA)—evaluated safety systems do not apply to disaster mitigation environments (Cruz et al., 2004). An August 2014 guidance document from NRC also recognized that U.S. nuclear plants are not prepared for “many hazards.” NRC further urged a “better account for plant system interactions and the performance of plant operators and other critical personnel in responding to such events; and [a] better estimate [of] the broad range of offsite health, environmental,
After discovering significant post-Fukushima nuclear disaster vulnerability assessment inconsistencies in U.S. licensee processes, the NRC provided them a new definition: “plant specific vulnerabilities are those features that are important to safety that when subjected to an increased demand, due to the newly calculated hazard evaluation, have not been shown to be capable to perform their intended functions (NRC, 2012).” The NRC Fact Sheet on Probabilistic Risk Assessment states that the U.S. nuclear facilities pose “no undue risk to public health and safety (NRC, 2014c).” The General Electric–designed boiling water nuclear reactors at the Fukushima Dai-ichi nuclear power plant, however, presently provide energy at 23 locations in the U.S. (NRC, 2014b).

Because intentional attacks can cause a site blackout, the Fukushima nuclear disaster lessons learned are applicable to attack-prone sites in the world. For example, infrastructure vulnerability to cyber attacks could result in power-grid loss and other systems failures. South Korean hydro and nuclear plant security was maliciously breached in December 2014 (BBC News, 2014; Reuters, 2014). South Korean plans for nuclear reactor cooling processes were obtained by an unauthorized entity (BBC News, 2014; Reuters, 2014).

Risk to Environmental Health
NEHA’s definition of environmental health includes the evaluation of hazardous agents in “air, water, soil, food, and other environmental media (Bisesi et al., 2013).” The Fukushima nuclear disaster caused a catastrophic release of radiological hazards into the ecosystem (IAEA, 2011; National Diet of Japan, 2012; PSR, 2011; Stohl et al., 2012). Extremely high levels of strontium, a bone-seeking radionuclide with a half-life of 28 years, are currently increasing in soil, groundwater, and ocean samples near the Fukushima Dai-ichi nuclear power plant (TEPCO, 2014b). The possibility for bioaccumulation of radiation in predatory fish may present in other parts of the world in the future (Sutton & Cassalli, 2011).

The Fukushima nuclear disaster caused the largest discharge of radiation into an ocean in the history of the world (Sutton & Cassalli, 2011); yet ocean discharges were monitored in a “rushed” and “panicky” manner by TEPCO personnel. TEPCO also focused exclusively on iodine and cesium (House of Commons, 2013). Other radioactive components, such as plutonium, americium, and curium, with half-lives of “thousands of years,” were not addressed at all (House of Commons, 2013). All five of the radionuclides are specifically listed by the Codex Alimentarius Commission as radiological concerns in foods following a nuclear accident (National Council on Radiation Protection and Measurements, 2010).

The World Health Organization (WHO) published a dose estimation report in January 2012, however, finding that the Fukushima nuclear disaster presented a limited, even small risk, to Japan and the world. The report stated that a “probable partial melting of the core of the three reactors” occurred (World Health Organization [WHO], 2012). The report may have led the world to underestimate the disaster (Mousseau, 2013; Perrow, 2013), while significant radiation releases to the environment were ongoing.

The WHO International Health Regulation (IHR), which was revised in 2005, seeks to “…provide a public health response to the international spread of disease…” It includes the natural, accidental, and deliberate release of radiologically contaminated materials (underlined by authors). The IHR legally binds 196 countries around the world, including Japan and the U.S. (WHO, 2005). WHO describes the IHR as event-based surveillance (WHO, 2014). Its language does not advocate the predisaster analysis of radiological hazard inventory end-fate consequences to environmental health. U.S. hazard vulnerability assessment processes also do not focus on the environmental health end fate of stored hazard inventories, potentially externalized to the community (NRC, 2014a), opening the door to disaster response and consequence management uncertainty.

The environmental health problems generated by the Fukushima nuclear disaster are also of a global nature. The Fukushima nuclear disaster produced “likely the largest radioactive noble gas release” to the air in history (Stohl et al., 2012). The Fukushima Dai-ichi power plant continues to discharge dangerous levels of radiation into the Pacific Ocean. Significant land, aquifer, and ocean contamination continues and is acknowledged by the site operator (TEPCO, 2014b). The consequences of the Fukushima nuclear disaster are also ongoing. The “ice wall” technology, engineered to contain the flow of ground water in contact with radioactive reactor building materials and potentially in direct proximity to highly radioactive molten reactor core content, was not working as planned (TEPCO, 2014a).

The Fukushima Nuclear Disaster: An All-Hazards Planning Reference Model
We present the disaster planning model below, established from Fukushima nuclear disaster lessons learned. We segment “Disaster Trigger Event,” “Man-Made Hazard,” and “Vulnerability Factors” to enable differentiation of independent vulnerability analyses. In this model, we follow the WHO preparedness equation denominator standard “Level of Preparedness” (WHO, 2007) and add “Adequacy of Response.”

Risk to Environmental Health = [Disaster Trigger Event] + [Man-Made Hazards x Vulnerability Factors]
Level of Preparedness and Adequacy of Response

We find that the “Risk to Environmental Health” is a consequence of the “Disaster Trigger Event” plus “Man-Made Hazards,” exacerbated by “Vulnerability Factors.” The impact of radiation release (“Risk to Environmental Health”), triggered by earthquake and tsunami (“Disaster Trigger Event”), caused the release of the radiation (“Man-Made Hazard”), which was precipitated by site blackout and subsequent loss of cooling system capacity (“Vulnerability Factors”). The consequences of a “Disaster Trigger Event,” “Man-Made Hazards,” and “Vulnerability Factors” present the independent opportunity for modification (or mitigation) to prevent the “Risk(s) to Environmental Health.” The model reflects our analysis that “Man-Made Hazards” and “Vulnerability Factors” may interact in multiplicative fashion.

Given the analysis of the Fukushima nuclear disaster, “Risk to Environmental Health” must be ameliorated by the division of plant supply chain and continuity of operations-based (internal) concerns from “Man-Made Hazards,” which may be potentially externalized to the community. Further, we posit that the
Fukushima Dai-ichi power plant operational resilience was dependent upon the denominator of our model, i.e., “Level of Preparedness” and “Adequacy of Response.”

Discussion

What Was Known
Cascading electrical systems failures of the Fukushima Dai-ichi nuclear power plant resulted in a massive expulsion of stored radioactive hazards, including varying concentrations of strontium, cesium, plutonium, americium, iodine isotopes, and radioactive noble gases to the environment (IAEA, 2011; National Diet of Japan, 2012; PSR, 2011; Stohl et al., 2012). As three of the four clustered Fukushima Dai-ichi nuclear power plant nuclear reactor cores melted (releasing massive quantities of radiation into the local communities), over 120,000 people evacuated their homes (Reconstruction Agency of Japan, 2014) and some will never return home. Foods, agricultural animals, and fish were restricted from shipping in many prefectures, though many Japanese affected by the radiation did not understand the risk as communicated by their government (National Diet of Japan, 2012). Reports of high levels of cesium, strontium, and plutonium in groundwater and ocean samples began to surface in 2012, followed by TEPCO confirmations that remediation processes were in doubt (TEPCO, 2014a).

What We Found
We exhibited in our model that interacting “Vulnerability Factors” exacerbated the power blackout–initiated release of “Man-Made Hazards” at the Fukushima Dai-ichi nuclear power plant, though the magnitude of “Risk to Environmental Health” is uncertain. “Level of Preparedness” and “Adequacy of Response”–related disaster planning and technology barriers (including the inability to record real-time emissions) prevented effective radiation risk assessment, which affected the quality of public health risk communication and hazard mitigation processes. Planned releases and uncontrolled leaks from storage vessels discharged radiation into the Pacific Ocean in enormous volume.

The process of hazard vulnerability assessment focuses on specific internal hazards that are likely to be present for a facility, and external events that are geographically, meteorologically, and even biologically predictable (American Standards and Testing Material International, 2004; Occupational Safety and Health Administration, 2005). For example in the U.S., Oklahoma is vulnerable to tornadoes, Florida is vulnerable to hurricanes, and California is vulnerable to earthquakes.

In addition, all geographic locations in the world are potentially vulnerable to intentional man-made acts of terrorism or other adverse event occurrences that are likely to occur in that community. The hazard vulnerability assessment tool combines notions of event probability and severity. Some hazard vulnerability assessment standards specifically advise, however, to “minimize planning for unlikely events (American Standards and Testing Material International, 2004).” The high consequence risk of an off-site radiation release due to a site power blackout was determined to be a low probability occurrence during hazard vulnerability assessments performed by Japanese officials and plant operators (National Diet of Japan, 2012). The man-made radioactive hazards did not receive disaster planning and response assessment priority. Japanese officials did not plan adequately for the off-site dispersion of radiation (Yasui, 2013), therefore the estimation of environmental health end fate was disregarded. The implications of this finding (and accounted for in our “All-Hazards Planning Reference Model”), though beyond the scope of this article, may provide important insight for future studies of community resilience that are not yet well formed on disaster planning for man-made hazards. Certainly, the resilience of a community is dependent upon the operational resilience (and required safety margins and environmental regulation) of corporations that create and process man-made hazards.

The lessons learned from the Fukushima nuclear disaster can also apply to other sites and nations. We discovered that U.S. hazard vulnerability assessment processes share similar disaster planning challenges, including the following paradigm groups: event, natural disaster, probability, supply chain, and continuity of operations-driven planning foci. Low-probability high-consequence disaster events receive lower priority in general. We found that OSHA-driven approaches, common to U.S. response rubrics, are likely inadequate (Cruz et al., 2004). We also found agency-specific and unstandardized disaster terminologies that merge concepts of hazard and risk. This may hamper hazard vulnerability assessment processes by minimizing focus on man-made hazards. We learned from the Fukushima nuclear disaster that the probability estimation of a disaster trigger event whether natural (such as severe weather), intentional, or accidental, may overshadow planning considerations for stored hazards. In reaction to the disaster, NRC moved to ensure that U.S. nuclear sites were prepared for flooding and communication failures, both considered the major vulnerabilities of the Fukushima Dai-ichi nuclear power plant (NRC, 2012). The General Electric–designed boiling water reactors (Organization for Economic Coordination and Development Nuclear Agency, 2011) are in use at 23 U.S. nuclear plants (NRC, 2014b), further underscoring the significance of the Fukushima nuclear disaster to the U.S.

Limitations
This analysis was based upon documents published by the time of the submission of the manuscript. Thus, unpublished documents and internal reports were not reviewed. In our Fukushima nuclear disaster analysis, the natural disaster trigger event refers to a double natural disaster (earthquake and tsunami) that caused the site blackout and instantaneously resulted in the release of radiation. We acknowledge the specificity of the conditions that we describe relevant to the Fukushima nuclear disaster. Because accidental and man-made disasters can also cause site blackouts, this limitation does not weaken our findings. Instead, we discussed the strength of our findings and their relevance to vulnerabilities that exist at most industrial plant locations.

Conclusion
Extensive barriers to risk assessment and communication existed prior to the Fukushima nuclear disaster that impeded disaster “Level of Preparedness” and “Adequacy of Response,” resulting in heightened “Risk to Environmental Health,” as we presented in the above model. Specific “Vulnerability Factors” unique to the Fukushima nuclear disaster, exacerbated the release of “Man-Made Hazards” as a result of a “Disaster Trigger Event”: multi-unit reactor configuration, spent nuclear fuel pools, risk assessment and communication capacity, and incident command system execution.
A uniform lexicon for disaster planning descriptions that effectively defines and standardizes concepts of risk, hazard, vulnerability, and natural disaster trigger event should be established internationally. The U.S. hazard vulnerability assessment process must additionally emphasize the estimation of, and planning for, the environmental health end-fate consequences of industrial hazard inventories potentially released off site. Contamination considerations for food, water, and human evacuation and other safety restrictions should be made jointly by industry, the government, and the community, in event planning, assurance, and oversight phases. 

The selection of “Man-Made Hazard” and “Vulnerability Factor” modification, substitution, assurance, and oversight phases. government, and the community, in event considerations for food, water, and human evacuation and other safety restrictions should be made jointly by industry, the government, and the community, in event planning, assurance, and oversight phases.

References


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Pandemic and All-Hazards Preparedness Reauthorization Act, 42 USC 201 (2013).


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