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Citizen monitoring during hazards: validation of Fukushima radiation measurements

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Abstract Citizen-led movements producing scientific hazard data during disasters are increasingly common. After the Japanese earthquake-triggered tsunami in 2011, and the resulting radioactive releases at the damaged Fukushima Daiichi nuclear power plants, citizens monitored on-ground levels of radiation with innovative mobile devices built from off-the-shelf components. To date, the citizen-led Safecast project has recorded 50 million radiation measurements worldwide, with the majority of these measurements from Japan. The analysis of data which are multi-dimensional, not vetted, and provided from multiple devices presents big data challenges due to their volume, velocity, variety, and veracity. While the Safecast project produced massive open-source radiation measurements at specific coordinates and times, the reliability and validity of the overall data have not yet been assessed. The nuclear disaster at the Fukushima Daiichi nuclear-power plant provides a case for assessing the Safecast data with official aerial remote sensing radiation data jointly collected by the governments of the United States and Japan. This study spatially analyzes and statistically compares the citizen-volunteered and government-generated radiation data. An assessment of the Safecast dataset requires several preprocessing steps. First, it was necessary to convert the data from the Safecast ionized radiation sensors since they were collected using different units of measure than the government data. Secondly, the normally occurring radiation and decay rates of cesium from deposition surveys were used to properly compare measurements in space and time. Finally, the GPS located points were selected within overlapping extents at multiple spatial resolutions. Quantitative measures were used to assess the similarity and differences in the observed measurements. Radiation measurements from the same geographic extents show similar spatial variations and statistically significant correlations. The results suggest that? actionable scientific data for disasters and emergencies can be inferred from non-traditional and not vetted data generated through citizen science projects. This project provides a methodology for comparing datasets of radiological measurements over time and space. Integrating data for assessment from different Earth sensing systems is paramount for societal and environmental problems.

Keywords Volunteered geographic information · Citizen science · Environmental monitoring · Fukushima · Radiation · Hazards

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Introduction

Volunteered Geographical Information (VGI) is a term used for a broad category of user-generated

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information that contains a spatial attribute (Elwood 2008). VGI sourced from social media platforms, such as Twitter, Facebook, and Instagram, have been used to study a variety of subjects including natural hazards, demographics, and health (Sui et al. 2013). Citizen science with geographic information is a form of VGI created with intentionality to contribute information about the environment (Fowler et al. 2013). Yet, reliance on citizen-led, non-authorized data is often considered a risk as its collection is often not standardized for official use or scientifically assessed (Flanagin and Metzger 2008). There is often low confidence in VGI as the collection is project-determined with sometimes limited metadata on the production of data and related data-driven map products (Langley 2014). VGI can be timelier to access than traditional sources of data, but its collection is not often scientifically organized for a sampled distribution which can make the resulting datasets difficult to generalize (Miller and Goodchild 2014). Citizens as sensors produce data in the spaces in which they inhabit as they leave a track of GPS movement data. An individual GPS trace does not provide overall situational awareness, but collectively, VGI can produce high temporal and spatial resolution data for select areas such as along roads (Tominski et al. 2012).

Citizen-led movements collecting scientific environmental data may contribute information for situational awareness during hazardous events (Sprake and Rogers 2014). Advances in sensor and geospatial technologies enable citizens to monitor exposure to hazards by innovative mobile devices built from off-the-shelf components (Hemmi and Graham 2014). Geolocated big data are often created and utilized with little consideration of validation. However, variability in values for environmental monitoring has a weight of importance as it denotes a possibly invisible source of harm that is spatially and temporally dependent. Varying standards for crowdsourced data can cause potentially valuable sources of environmental information to be overlooked for analysis and to not be as trusted as much as a government dataset (Fairbairn and Al-Bakri 2013; Fowler et al. 2013). If validated, citizen science projects could provide reliable environmental monitoring data that acts as a warning system for emergency response and for longitudinal scientific studies on hazards (Sprake and Rogers 2014).

VGI includes a variety of types of spatially enabled data whose collection is typically project driven (Fast and Rinner 2014). Recent emphasis in data analysis has been placed on the volume of data as opposed to the veracity of the information and the resulting analysis (Flanagin and Metzger 2008). Assessing VGI in integration with earth sensing systems is important for jointly meeting big data challenges of volume, velocity, variety, and veracity (Moran et al. 2015; Fairbairn and Al-Bakri 2013). VGI must be compared to a dataset with similar relevant dimensions. Space and time are critical factors in the collection of radiological data due to dispersion creating an uneven spatial distribution and radioactive elements having a temporal decay. The Safecast project is used as a case study of crowdsourced radiation measurements that is analyzed with government datasets in order to provide a methodology for comparison of environmental hazard data that have relevant dimensions of space and time. If the Safecast data is reliable, public availability of timely VGI measurements would be particularly valuable for reliably informing populations exposed to radiation.

After a Japanese earthquake triggered a massive tsunami in 2011, Fukushima nuclear reactors failed and resulted in a radioactive fallout. Radioactive releases into the atmosphere have spatio-temporal dimensions as radiation disperses over space and decays over time. The Safecast project began to crowdsource radiation measurements to a collective map by enabling citizens to acquire standardized Geiger counters online and deploy them in the field (Brown et al. 2016b). Radiation measurements using Safecast are continually uploaded with an exponential growth in entries to 14 million in Japan and 28 million globally as of May 2015 (Bonner et al. 2015). Unlike Chernobyl and Three Mile Island, this is the first case of a nuclear disaster in which radiation-measuring technology is rapidly available for public use.

In the case of Fukushima, Japanese scientists immediately adopted a technological response by using off-the-shelf parts to produce handheld scientifically calibrated Geiger counters (Bonner et al. 2015). VGI projects for local environmental monitoring are made up of voluntary citizens as sensors that provide information for collective actions (Flanagin and Metzger 2008; Fairbairn and Al-Bakri 2013). Safecast uses these volunteer citizen sensors to produce a publicly available, raw measurement collection of radiation levels at specific places and times. Japanese citizens continue to monitor radiation both as a public service for open data and for personal awareness of local radiation exposure (Bonner et al. 2015). Citizen collected radiation measurements have been challenged as not being as credible as official measurements but these projects can gain credibility by showing valid methodologies and standards (Hemmi and Graham 2014). If validated, VGI measurements of radiation could be used as a reliable, citizen-led early warning system to detect radioactive spikes and hotspots.

In order to assess the validity of the citizen science measurements, a spatio-temporal transformation can be made to compare the datasets at standardized dimensions. The global concern for the nuclear incident in Japan resulted in a variety of types of monitoring and models for radiation dispersion. Public access to radiation data provides an opportunity for assessment of comparable dimensions of citizen science and government data. The Department of Energy (DOE) and National Nuclear Security Administration (NNSA) produced a large-scale airborne remote sensing survey of the radiation levels in the Fukushima prefecture (Department of Energy 2011). In addition, other official measurements and models of the radioactive fallout following Fukushima are available for comparison. While this research provides a methodology for comparing datasets of radiological measurements, a similar approach can be applied to other spatio-temporal data in order to make dimensionally standardized assessments.

The objective of this study is to spatially analyze and statistically compare citizen-volunteered and government-generated radiation data. A spatial analysis of Safecast could result in insights about crowdsourced spatial data which is not sampled according to traditional methods. VGI is particularly situated to gain human-centric information as it is spatially distributed only in areas of human activity. While generalized spatial extents are typical of government data, human occupied geographical areas are the most essential areas to monitor radiation for public welfare. This citizen science collection is available for public usage, yet steps need to be taken to assess the reliability and validity of the data. Validation is critical to ensure that accurate information is available for evacuees returning to affected areas as local levels of radiation fluctuate and real-time measurements are not available. This study serves to provide a methodology for comparison of datasets with varying spatio-temporal resolutions.

Background

Event

On the 11th of March 2011, the 9.0 magnitude Great East Japan Earthquake triggered a tsunami 70 km off the coast of Japan at an underwater depth of 24 km (Povinec et al. 2013). The earthquake was followed by severe aftershocks, and the island of Honshu shifted 2.4 m east due to its force (Povinec et al. 2013). The eastern coast of Japan was hit by tsunami waves up to 40 m high that inundated up to 10 km inland (Povinec et al. 2013). The contributing impacts of these natural disasters led to a nuclear crisis at Fukushima Daiichi nuclear-power plant.

The Tokyo Electric Power Company (TEPCO) claimed that with five layers of protective devices the nuclear generators were absolutely “fail safe” against earthquakes and tsunamis (Nakamura and Kikuchi 2011; Figueroa 2013). Commissioned in 1971, the Fukushima Daiichi nuclear power plant is an old design of multiple connected plants on the main island of Honshu in the Futaba District of the Fukushima Prefecture (Nakamura and Kikuchi 2011). The nuclear plant is in an area of increased earthquake activity, yet studies approved the ability to withstand an earthquake or tsunami with a few improvements (Funabashi and Kitazawa 2012).

At the time of the earthquake, the Fukushima nuclear power plant was active. When the earthquake occurred sensors notified the technicians and automatically began the shutdown procedures for the nuclear cores. The nuclear power plant had a 10-m high seawall which was swept over by the 20 m high tsunami (Funabashi and Kitazawa 2012). The Fukushima power plant lost power as the backup diesel generators flooded and diesel tanks washed out to the ocean. The nuclear workers at the power plant were working without coolant available or diesel generators for electricity (Nakamura and Kikuchi 2011). The cores started to overheat, and a lack of coolant led to a partial meltdown and a series of intentional and accidental radioactive releases into the atmosphere and the ocean (Nakamura and Kikuchi 2011;

Funabashi and Kitazawa 2012). These events were followed by a series of four hydrogen explosions which damaged the units at the facilities (Povinec et al. 2013).

The nuclear explosions at the Fukushima Daiichi nuclear-power plant resulted from a complex natural disaster that overwhelmed the system. Nuclear facilities are particularly vulnerable in disaster-prone regions with aging infrastructure (Funabashi and Kitazawa 2012). In the case of the coastal nuclear facility in Fukushima, multiple safety fall-backs failed as the circumstances led to a level seven nuclear accident, the highest according to the Nuclear and Radiological Event Scale (Visschers and Siegrist 2013).

The Fukushima incident attracted enormous international attention. In the weeks following the natural disasters, the nuclear power plant was still releasing radiation, but there was minimal public awareness of the extent of radiological emissions and even confusion amongst government officials (Funabashi and Kitazawa 2012). The national government was under incredible stress to manage response to the overwhelming devastation of an earthquake, tsunami, and nuclear disaster. It was recognized that widespread data on the extent and intensity of radiation is absolutely critical in order to provide situational awareness to decision makers.

Situational awareness of radiation

Nuclear disasters present estimation challenges in modeling the dispersion and intensity of radiation over space and time as the distribution is highly dependent on the weather and the characteristics of the source (Sugiyama et al. 2012). Dispersion modeling is useful to inform officials on environmental conditions for critical decision making of potential or actual impact from harmful releases (FEMA 1996). Policy makers often require estimates of dispersion of toxins and chemicals to be modeled before permitting a facility to operate (Snell and Jubach 1981; Bander 1982). Mathematical algorithms have been developed to model particle spread in the atmosphere and deposition in relation to the present or an extreme environment by using data inputs of meteorology, terrain, and characteristics of the source (Terada et al. 2012; Cervone and Franzese 2014). Plans and procedures are typically put in place to have real-time modeling of dispersion estimates in order to make scientifically informed predictions and evaluate risks (Cervone and Franzese 2014). Real-time modeling was the purpose of the System for Prediction of Environmental Emergency Dose Information (SPEEDI) which was instituted by the Japanese government as a network of ionized radiation sensors to provide the input to model radiation dispersion (Funabashi and Kitazawa 2012).

Maintained to provide real-time dose assessment in radiological emergencies, SPEEDI is a radiation sensor array implemented in 1984 by the Japanese Nuclear Regulation Authority (Funabashi and Kitazawa 2012). However, when the earthquake occurred, the system was unable to cope as data link connections were lost and some devices along the coast were directly damaged by the tsunami. Japanese local authorities were equipped with devices to measure radiation, but according to the Fukushima Nuclear Accident Independent Investigation Commission, only 1 of 24 radiation monitoring posts functioned when needed (Hemmi and Graham 2014; Povinec et al. 2013). Since the power supply around the reactor was lost, TEPCO and government measurements were taken in other ways through the installation of temporary monitoring posts and sampling by car.

Many local government administrators did not have awareness to make an informed decision about radiation risk and many officials waited for word from the federal government to evacuate (Idogawa 2014). The federally issued evacuation zone was initially minimal and failed to take into account the direction of the radiation plume. Therefore, as many people were moving out of the coastal tsunami zone, the population was unaware of the radiation exposure and, in some cases, evacuated into areas of higher radiation (Povinec et al. 2013; Meybatyan 2014). Authoritative sources did not provide answers on the extent of the radioactive releases, and an estimate from SPEEDI was not released to the Japanese Prime Minister until the 23rd of March due to validity concerns from minimally available data (Funabashi and Kitazawa 2012). The SPEEDI models were not taken seriously as some considered the data not functional for decision making as all the variables needed for the calculations were not available (Meybatyan 2014).

Initial SPEEDI estimates at the source were limited as the network was damaged, but the source term release rate can be reconstructed based on observations away from the Daiichi nuclear-power plant by modeling concentrations back to the source (Cervone and Franzese 2014). The Department of Energy (DOE) and National Nuclear Security Administration (NNSA) collected large scale surveys of radiation readings from 17 March until May 2011 (Department of Energy 2011). DOE/NNSA activated the US National Atmospheric Release Advisory Center (NARAC) to model plume concentrations by all available measurements which included the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT) and on-site Tokyo Electric Power Company (TEPCO) (Sugiyama et al. 2012). In the months that followed, more sources of radiation measurement surveys became available such as through the Japan Atomic Energy Agency (JAEA) Database for Radioactive Substance Monitoring Data. The JAEA government radiation surveys were taken at specific times for large scale monitoring a few times a year from 2011 to 2013 (Japan Atomic Energy Agency 2014). Government survey data are collected systematically leaving standard spatial and temporal gaps. Environmental monitoring of radiation could be augmented by non-traditional sources.

Safecast project

Safecast is a Volunteered Geographical Information (VGI) project that crowdsources radiation readings by using voluntary citizens as sensors (Flanagin and Metzger 2008; Fairbairn and Al-Bakri 2013). In the aftermath of the Fukushima nuclear disaster, Japanese citizens immediately adopted a technological response by using off-the-shelf parts to produce handheld scientifically calibrated Geiger counters (Bonner et al. 2015). Volunteers built crowdfunded Geiger counters and distributed the devices to collect radiation measurements immediately after the nuclear disaster (Bonner et al. 2015). In the years following, the bGeigie Nano can be purchased online as a build your own kit that is used across the world. The Safecast project has experienced exponential growth so that in 4 years it recorded over 45 million measurements.

This citizen-led project is user-generated (Elwood 2008) to enable the population to collect timely local radiation levels on-the-ground. Citizens collect radiation measurements as a public service, but to maintain an open data stance, Safecast avoids interpreting the data (Bonner et al. 2015; Hemmi and Graham 2014). The Safecast project is committed to using open-source technologies and providing environmental monitoring through a global network for open-data (Abe 2014). Safecast data is completely accessible under the Creative Commons license (Creative Commons 2015).

The collective web map provides publicly available open data of radiation levels. Registered users upload their device recorded GPS coordinates and timestamped measurements to a collective map. The data is collected through on-ground methods such as attaching the Geiger counters to moving vehicles, carrying them by foot, and placing them as static sensors (Safecast 2015b). Continuing collection is useful for evacuees briefly returning to affected areas as local levels of radiation fluctuate and real-time localized measurements are not available.

Data

In order to compare the observations with spatial and temporal considerations, this research methodology involves the integration of four radiation related datasets in the Fukushima area. Unit standardization is a preprocessing step as radiation measurements are collected in different types of units based on their purpose. Counts per minute (noted as cpm) is a rate of the detection of ionized radiation particles measured but it is not an SI unit (International System of Units) and it cannot be converted to a biological dose by a universal factor. Microsieverts (noted as μSv/h) is a derived unit of radiation measurement of biological dose. Becquerel is a unit of quantity for a material in which the rate of activity is one nucleus decay per second (Table 1).

Safecast–Fukushima measurements

The Safecast bGeigie Nano is a Geiger counter developed as a cost effective device for ionized radiation monitoring (Bonner et al. 2015). The bGeigie Nano can be bought online as a kit designed with off-the-shelf parts except for the LND7317 pancake sensor itself (Safecast 2015b). The sensor is a Geiger–Müller sensitive to gamma, beta, and alpha, but the Safecast manual instructs the sealing of the sensor to prevent alpha detection and has a separate collection for beta measurements (Safecast 2015a, b). The device is preset to monitor radiation from

Table 1 Table summarizing data sources with the number of measurements within the spatial extent and purpose of their use in case study

Dataset	Dates (quantity)	Units	Purpose
Safecast	2011–2015 (6,249,165)	Counts per minute (cpm)	Citizen science project to validate
DOE	2011 (107,147)	Microsieverts (μSv/h)	Government data for comparison
AIST	2007 Survey (121)	Microsieverts (μSv/h)	Background radiation present
JAEA	26 May 2011 (33,266), 2 July 2011 (32,274), 5 November 2011 (32,656), 10 February 2012 (5439), 31 May 2012 (28,992), 28 June 2012 (33,312), 28 December 2012 (33,323), and 11 March 2013 (5457)	Becquerel (Bq)	Specify decay ratio of cesium

radionuclide ^{137}Cs in counts per minute (cpm) (Safecast 2015b). The detection device has an SD card memory to log observations and a receiver to connect to Global Positioning System (GPS) to record the location.

Safecast radiation measurements are uploaded to a collective web map with a GPS coordinate and timestamp as individual point measurements. The measurements are visualized in a browser-based map and downloadable through an API. The radiation measurements are collected using hand held sensors that are carried by individuals or statically placed units. A real-time feed of static sensors is now also available for measurements consistent to locations (Safecast Real Time Radiation Monitoring 2016). The same device at the same place can be more indicative of an observed change in radiation than a device which is mobile or a different device observing a measurement in a formerly monitored location. The Safecast project reached its goal of collecting at least one radiation measurement on every road in Japan (Franken 2014).

The technical expertise behind the project adds a sense of credence as the Safecast team has scientific backgrounds in engineering, information systems, applied physics, and energy acceleration (Bonner et al. 2015). The sensors were calibrated scientifically at multiple official testing laboratories and found to have an error of positive or negative ten percent which is an excellent error rate for a Geiger counter (Safecast 2015a). As a crowdsourced project, Safecast relies on the statistically improved accuracy of multiple samples over many units (Safecast 2015a). Multi-point radiation level collection was field-tested with local government permission. Problems in collection were addressed, such as, standardizing the device, speed of a moving vehicle, and attaching the device outside the car. Safecast collects a much larger quantity of measurements than traditional radiation surveys at these times and places.

Safecast data continues to be collected to this day and can give a longitudinal view of how radiation has decayed over the years since the nuclear disaster. On the average, there are about 10,000 Safecast observations per week, with six instances with over 100,000 measurements per week; the maximum occurred in 2013 with over 200,000 observations.

DOE: Fukushima measurements

The Department of Energy (DOE) and National Nuclear Security Administration (NNSA) worked to get a broad airborne remote sensing survey of the Fukushima Prefecture radiation levels which provides a complete footprint of the radiological release over land (Lyons 2011). The United States Aerial Measuring System (AMS) responded to the radiological event by flying over a hundred survey flights from 17 March 2011 until 28 May 2011 (Lyons and Colton 2012).

AMS collected radiation measurements with large thallium activated sodium iodide (NaI(T)) crystals on fixed-wing aircraft and helicopters over broad swaths standard pattern. The AMS survey flights were flown for the fixed-wing airplanes at 140 knots with an altitude of 550–700 m above ground at 610–1610 m line spacing while the helicopters were flown at 70 knots 152–305 m above ground with 305–610 m line spacing (Lyons and Colton 2012). The AMS mission encountered different conditions than training assumptions that the terrain was flat and that the release was of short duration instead of over multiple days. An initial question involved the ability to extrapolate the airborne observed data to 1 m from the ground exposure rates. An analysis technique was applied using ground measurements to extrapolate the amount of radioactive material in the air to the quantity deposited on the ground.

The DOE/NNSA provides a publicly available set of raw aerial and extracted ground exposure rates (Department of Energy 2011). The public DOE dataset has over 107,000 observations that cover roughly $20,000\,\mathrm{km}^2$ over the Fukushima Prefecture for a period of 5 weeks from 2 April 2011 through 9 May 2011. The DOE decayed the radiation to 30 June 2011 with ^{134}Cs and ^{137}Cs decay rates assumed at a 1:1 ratio.

AIST: background radiation survey

The Japanese National Institute of Advanced Industrial Science and Technology (AIST) completed a 2007 survey of natural background radiation in µSv/h AIST (2007). The AIST data covers the entire island of Japan at about half a kilometer resolution and has a natural spatial variation in the background radiation that is dependent on topography. The values of background radiation range from .06 to .13 µSv/h for the study area. This data allows the removal of the effect of background radiation in order to only decay radiation measurements that are above naturally occurring levels by location.

JAEA: cesium deposition surveys

The Japan Atomic Energy Agency (JAEA) took 9 airborne surveys of the energy spectrum of gamma ray radiation from 29 April 2011 until 11 March 2013. The deposition densities of ^{134}Cs and ^{137}Cs were assessed by sorting out the energy spectra of radioactive cesium. The airborne monitoring cesium deposition density surveys are raster datasets with spatial units $500\,\mathrm{m}^2$ have values for the deposition of radioactive cesium (Japan Atomic Energy Agency 2014). Ratio between ^{134}Cs and^{137}Cs in the Fukushima area from surveys performed by the Japan Atomic Energy Agency between 2011 and 2013. The ratio monotonically decreases as a function of time because of the shorter half-life of ^{134}Cs. The proportion of cesium in the surveys is measured in units of becquerel. Further information on each survey taken can be found on the Database for Radioactive Substance Monitoring Data website under Airborne Monitoring in the Distribution Survey of Radioactive Substances (Japan Atomic Energy Agency 2014).

Methodology

This research ultimately provides a methodology to compare datasets of radiological measurements over time and space. Fusing datasets with different spatial and temporal resolutions can point out inconsistencies in measurement which are otherwise ignored due to reliance on single sources of official data. Using multiple datasets ensures that both datasets are considered critically, and similar trends may signal reliability of the data. Comparable measurements from DOE would provide validation for Safecast and demonstrate that we can infer scientific data from non-traditional and not vetted data. In addition, this comparison can give the Safecast dataset a vote of confidence to be used in areas in which no official data is available as well as to direct future data collection. Here, the Safecast data is compared with the DOE aerial survey data by overlapping spatio-temporal observations.

Unit conversion

As seen in Fig. 1, the steps ensure that the datasets are compatible before comparison. Safecast and DOE are measured in different radiation units so conversion to a standard unit is necessary. The Safecast data is measured by Geiger–Müller tubes that record counts per minute (cpm) as a rate of the detection of ionized radiation particles. DOE uses the unit of microsieverts per hour (μSv/h) so it is necessary to convert to the same unit. The μSv/h type of measurement is also used to record detected radiation, but it is measured as a derived unit of radiation as a biological dose based on using the radiometric capabilities of the device to determine the energy levels of radiation and the characteristics of the specific type of radiation. Ion

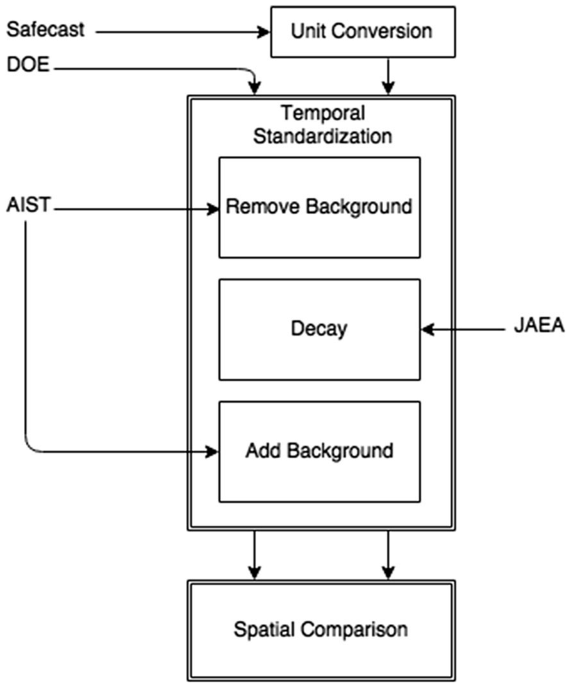


Fig. 1 Flowchart of the methodology developed to compare Safecast and DOE data which takes into account the spatial distribution of the natural background radiation and of the cesium deposition measured by field surveys

chambers used to measure radiation dose cannot measure particle counts, however, Geiger counters can use an energy compensation technique to produce dose readings by applying a known factor specific to the conditions. Therefore, the Safecast radiation measurements were converted from cpm to μSv/h using the following conversion factor. This conversion factor is based on the observed ^{137}Cs contribution and is used by Safecast to convert cpm observations to μSv/h for their own implementations.

$$1\mu Sv/h = \frac{1}{334} cpm \tag{1}$$

Temporal standardization

Safecast and DOE radiation measurements can be compared at multiple time frames by decaying the datasets to certain dates. This decay process uses other datasets that have data in the Fukushima area. The AIST Background Radiation Survey data covers all of Japan and is assumed to be temporally constant as it is based on reported survey averages. The background radiation survey is in μSv/h so it does not need to be converted. The AIST survey is considered spatially in order to remove the effects of background radiation from the Safecast and DOE datasets before the decay step and then add the background values back into the calculation. The JAEA cesium deposition surveys have varying extents that are always within the Fukushima area but use the units of becquerel. However, only the proportion of the isotopes of cesium are used for processing so it is unnecessary to convert the cesium survey to another radiation unit. The JAEA survey contains the proportion of the radioactive cesium isotopes on 9 survey dates between 29 April 2011 until 11 March 2013. The proportion of ^{134}Cs to ^{137}Cs provides a spatially observed ratio of both radioactive isotopes which is used to temporally decay the radiation measurements with different decay rates to each of the survey dates.

As shown in Fig. 1, the background radiation values are removed before the decay function is applied and then the background radiation values are added back in so as to not impact the actual observed value. We apply radiation decay rates to the Safecast and DOE datasets, just as models of radiation dispersion and deposition estimate the decay rates of radioactive elements over time. The decay rates are based on ^{137}Cs and ^{137}Cs as JAEA cesium deposition survey data are available over a 2 year period around Fukushima. While ^{131}I is a major concern immediately after an event, the radiation contribution of beta decaying iodine is essentially non-existent in 3 months time as it has a half-life of only 8 days (Xu et al. 2013). ^{137}Cs is a common nuclear reactor fission product highly effected by the weather as it has high water solubility and will deposit with long term consequences given its decay rate of 30.17 years (Morino et al. 2011). ^{137}Cs does not occur naturally in the environment, but it is a nuclear fission product from reactor cores. Therefore, the presence of ^{137}Cs is a clear indicator of nuclear incidents and the standard radionuclide used for monitoring. ^{137}Cs will be detectable for at least 600 years. Decay rates of cesium isotopes are distinguished between as at initial emission ^{134}Cs is assumed to be equally present with ^{137}Cs, but ^{134}Cs decays at a faster rate with a half life of 2.06 years. Therefore, over time less ^{134}Cs is present in the environment and the ratio of cesium isotopes decrease at a predictable rate.

The following formula estimates the decay of observed amount of cesium radionuclide to a future date.

$$A = A_0 e^{-(0.693t/T_{1/2})} \quad (2)$$

where A is final activity of source, A_0 is the initial value, t is decay time, and $T_{1/2}$ is the given isotope's half life. The $T_{1/2}$ for ^{134}Cs is 2.06 years and ^{137}Cs is 30.17 years.

The proportion of the concentration of ^{134}Cs and ^{137}Cs from the JAEA deposition survey is used to decay the radiation measurements at different decay rates. The Safecast and DOE datasets are decayed forward to the dates of 26 May 2011, 2 July 2011, 5 November 2011, 10 February 2012, 31 May 2012, 28 June 2012, 28 December 2012, and 11 March 2013. The decay rates for Safecast and DOE values are not considered constant between the surveys but are temporally interpolated based on the cesium proportion declining. As shown in Fig. 2, there is a continual decline of ^{134}Cs in the observed ratio due to the difference in the decay rates so that we are able to predict a ratio for 31 December 2015. The values at the following survey date are decayed from the values of the previous survey time while incorporating new data at the same proportional rate.

The box plot in Fig. 2 shows the predicted ratio of the cesium isotopes for 2015 as a temporally interpolated ratio decrease of ^{134}Cs. The interpolated ratio allows us to make ratio dependent predictions of decayed values at dates after the last deposition survey. The blue line uses the formula for half-life decay while the pink line is linear interpolation. The predicted values significantly diverge around 2014.

Spatial comparison

A comparison is now possible as decaying the Safecast dataset in the study area to specific dates provides a large scale quantity of measurements standardized to the same times which can be averaged over spatial units. In order to not load in the full the datasets, the data are first scaled down by a spatial clip to the relevant study area by the spatial extent of the DOE measurements. The spatial distribution of natural background data is used to spatially relate each Safecast and DOE point with the closest AIST Japan radiation survey measurement. The spatial resolution of the natural background radiation survey is approximately half a kilometer. The incorporation of background radiation data ensured that we do not decay values under normal environmental levels in that area.

The citizen science project creates data at different spatial distributions than typical government surveys. Citizen science projects produce datasets at different dimensions than official government sampling of the environment. The DOE aerial survey covered large swathes of territory in a grid pattern; by contrast, the majority of Safecast observations are made along roads and urban areas, such as the cities of Iwaki, Fukushima, and Koriyama. Therefore, data is

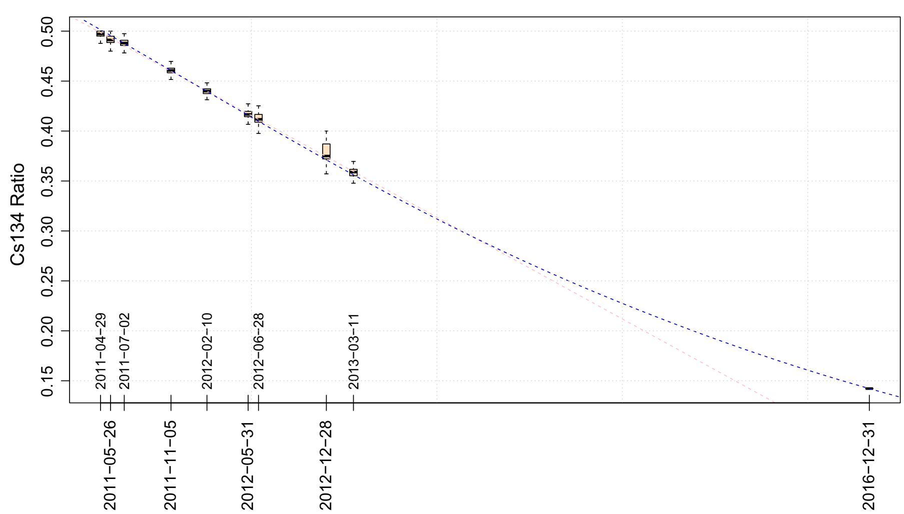


Fig. 2 *Boxplot* of distribution of $^{134}Cs/^{137}Cs$ ratio at each survey date with outliers

compared only in areas that have data located nearby in a grid of 500 m^2.

Results

A comparison can now be made between the entire Safecast and DOE datasets which are decayed to each survey date with consideration for background radiation and the decay rate based on the ratio of radioactive cesium isotopes.

To spatially compare the Safecast and DOE data, the dataset is rasterized on the same grid of 500 m^2 and radiation measurements corresponding to each cell are averaged. The rasters are created for DOE and Safecast in a UTM zone 54 projected environment. Half a kilometer is a spatial standard for radiation as the Japanese Nuclear Regulation Authority produces radiation measurements at this scale (Japanese Nuclear Regulation Authority 2014). In addition, the cesium deposition survey is recorded at 500 m^2. While spatially variations do occur at a much finer resolution than 500 m, at some point it is necessary to average the data in order to visualize aggregate spatial patterns and compare the values of the two datasets (Table 2).

The spatial distribution of the Safecast and DOE datasets are visually similar, as seen in Fig. 3. In the left panels, the plume of higher radiation values can be observed northwest of the Fukushima Daiichi nuclear power plant in both the Safecast and DOE datasets. The Safecast dataset increases in the quantity of measurements over time, but does not have a comprehensive distribution of the radiation plume immediately after the event. In the right panels, the spatial distribution of the datasets are visualized by viewing the number of measurements in each 500 m^2 area. The spatial distribution of the Safecast data is along roads and the count is highly variable based on the movements of the population. The highest quantities of observations are in cities where priority is on the radiation exposure of the population. The DOE dataset has more observations in areas of higher radiation as the concentrated areas of the plume around the nuclear power plant were prioritized in tasking.

Table 2 The R^2 values for each date to which the datasets were decayed

Date	R^2	RMSE
26 May 2011	.71	1.81
2 July 2011	.80	1.79
5 November 2011	.87	1.56
10 February 2012	.88	1.51
31 May 2012	.87	1.44
28 June 2012	.87	1.43
28 December 2012	.68	1.32
11 March 2013	.69	1.28

A linear model is used to describe how much of the variation in the average of the values is explained by the spatial distribution of the datasets. The Safecast measurements slightly underestimate the level of radiation as compared to DOE. Figure 4a displays an R^2 of .87 relationship between the Safecast and DOE datasets. There is a strong relationship between the Safecast and DOE datasets for all of the survey dates.

Figure 4b shows that there are many observations with very small fitted values as part of the distribution and of the most extreme errors there is more over than under estimation. For small residual values there is a strong correlation with few errors and the majority of errors are only plus or minus half of a μSv/h.

While Fig. 3a, b visualize the averages of radiation values in each 500 m^2 area, it is difficult to see the quantitative differences in the spatial variations of the values. Therefore, level plot comparisons are used to display variances of the spatial trends of the Safecast and DOE data along the axes in the areas of overlap. Figure 5a, b show only the 500 m^2 locations in which there are measurements from each dataset before 5 November 2011. Spatial variations in the data visually identify the high concentration radioactive plume from areas that do not have elevated levels of radiation. The spatial standardization of units helps to bring out the between dataset similarities and differences. The high radiation plume area has peaks in the same areas but the DOE has higher observed values in some of these areas. This intuitively makes sense as Safecast observations were not initially collected in the areas of highest radiation concentration. While the extremeness of the highest values is not captured, the Safecast dataset still picks up the same radiation peaks. The observation of lower average values may be related to most of the Safecast measurements being recorded at the ground level after the airborne collection of the DOE. The DOE airborne

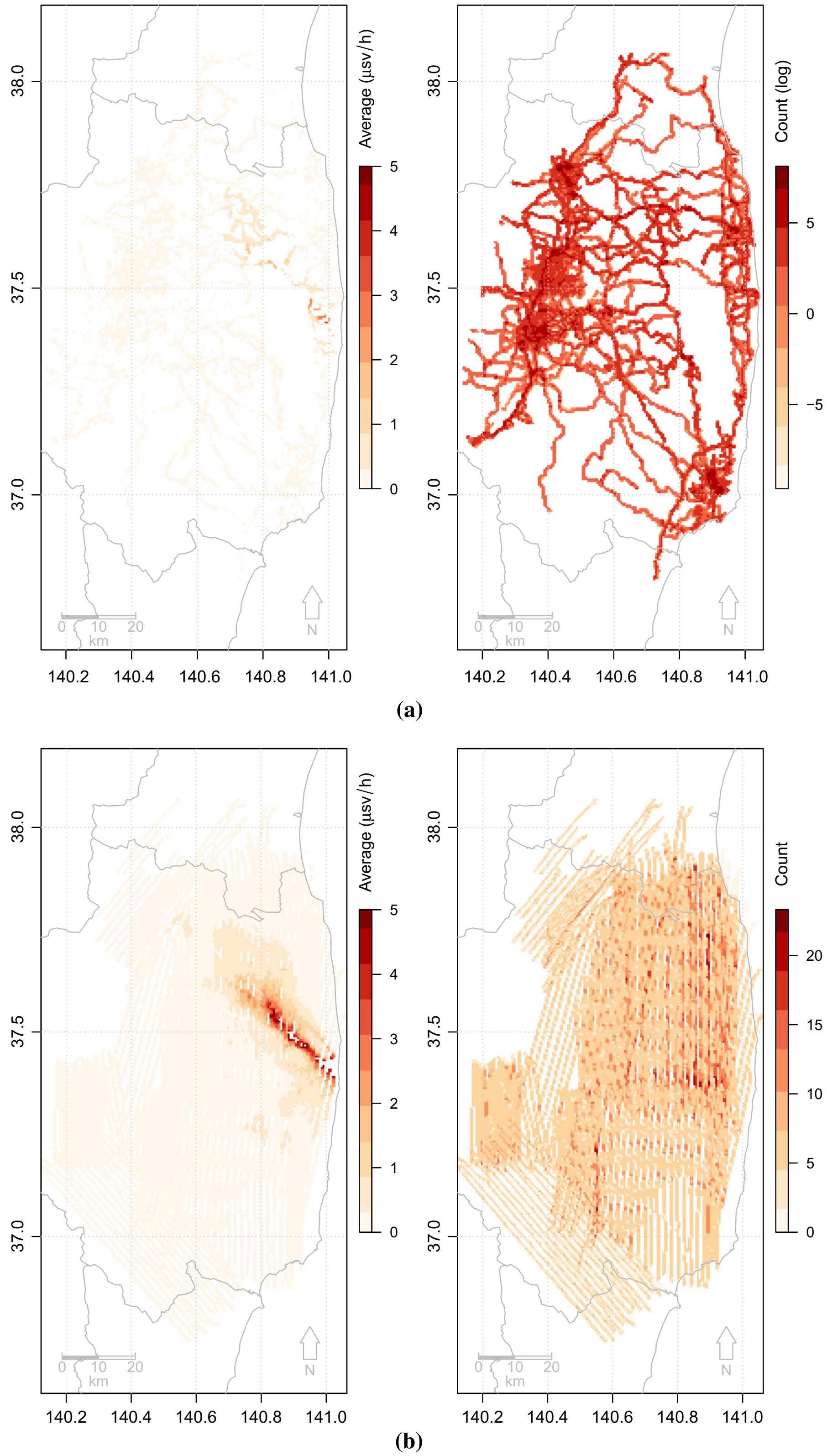


Fig. 3 A 500 m^2 raster grid is used to visualize the spatial distribution of data as the average radiation value and quantity of measurements in area collected up until 5 November 2011. **a** Safecast. **b** DOE

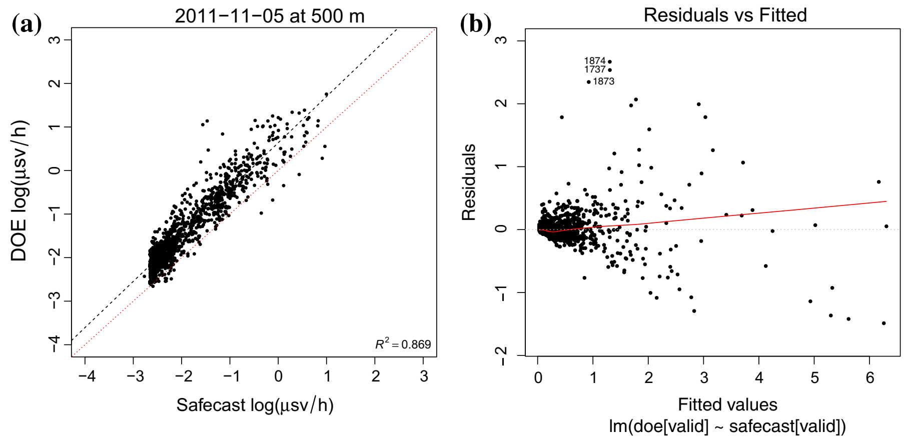


Fig. 4 Linear model of 500 m^2 at 5 November 2011. **a** Linear model. **b** Residuals of the linear model

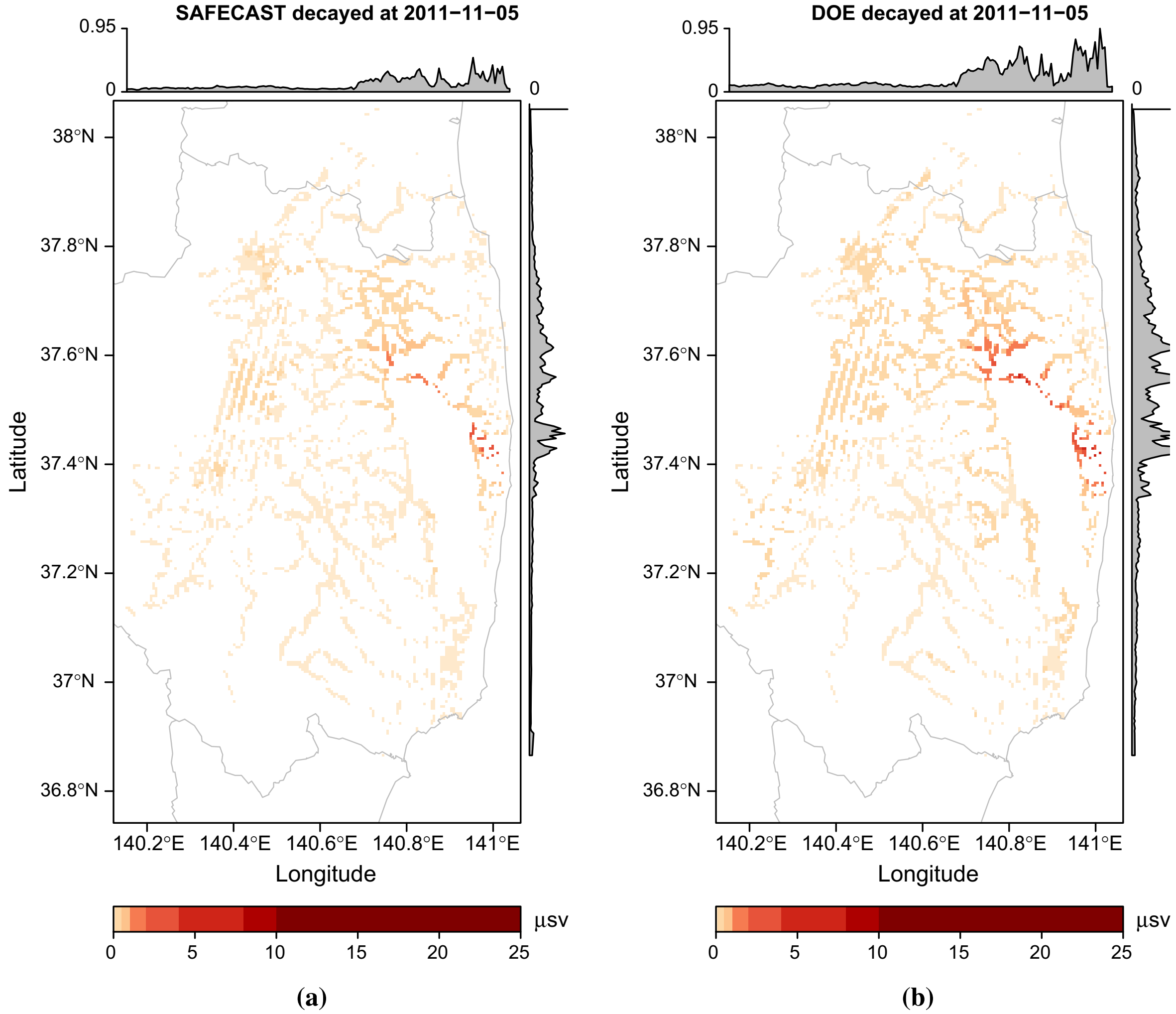


Fig. 5 Level plot comparison of 5 November 2011 that is clipped to areas with overlapping data. **a** Safecast. **b** DOE

collection measured more concentrated radiation which had not yet dispersed. The Safecast data measured at the ground level over time after the cesium has been deposited and received dispersion effects from the environment.

In order to check the decayed datasets, data from that same time period can be used to compare to the decayed time period. Temporal slices of observed Safecast data are used to check the decayed values as shown in Fig. 6. The Safecast dataset decayed to each survey date is compared to the observed μSv/h converted Safecast data for 2 weeks before each survey date. By limiting the temporal extent, the spatial distribution is limited as data from a 2 week period has fewer observations. The data was rasterized at 500 m^2 spatial units of average values. Raster cells were used for analysis of spatial units only if there is a common set of observations that allows for direct comparisons between the two datasets.

Discussion

Crowdsourced big data encourages fresh reflection on the validation of measurements in spatio-temporal dimensions. Environmental monitoring is typically considered an activity in the domain of governments, but there is now public access to devices needed to take scientific environmental measurements as well as to create spatio-temporal information for real-time monitoring. The use of crowdsourced data introduces questions of validity for aspects which should be considered regardless of the source of the data. Citizen science projects encourage technical metadata questions by comparing collection strategies, verifying measurements, locational accuracy, timestamps, and entry errors.

Safecast provided guidelines and educational programs for collection to reduce human error. One method of collection is taking measurements from moving vehicles and the Safecast project provides instructions on how to mount to the devices to vehicles. Experimentation of the Safecast project in conjunction with Japanese universities evaluated that there are consistent measurements of Geiger counters on moving vehicle compared with motionless sensor measurements (Safecast 2015c). Likewise, airborne government datasets undergo methodological checks on extrapolation from airborne height to the surface.

Crowdsourced datasets are increasingly being collected to monitor and inform on hazards in the environment using digital devices with GPS records. These measurements exponentially accumulate to large volume datasets as more devices come online and increase the velocity of real-time data (Safecast Real Time Radiation Monitoring 2016). Standardization and processing is required to handle a variety of data types for analysis. The purpose of analysis is to check the veracity of the Safecast measurements compared to other observations. Citizen science needs to be validated for credibility of the individual projects. Checks are typically built into government projects and likewise standards can be implemented for crowdsourced projects.

There is a trade off between controlled collection with agreed upon conventions and grassroots movements which develop quickly then take on standards based on need over time as additional considerations come along. Instead of being held back by standardized constraints, citizen science operates out of the box by developing their own devices, and policies which are flexibly navigated as a result of conditions. Whereas government investment involves an inherent cost for each environmental survey, citizen science projects often crowdsource funding to share amongst those who wish to contribute to a cause or who take a personal involvement by purchasing the device to assemble for use. Safecast attracted attention and financial support from those who wanted to help after the disaster.

Typically, governments invest in large scale environmental monitoring collections as justified by perceived risk. Therefore, government collections of hazardous radiation incidents occur most frequently after a motivating incident. Safecast collects radiation measurements at a grander scale than government surveys would be able to justify monitoring over many years (Safecast 2015a). Government support or involvement in voluntary citizen science projects could prove useful to extend monitoring.

The co-founder of Safecast gave an interview on the third anniversary of the project and spoke of the goal to have a Safecast observation on every street in Japan (Franken 2014). Safecast reported that almost all major roads in Japan had measurements taken and most of them repeatedly over time (Brown et al. 2016a). That is an impressive statement for coverage, but the project could have a goal of collection by location instead of a varied and arbitrary spatial resolution. Roads have different extents and in order to have a comprehensive dataset the measurements could be tasked to within a standard size of a spatial area unit. Safecast could set up a global tasking team to inform participants where observations are needed to improve coverage.

Safecast encourages citizen participation which can lead to educational awareness of radiation exposure. Collection of radiation measurements serves as a form of experiential learning of normal and abnormal levels in the local areas of participants which can inform an understanding of relative risk. Participation is a form of experiential learning in which normal and elevated levels are perceived in context. Increased public participation in radiation monitoring could improve education of a silent environmental factor and lead to informed decision making in the event of a nuclear incident.

Hazard maps of radiation are often presented in an aesthetic manner that does not encourage an understanding of the associated risk (Brown 2014). The visualization of the radiation measurements needs to be in a meaningful way that is understandable to the population through the use of comparative radiation values in the legend. The perception of risk could be expressed based on the amount of time spent in places. GPS movement trails could be used to produce a map showing a calculation of human radiation exposure at a certain space for a certain time.

The visualization of large quantities of radiation comes with challenges as the data is not equally distributed over space and time. An interactive map would be the most capable means of viewing the intensity of radioactive exposure rates as a function of settings of time, space, and emission. Tominski et al. (2012) used Safecast measurements for visualization of trajectories through cartographic display of trends in values along a major highway. The spatial distribution of radiation can be explored visually as differing over space with horizontal and vertical orientations.

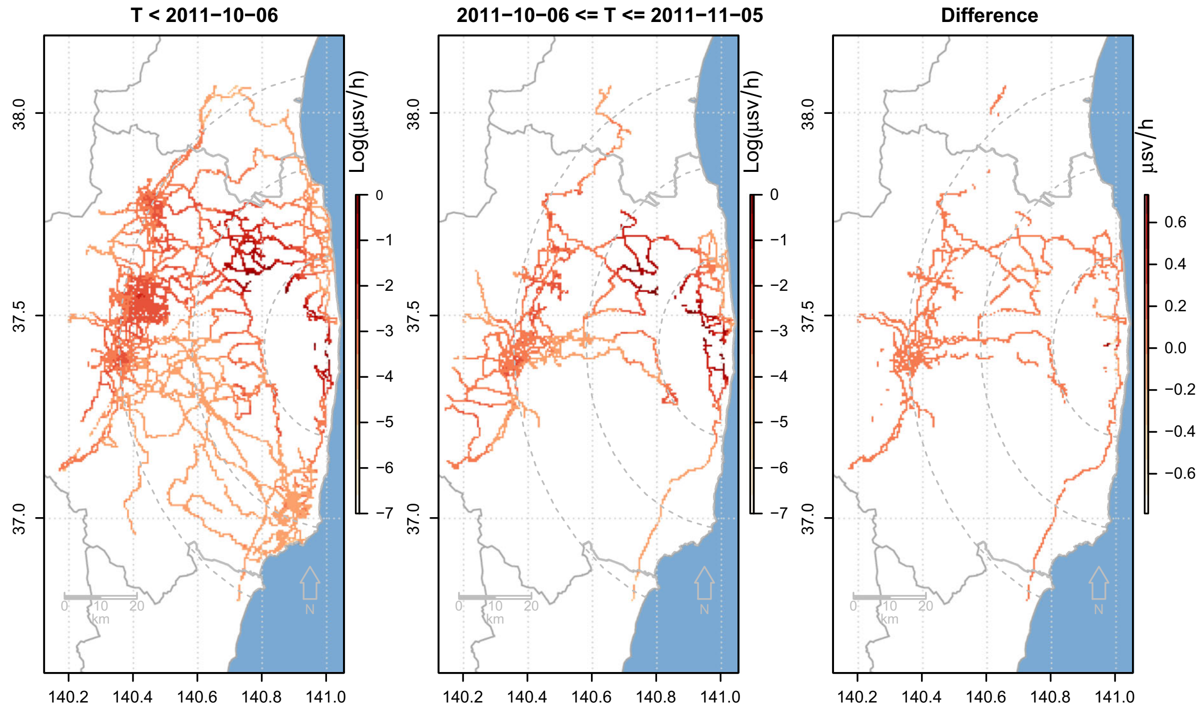
Government produced environmental datasets are generally collected at a large-scale and require timely availability of sensors, expertise applied for calibration, and a strategy for collection. However with the proper motivation, the lay-person may be willing to act as a "citizen sensor" by using an individually purchased sensor device. Traditional collection implies previous awareness of a problem which informs the need to monitor. Safecast started immediately after the disaster and adopted a long term approach to ensure accessibility to radiation data and to act as a warning system of changes in the environment. Safecast continued long after the immediate harm for the disaster as a team of volunteers continued collection for scientific reason which provided a long time series useful for scientific study.

Fig. 6 Comparison of temporal slices of original values to decayed dates. **a** *Left* Safecast decayed to 5 November 2011. *Center* Temporal slice of 2 weeks before decay date. *Right* Difference between decayed and temporal slice of data. **b** *Left* Safecast decayed to 11 March 2013. *Center* Temporal slice of 2 weeks before decay date. *Right* Difference between decayed and temporal slice of data. **c** *Left* Safecast decayed to 18 September 2015. *Center* Temporal slice of 2 weeks before decay date. *Right* Difference between decayed and temporal slice of data ▶

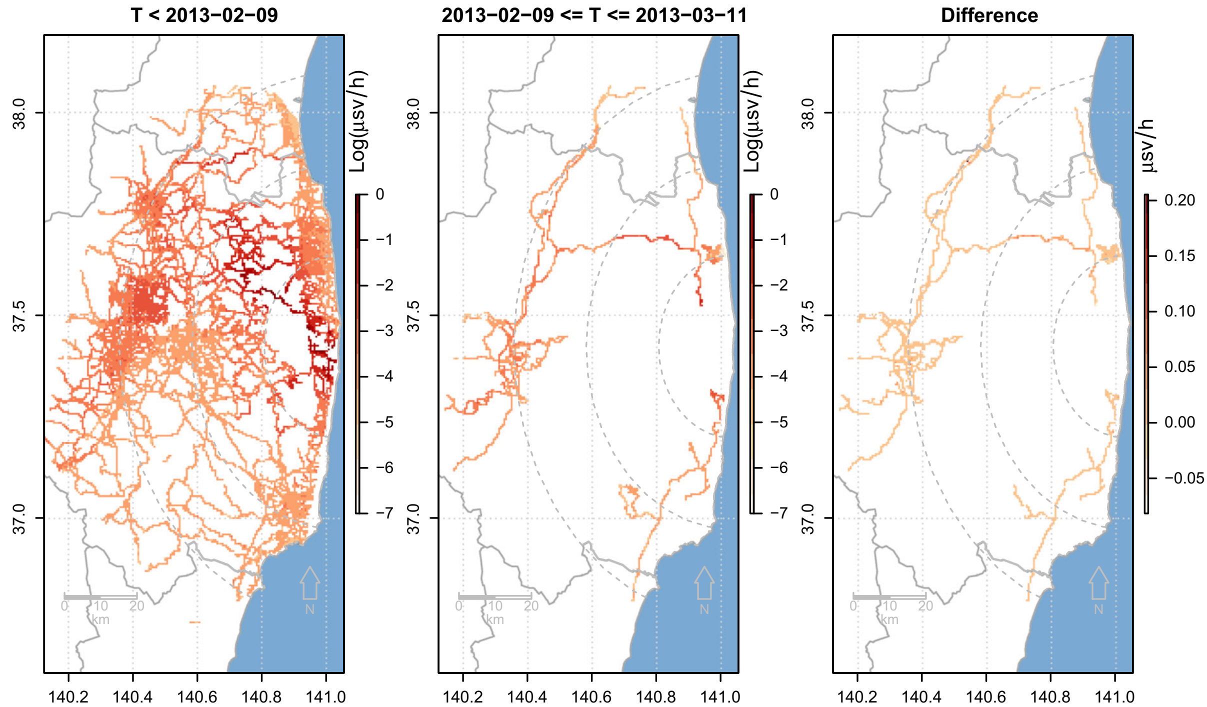
Conclusions

Citizen science is a growing movement that uses citizens as sensors to observe phenomena in their environment. The creation of VGI can be tasked to specific areas so the data is not just spatially variable to where people are located and temporally to how often measurements are taken in those areas. This pattern of observations can be very different than government produced datasets. Safecast provided on the ground data in urban areas and along roads while the DOE was collected in large swath patterns from planes with measurements extrapolated to the ground. While the government produced surveys only at specific dates, the crowdsourced project was temporally continuous to provide real-time data, particularly in urban areas. The integration of growing spatio-temporal datasets involves big data challenges as observations increase over time from many volunteers.

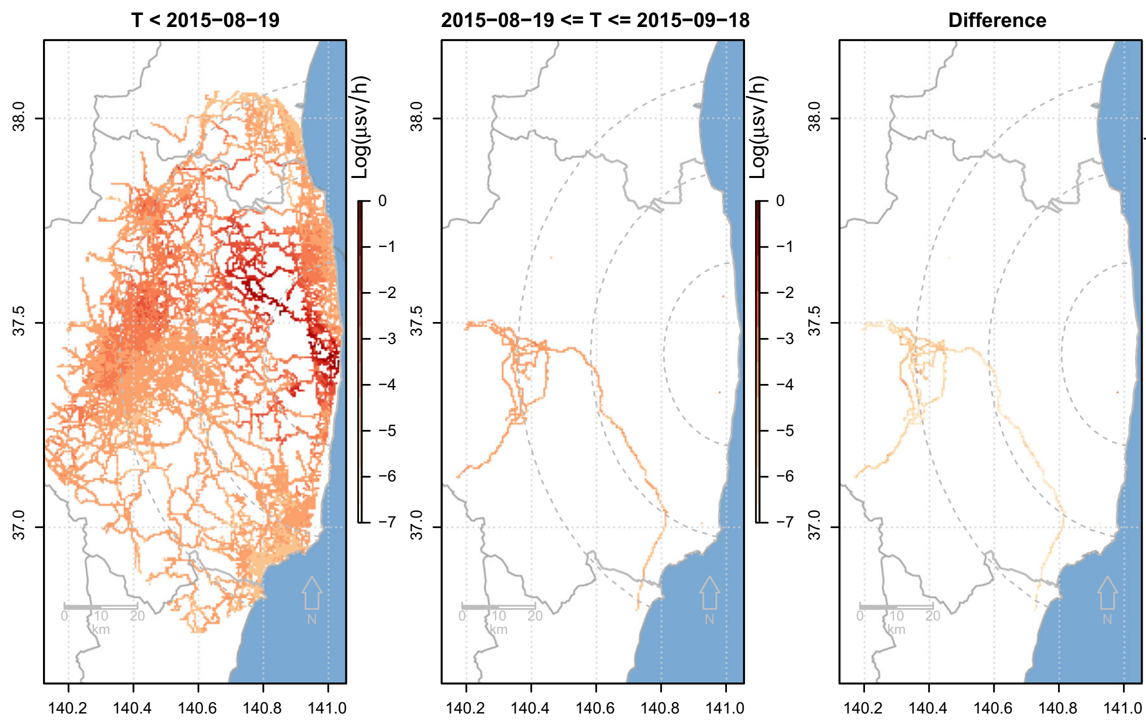
The initial visual observation is that Safecast spatially varies with radiation values that spike in the same areas as in the DOE data. It is easy to observe the radiation plume that was directed northwest from the Fukushima Daiichi nuclear power plant. In order to even make a visual comparison, it was necessary to standardized the dataset to the same spatio-temporal dimensions. A methodology is provided to compare datasets of


T < 2011−10−06
2011−10−06 <= T <= 2011−11−05
Difference
Log(µsv/h)
µsv/h
38.0
37.5
37.0
140.2
140.4
140.6
140.8
141.0
0
−1
−2
−3
−4
−5
−6
−7
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
0 10 20
km
N

(a)


T < 2013−02−09
2013−02−09 <= T <= 2013−03−11
Difference
Log(µsv/h)
µsv/h
38.0
37.5
37.0
140.2
140.4
140.6
140.8
141.0
0
−1
−2
−3
−4
−5
−6
−7
0.20
0.15
0.10
0.05
0.00
−0.05
0 10 20
km
N

(b)



(c)

Fig. 6 continued

radiological measurements over time and space. It is important to ensure that the radiation measurements are not decayed below the natural background radiation of the area and that the decay rate takes into consideration the varying proportions of radioactive isotopes over years. The comparison of radiation measurements used an integration of data from heterogeneous datasets to assess the validity of observed values over time and space.

Further work could involve data collection considerations such as spatio-temporal optimization of radiation monitoring to scientifically observe the spatial distribution of the dispersion of the radioactive plume. In addition, volunteer guidelines with safety procedures could be evaluated for tasked collection of areas without consistent radiation measurements. This would provide a more complete footprint of the distribution of radiation. The DOE atmospheric variance of airborne level measurements versus ground level was calculated based on surveys before it was made publicly available. The spatial variations of above ground radiation could be further investigated by analyzing the altitude variation of radiation measurements through the use of Unmanned Aerial Vehicles (UAV's). Tools from dispersion and deposition models could help to model the atmospherically layered variations.

The Safecast collection grew organically to develop long term objectives of scientific relevance. VGI projects could play a role in monitoring for environmental hazards by acting as an early warning system and providing situational awareness along with increasing public awareness in real-time. Citizen science projects encourage continual collection which could lead to the identification of unreported or unmeasured hazardous spikes. Validation of Safecast demonstrates that we can infer scientific data from non-traditional and not vetted data. Citizen science can provide real-time data for situational awareness which is crucial for decision making during disasters.

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