Safecast: successful citizen-science for radiation measurement and communication after Fukushima

Azby Brown[1,3]**, Pieter Franken**[2,3]**, Sean Bonner**[2,3]**, Nick Dolezal**[3] **and Joe Moross**[3]

[1] Kanazawa Institute of Technology, Future Design Institute, 1-15-13 Jingumae, Shibuya-ku, Tokyo 150-0001, Japan
[2] MIT Media Lab, 75 Amherst St, Cambridge, MA 02139, USA
[3] Safecast, Dogenzaka Pia 8F, Dogenzaka 1-22-7, Shibuya-ku, Tokyo 150-0043, Japan

E-mail: azby@me.com

Abstract

The Fukushima Daichi Nuclear Power Plant disaster, which began on 11 March 2011, provided a crucial opportunity to evaluate the state of preparation on the part the powerplant operator (TEPCO), relevant Japanese government agencies, and international oversight bodies, to gather necessary information on radiation risks quickly and to share it with those tasked with emergency response as well as with the general public. The inadequacy of this preparation and the chaotic nature of inter-agency and inter-governmental communication has been well noted in several official reports on the disaster. In response, Safecast, an international, volunteer-based organization devoted to monitoring and openly sharing information on environmental radiation and other pollutants, was initiated on 12 March 2011, one day following the start of the accident. Since then the group has implemented participatory, open-source, citizen-science-centered radiation mapping solutions developed through a process of collaborative open innovation. The information Safecast provided has proven useful to experts, to policy makers, and to the public. This paper briefly describes the methodology and toolsets Safecast has developed and deployed, as well as organizational and social aspects, and summarizes key results obtained to date. In addition, it discusses appropriate criteria for evaluating the success of citizen-science efforts like Safecast, and places it in context with other non-governmental radiation monitoring efforts.

(Some figures may appear in colour only in the online journal)

1. Introduction

The Safecast project was initiated by a small group of individuals on 12 March 2011, one day following the start of the Fukushima Dai-ichi Nuclear Power Plant disaster. This accident highlighted the inadequacy of official preparation for such a disaster, and the chaotic nature of inter-agency, inter-governmental, and public emergency communication. Particularly, the powerplant operator (TEPCO), relevant Japanese government agencies, and the international oversight bodies, such as the International Atomic Energy Agency (IAEA), failed to gather necessary information on radiation risks quickly and to share it both with those tasked with emergency response and with the general public. These failings have been well noted in several official reports on the disaster, including those issued by The National Diet of Japan Fukushima Nuclear Accident Independent Investigation Commission (NAIIC) [1] and by the IAEA [2]. During the initial weeks of the disaster in particular, citizens were given little actionable information concerning actual radiation levels, and what was presented both by official spokespersons and in the media was often incomplete and/or contradictory.

Initially, the founding members of Safecast primarily sought to aggregate publicly available radiation data for Japan and make it available in the form of online maps. This was one of many efforts by initiated by citizens in Japan and abroad to address shortcomings in publicly available information regarding the spread of radiation and other potential public hazards in the wake of the disaster. The Safecast effort began as an informal coalition of groups and individuals, and initially published data on a site known as RTDN, which was owned by one of the collaborating groups, a private design studio based in the US. This effort was hampered by the lack of available data, both official and independent, as well as by restrictions on its use in some cases. In addition, the independently gathered radiation measurement data available at that time was primarily from the Tokyo region, with very little publicly available from the Fukushima region and elsewhere. Also, there was no standardization or consistency in the available data in terms of detector type or processing methodology. This combination of factors led to a decision by the group after several weeks that it would be necessary for volunteers to collect radiation readings themselves with standardized equipment in order to fill the void. As the group attempted to purchase radiation detectors during March 2011, however, it rapidly became apparent that the available global stock had already been nearly depleted. At a group meeting in Tokyo on 17 April 2011, attended by experts in hardware and software design, radiation detection, communication, and development, a decision was made to rapidly develop and test a new type of mobile detector which could be attached to a vehicle and linked to GPS and a data logging system. The necessary features of a publicly-available online database and map system for communicating the measurements openly to the public were also discussed. The need for an independent identity for this newly focused activity was recognized by all, and the group name 'Safecast' was chosen at this time.

In general, Safecast and similar efforts can be considered real-world tests of the principles and capabilities of 'citizen science', and their results are worth examining for this reason. As Franzoni and Sauerman point out, citizen science itself, sometimes called 'crowd science', 'networked science', or 'massively collaborative science', has been defined differently in different contexts, and since the field is growing and changing rapidly, truly qualitative definitions and evaluative principles remain elusive, as do objective criteria for what constitutes

'success' [3]. The availability of sophisticated, low-cost sensors and computing and technologies in recent decades has stimulated the growth of increasingly ambitious citizen-based data collection efforts. Nevertheless, the scientific validity of citizen projects has not always been adequately demonstrated. While it is often assumed that citizen science should be regarded as 'complementary or even subordinate' to formal science [4, 5], Bonney notes that, 'With appropriate protocols, training, and oversight, volunteers can collect data of quality equal to those collected by experts' [6]. Any evaluation of the success of a citizen science project will depend upon demonstrating that its data has been collected with sufficient rigor and consistency to be useful to experts, to policy makers, and the to the public.

Safecast uses the 'crowdsourcing' model of data collection. Like citizen science, crowdsourcing is difficult to define precisely. Mansell observes:

> *'Crowdsourcing was defined initially as "the act of a company or institution taking a function once performed by employees and outsourcing it to an undefined (and generally large) network of people in the form of an open call" (Howe 2006, np), for example, the paid for activity supported by Amazon Turk. The meaning of crowdsourcing has since been extended to apply to activities aligned with open source software principles (Howe 2008, Malone et al 2009). It now refers to any activity where a task is issued to an open or undefined online community (Brabham 2012, 395)'* [5, 7–10].

As will be shown in more detail below, Safecast's implementation of crowdsourcing fits into the latter definition, being based on open-source hardware and software, with activity directed by a loosely-connected online group. As such it embodies the 'emerging open collaborative culture' [5, 11–15]. While many citizen science projects involve finite experimental goals and joint problem-solving, others seek primarily to assemble databases of observations [5]. Safecast can be considered an example of the latter, and its primary public output is up-to-date, scientifically valid crowdsourced radiation maps of Japan and other parts of the globe. The achievement of specific social outcomes, however, particularly the promotion of openness, has also been a major motivation of the project from the start.

From the start of the Fukushima disaster, the institutions tasked with communicating radiation risk information to the public proved unable to handle the problem adequately, and this caused the public to search for its own solutions. Safecast's effort and others like it are public responses to institutional inadequacy. The value and credibility of Safecast data was quickly recognized in Japan and abroad as a reliable and independent source of information about the radiation risk from the Fukushima accident, as well as a notable example of social engagement [16, 17]. The rise of technically capable citizen-science efforts like Safecast has not fully made up for the lack of trust in official information, but provides an important additional source of unbiased data which citizens can use when making decisions. Again, the increasing inclusion of Safecast data and experience in official institutional discourse concerning radiation risk, measurement, and disaster response suggests that the importance and value of providing this kind of option has been recognized by policy makers at many levels [18, 19].

2. Method

The first Safecast mobile detection systems were improvised but functional, and through rapid design iteration, informed by field experience, soon became more robust and reliable. Because the water-resistant poly- carbonate cases (manufactured by Pelican, Inc.) chosen to house the detector and communication equipment bore a strong resemblance to Japanese lunch boxes, known as '*bento*', the system was dubbed the 'bGeigie', short for 'Bento Geiger Counter'

Figure 1. Early bGeigie GPS-equipped data-logging mobile radiation detector.

(figure 1). Early generations of bGeigie, which were soon made more compact and self-contained, contained an off-the-shelf 'Inspector' brand pancake-tube Geiger counter, an industry-standard device manufactured by US-based International Medcom, Inc. Whereas the very first bGeigie units required a laptop computer for data logging, these were soon superseded by units which utilized the open-source Arduino platform for computation, a compact GPS unit, and internal SD card-based data logging modules, also open-source, all of which were integrated into the polycarbonate housing. This technical combination greatly enhanced the ease-of use of the system, basically allowing 'set and forget' operation by even non-technical operators. The first online maps of data gathered with the bGeigie system, in parts of Tokyo, were published online on 23 April 2011. The first data from Fukushima Prefecture was gathered the following day, in the city of Koriyama. From this tentative beginning, the Safecast dataset of radiation measurements has grown rapidly, with measurements from over 60 countries and from every continent in the world.

Open-source and open-data methodologies were key components of the Safecast project from the start. Safecast's principles regarding openness are actually quite similar to those deemed necessary by the UK Royal Society: '…"intelligent openness" implies that information resources "must be intelligible to those who wish to scrutinize them; data must be assessable so that judgements can be made about their reliability and the competence of those who created them; and they must be usable by others"' [5, 20] The embrace of open methodologies, along with careful decisions to leverage new fabrication technologies, such as 3D printing, laser-cutters, rapid fabrication of printed circuit boards (PCBs), allowed an unusual degree of rapid, agile, iterative development, which from the start drew upon a technically skilled pool of volunteers scattered around the globe. No fewer than seven incrementally-improved hardware detector designs were built, tested, and deployed by Safecast during the first eighteen months following the start of the disaster, a degree of productivity rarely achieved by even well-funded national or university labs, or by the best-motivated technical start-ups. The bGeigie Nano, a very compact, reliable detector unit which was designed to be sold online as a kit, has been in use since late-2012, and the majority of units used by Safecast volunteers at present are of this type (figure 2). Approximately 500 bGeigie Nanos have been distributed to date to buyers and users in many countries. Including the deployed base of previous detector models, the total number of Safecast-designed units worldwide is approximately 1000. At the time of this writing, new units for both mobile and fixed, realtime data streaming are currently

Figure 2. bGeigie Nano.

in prototype or early deployment, as is a system for measuring air quality (including sensors for PM 2.5, NO_2, O_3, CO) [21].

The Safecast project represents an innovative model of rapid, integrated, open development, simultaneously addressing requirements in several disparate fields, including hardware design, software design, engineering, radiation science, visual design and communication, and social design factors. The primary goal is to provide needed information to the wider public, in the form of easily-accessible maps and other visualizations, and because of this, ease of use, legibility, and intuitive understanding on the part of even poorly-informed citizens have been the primary drivers of the design of the system as a whole. The strong desire to make Safecast data as easily accessible as possible has led to radiation maps of consistent design being developed and made available free of charge through online web browsers, on the iOS platform, and on OSX (with development of versions for Android and Windows being encouraged, but as yet incomplete) (figure 3).

The primary components of the Safecast system are the hardware, specifically radiation detectors and peripheral devices, such as for data uplink and display; the database, including the API for uploading, accessing, and managing the data; and the visualizations, specifically maps made available on a variety of platforms as described above. The system is designed as a vertically integrated whole.

2.1. Hardware

The currently deployed generation of bGeigie detectors record radiation readings as running 60 s and 5 s raw counts, both polled every 5 s, using an Arduino to process the counts and GPS data and write them to the SD card (or through Bluetooth in some units) as text strings [22]. These strings contain a time stamp, the radiation reading in the form of a raw count (CPM),
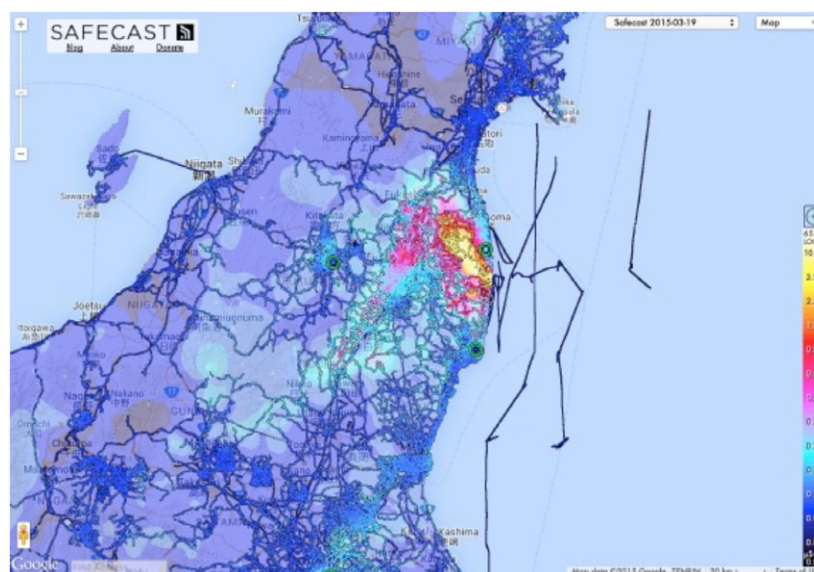
Figure 3. Safecast web-based tilemap.

and the GPS coordinates. One string is written for each data point, and one log file is written by the device for each calendar day it is in use. These log files are uploaded to the database by the user via the Safecast online API [23], or through a dedicated smartphone application, in the case of Bluetooth-enabled units. The API allows the user to examine the data in the form of a map, to check each data reading for errors, and to add pertinent explanatory metadata, such as the location, the person who gathered the data, from what height and orientation, etc. It is important to note that the system allows users to protect their privacy if so desired by using a nickname, but a valid email address is required to allow moderators to send inquiries when necessary.

2.2. Database and maps

The database serves two primary purposes. One, it is intended to provide an archive of independent data that can be freely used by anyone for any purpose. Two, it is used to generate the widely accessible visualizations, primarily maps, that Safecast publishes [24]. Details of the data processing methodology, including schematic diagrams, are openly available online [25] (figure 4). Thanks to volunteer efforts, the dataset has grown quickly, and at the time of writing contains over 40 million discrete data points, the largest independent open dataset of its kind (figure 5). In addition to the data gathered by Safecast volunteers, Safecast includes many other openly available radiation datasets in its maps, implemented as selectable layers. These include data from the Japanese government, the US Department of Energy (DOE), US Environmental Protection Agency (EPA), US National Oceanic and Atmospheric Administration (NOAA), Geosciences Australia, and others, with more being included as they are identified and made available. This allows users to compare Safecast data with these other datasets. The user interface of the maps has many user-customizable features, such as several choices of underlay map, including Open Street Map, the ability to toggle interpolation on and off, and to select the color LUT used for displaying radiation levels. The online map also allows users to query the readings in any location via API links, in order to display more
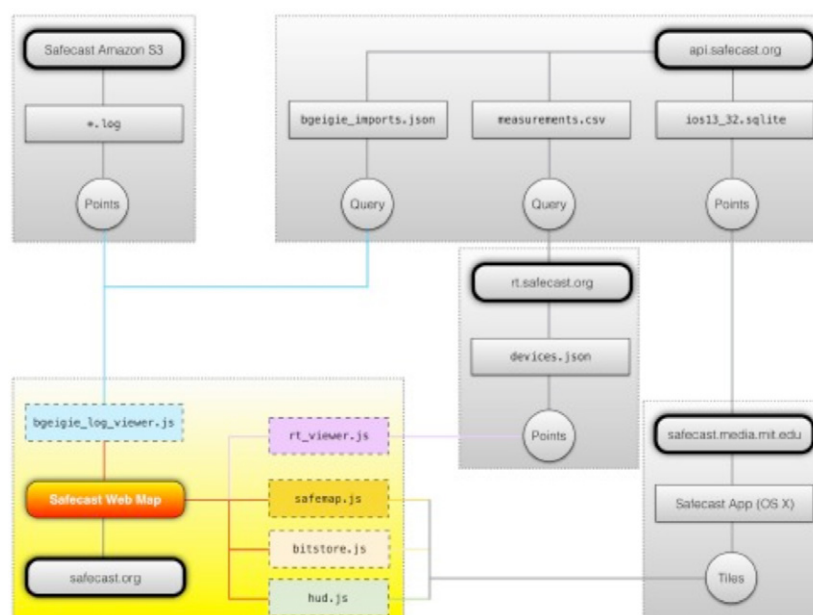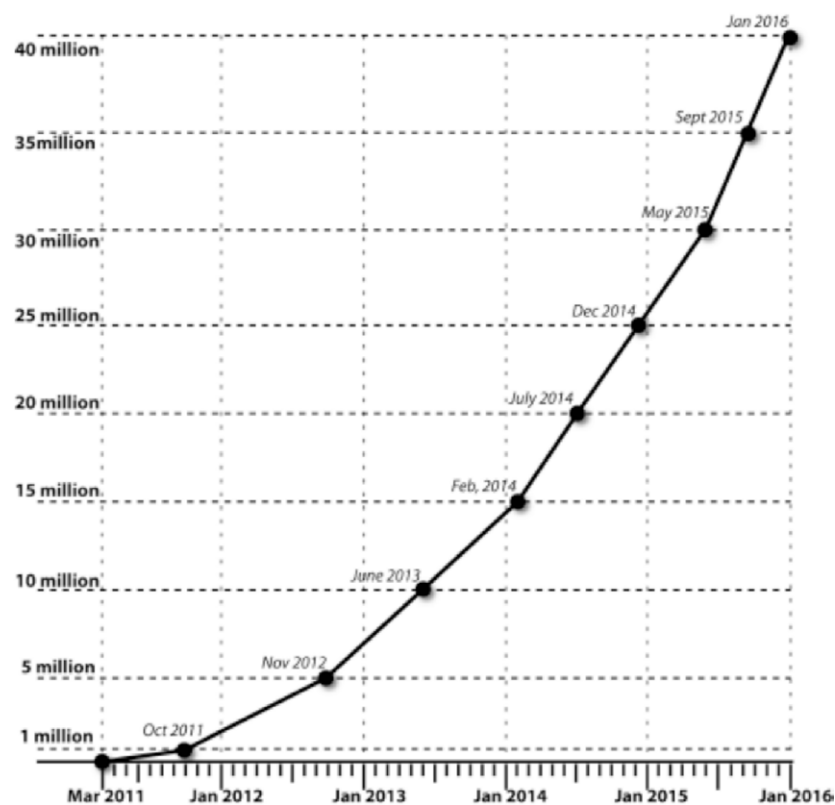
Figure 4. Data processing flowchart.

Figure 5. Growth of Safecast dataset.

detailed information about when the readings were taken, by which user and which device, and to select a set of readings bounded by a specific geographical radius or time frame. More query and filter features for the data are available on the API page. The user interface for the maps and for the API are constantly being refined and improved based on user feedback.

2.3. Quality control

Once a log file is submitted by a user, an automated email notification is sent to a group of experienced moderators tasked with confirming the quality of the data and approving it for inclusion in the database. This task requires judgement and experience, as well as familiarity with normal radiation levels in various parts of the world. If an anomaly or error is suspected, the moderator will contact the user via email to ask for confirmation and/or explanation. Recent inquiries prompted by unexpectedly high radiation readings have included measurements taken at a former Uranium processing site, which proved to be accurate, and data submitted by a user who had accidentally allowed his detector to go through a museum x-ray machine. In the case of the latter, after discussion the moderators decided to reject the entire log file, and to ask the user to remeasure the site at his earliest convenience. Such action is typical in such cases. Fortunately, only a very small percentage of uploads, approximately 0.1%, have prompted queries. In addition, if a user later notifies the moderators to say that a data log contains an error and was uploaded by mistake, it is possible to filter the erroneous data points out so they do not appear on the maps. This must be done by the database administrator manually, but fortunately, to date it has been rarely required. Safecast considers it extremely important to keep humans in the quality-control loop in this fashion, but is evaluating a number of strategies for dealing with an expected exponentially larger future data load which could tax the time and capacity of the moderators. Legitimate questions may be raised regarding the ability of the quality-control system to protect against intentional malicious manipulation of the dataset. Manipulation could be accomplished, for instance, by editing log files prior to uploading them to change the recorded radiation readings, by shielding the detector in order to achieve erroneously low readings, or by placing it near a radioactive source in order to achieve erroneously high readings. Like many other self-policing crowdsourced data repositories, the Safecast system presently relies primarily on the vigilance of community members and moderators to detect and correct errors. Database management itself is performed by a small team of experienced administrators, and internal database access is limited to them. The core volunteer team includes data security and forensics professionals, and security measures intended to protect the database itself from malicious access are in place and under continuous evaluation and review.

2.4. Community and organization

In terms of organization, Safecast has adopted an ad-hoc voluntary structure which has precedents in the open-source community—the 'open collaborative culture' referred to above—and is as made egalitarian and non-hierarchical as possible. With the exception of a handful of mission-specific tasks for which it is deemed worthwhile to pay a person with the requisite technical skills to attend to without interruption (such as keeping servers running), it is entirely a volunteer effort. As such, the motivations and communication style, as well as the overall 'culture' of the group, are very different from those of for-profit or bureaucratic institutions. The hierarchically 'flat' structure also stands in contrast to most other leading NPOs, which often have a top stratum of paid administrators. The organizational structure of Safecast developed initially in an ad-hoc, multiply-connected network fashion, and once it

was apparent that this in fact enhanced the group's flexibility, speed, and agility, a consensus developed that this characteristic should be nurtured. Safecast also benefits from the participation of several advisors, all influential in their fields, such as software development, radiation science, government, and design.

The Safecast community can thus be considered an example of 'information commons', as Mansell observes, in which:

> *'Groups are likely to reach decisions on the basis of informal discussion, the procedures for decision making are more fluid, and choices about how to organize and classify data are relatively impromptu or set by the affordances of open digital platforms, rather than by standards established by science professionals. There may be informal or semi-formal hierarchies of authority including moderators, administrators, and initiators of groups, implicit obligations for reciprocity, and norms that facilitate trust, but there is less attention to professional accreditation and priority. In these groups, information is commons-based "when no one uses exclusive rights to organize effort or capture its value" (Benkler 2004, 1110)'* [4, 26].

Care has been taken within Safecast to develop hardware and software systems, and to nurture the growth of a community, that are attractive to citizen scientists worldwide and which encourage wide participation. Not surprisingly, the degree of technical knowledge and aptitude necessary for participating in the Safecast project as a data-gatherer are greater than those required for average end-users of the visualizations, i.e. people who simply want to check radiation levels on an online map. People who participate as data contributors usually build their own bGeigie Nano from a kit, and master the process of uploading data fairly easily.

The decision to make the bGeigie Nano available only in kit form grew out of the group's experience that when people were simply given a radiation detector to use, many would use it for a few weeks or months, and then lose interest once their initial curiosity was satisfied. By contrast, individuals who pay for a detector kit and then build it invariably develop a sense of pride and the desire to use it frequently, and to share their knowledge and experience with friends and family members. The cost of a bGeigie Nano kit purchased online at the time of this writing is $450, which is admittedly too expensive for many who would like to participate, particularly in emerging economies. It is important to note however that this price does not include a profit mark-up. Safecast also provides parts lists and plans on an open-source basis that make it possible for anyone who desires to source the components and build it on their own. Individuals who have done this have found that the cost exceeds the price of the kit version [27]. Nevertheless, both the cost of purchase and the time and skill required to build the unit result in a process of self-selection which attracts relatively technically adept and motivated volunteers. Regardless, the need to provide lower-cost options has long been recognized by the group, and is an important focus of current development efforts. The bGeigie detector units are designed to be as simple and foolproof in operation as possible, however, and with brief training many citizens previously inexperienced in gathering radiation data are able to do so successfully. Safecast keeps a stock of 'loaner' units on hand as well for the use of journalists, academics, and others who offer to survey desirable locations.

The international community of Safecast and its development teams are intended to be as inclusive as possible, and have attracted a very wide cross-section of people, from experts and working professionals, to students, including many still in high-school, to retirees and hobbyists, as well as teachers and academics, filmmakers, writers, community organizers, and people from almost every walk of life. Because the initial focus of the group has been in Japan, it is not surprising that many volunteers are Japanese. Safecast is nevertheless unique among citizens' based radiation monitoring groups in Japan in the large proportion of non-Japanese

Figure 6. Safecast bGeigie Nano building workshop, Washington DC, April 2014.

who participate, including many of the senior volunteers, and in the international reach of its network and activity. The majority of Japanese volunteers live in Fukushima, and many are quite active.

Safecast conducts many kinds of outreach activities which help fulfill the group's mission of providing information to the public and also to expand the network of volunteers. In addition to reaching out to academics and other experts for their help in clarifying technical, scientific, or other points (such as law or government), Safecast is frequently asked to hold information sessions for schools, companies, and community groups. The group also holds frequent workshops where attendees can learn how to build and operate a bGeigie Nano (figure 6). These workshops, which are held on an almost monthly basis in different locations in Japan and abroad, usually include participants from a wide age range, from middle school to senior citizens, many of whom have no prior experience with soldering or assembling electronics. To date, many detector-building workshops have been held in Tokyo and in Fukushima, as well as in Taipei (Taiwan), Hong Kong, Strasbourg (France), and Washington, DC. Educational programs such as these play a growing role in Safecast's overall activities, and several examples will be described in more detail below.

2.5. Social and other media

Because of the international nature of the group, Safecast relies heavily on social media, blogs, and online discussions to reinforce community bonds and to share information [28–30]. Safecast hosts several online discussion groups, including for radiation issues in general, for Safecast hardware questions, and for other technical subjects. These online discussions in particular have attracted the participation of experts and are a forum for unfettered debate of contentious issues. Safecast's strong social media presence is directed both inward and outward. The majority of communication within and among teams, such as those working on hardware development, API revision, mapping, or outreach and education, is done through social media and 'teamware' such as Slack [31]. Safecast has through necessity taken the 'virtual team' concept to an extreme. In fact, though face to face meetings and work sessions are held regularly at the small Safecast office in Tokyo, these rarely include more than three or four people, and are rarely more frequent than once or twice a week, in the evenings when volunteers are free from work. Larger gatherings are held when

preparing for events, and at the events themselves, but most communication within the group is done online.

Social media messaging is directed outwards as well. The group has been credited with a high degree of media savvy, and has communicated its message through many major media outlets in Japan and abroad [32–35]. Skill with media and messaging was recognized early on as essential to success, to fundraising, and to achieving a level of name-recognition that could enhance the group's influence worldwide. The purpose for this remains aiding communication and increasing participation. Safecast is fortunate that it has many members who are comfortable with media, who have writing skills as well as on-camera skills, and who are good at presenting a consistent message either individually or in groups. Frequent contact with media from all over the world has also enabled Safecast to closely observe and evaluate the weak state of scientific literacy in media, particularly as it relates to radiation issues. One result has been the publication by Safecast of a series of 'backgrounder' reports and summaries which are provided to media representatives to help them get up to speed on issues in Fukushima and concerning radiation in general [36–38]. The Safecast Report, the inaugural volume of which was published in March 2015, grew out of these efforts to provide an informative but readable summary of important issues and developments for media as well as the general public [39].

2.6. Transparency

Transparency and credibility are recognized as essential for the success of the Safecast project. This is particularly true because of the lack of public trust in information provided by the Japanese government in the wake of the Fukushima accident, primarily because it demonstrably failed to exhibit either of these characteristics. The Safecast community considers the use of open-source hardware and software to be essential to achieving transparency, because all designs are publicly available for scrutiny, and also for improvement. Any outside observer can independently evaluate the group's tools and methodology. An adherence to open-data publication principles goes hand-in-hand with this approach. Unlike most environmental radiation data provided by the Japanese government, or by most governments for that matter, the Safecast dataset can be downloaded in its entirety and used with no preconditions whatsoever, by any person or entity that desires to, anonymously and without the need to contact Safecast. The group considers it essential to open the data, as well as the hardware and software designs, to independent critique in this way, as an essential component of the effort towards transparency and trust-building.

All Safecast designs and software are made available under open-source licenses, such as the Creative Commons CC0 and other 'share alike' licenses [40]. All development documentation and most programming code is openly available for reuse and modification on open online repositories like GitHub [41]. The group has declined otherwise attractive offers for collaboration because the prospective partner did not share this commitment to open-source and open data. For Safecast, the default mode is towards greater transparency and sharing, and the group tries to set an example of close adherence to these principles. As in the case of many other fundamental approaches adopted by Safecast, a prime motivation has been the recognition that many of the failures of government in the wake of the Fukushima disaster were due precisely to underlying institutional resistance to transparency and openness, as well as to full participation by citizens. It is hoped that by demonstrating that the public can be better served by open, transparent, and participatory communication and decision-making, innovations in governance which move in that direction can be encouraged.

2.7. Non-partisanship

Radiation and its environmental and health effects are issues which are fraught with deep-seated controversy. Unfortunately, it has been difficult until now to find radiation data which truly has been free of bias, or of the perception of bias, because most individuals and organizations with the capability of providing it have either overtly identified themselves as either pro- or anti-nuclear, or have found it difficult to free themselves of accusations of hidden agendas, justified or not, in one or the other direction. Unfortunately this has even been the case for the most meticulously and conscientiously gathered data provided by official agencies (actively pro-nuclear or perceived as such regardless of what their data shows), as well as for most established environmental groups (usually self-identifying as anti-nuclear and so also prone to accusations of bias regardless of the quality of their data). For this reason, from the outset, Safecast has taken a position of not siding with either the pro- or anti-nuclear camps, and to demonstrate the advantages to science and to the public of having an independent organization devoted solely to providing the most accurate and credible data possible. Safecast often emphasizes that it is 'pro-data'.This is an ethical decision as much as a practical one, and in terms of public communication, it has been one of the greatest challenges faced by the group.

Any group engaged in environmental monitoring comes under tremendous pressure to take sides, usually from the anti-nuclear camp, which seeks credible allies. In cases where Safecast data has contradicted claims made by antinuclear activists, it has sometimes been perceived as an attack, and accusations of a hidden pro-nuclear agenda have been raised, often in anonymous online blogs. Establishment and pro-nuclear bodies, on the other hand, sometimes tend to initially perceive Safecast as a potential adversary, but when they learn that the group is not anti-nuclear, have occasionally sought its support as well. It is very difficult to navigate these contentious waters and to maintain open communication with all parties without taking sides. Nevertheless, non-partisanship is considered essential to the success of the Safecast project, and the independent, 'pro-data' policy will remain.

3. Results

The results obtained to date by the Safecast project are both tangible and intangible. Some tangible results can be expressed in metrics, such as the size and rate of growth of the database (currently over 40 million datapoints, adding approximately 1 million per month); the number of volunteers (over 900 registered API users, over 50 of whom have logged more than 100 000 data points each, 6 of whom have logged over one million each); the number of Safecast detectors deployed (approximately 1000, including about 500 bGeigie Nanos); the number of mentions in the media (over 30 newspaper articles in Japan and abroad, 6 features by major broadcast media, at least 50 mentions in online media); etc. But the intangibles are considered more important by the group itself, and provide its primary internal measure of success. These intangibles include perceived shifts in attitudes in society, a growing sense of community, increased interest in the capabilities of citizen scientists worldwide, and greater recognition of Safecast on the part of official agencies and regulatory bodies.

While the immediate initial project of Safecast has been to independently monitor and publish information on radiation levels and other environmental hazards, from the outset the group has sought to encourage more fundamental shifts in social expectations, in the direction of openness and participation. The impact the Safecast project has had so far, has, in the view of group members, brought much greater recognition of these potentials worldwide.

Another important result lies in being widely perceived as credible by people and groups of quite varying interests and political stances vis a vis nuclear radiation. Safecast has gained

a reputation for objectivity both in its data and it its commentary, is increasingly sought by journalists and others for fact-checking, and has become known as a group which can provide accurate and informative commentary during media tours of Fukushima. Group members have frequently been able to debunk speculation and rumor on the basis of first-hand data and intimate familiarity with the available information, as well as contact with trusted experts [42]. Nevertheless, in the current media environment, even solidly debunked misconceptions are prone to resurface.

The degree of credibility Safecast has earned can be exemplified by attendance at the group's workshops, such as one held in Washington DC in April 2014, sponsored by the National Resource Defense Council (NRDC) [43]. Attendees included representatives from many anti-nuclear and environmental groups as well as from the US DOE and the Department of Homeland Security (DHS). These participants built bGeigies together, and afterward as a group measured radiation levels on the Washington Mall. Similarly, the Safecast workshop held in Strasbourg in October 2014 included attendees from both the French national radioprotection agency (IRSN) and a leading anti-nuclear group (CRIIRAD) [44]. Safecast has often been able to bring together people who normally regard each other as adversaries, to encourage them to recognize their shared interests and concerns, and to forge more productive relationships.

Safecast faces criticism from time to time on technical grounds, usually from establishment experts who have never used the bGeigie system but are nevertheless skeptical of its stated specifications and performance. For decades, the conventional 'best' approach to radiation monitoring has been to have a small number of certified experts conduct measurements using expensive and sensitive detectors, and experts trained in this methodology have sometimes resisted new technical approaches. Safecast's primary innovation has been to replace the conventional approach with the deployment of hundreds of low-cost detectors of identical design, which are used to take repeated measurements of the same areas. The benefits of the Safecast approach include increased statistical accuracy over time through larger sample sizes and redundancy. The possibility of similar approaches has been discussed by experts for several years [45], but Safecast's success has provided an important proof-of-concept, and many similar efforts are now being undertaken on a national scale, including one recently announced with great fanfare by the US Defense Advanced Research Projects Agency (DARPA), which will involve the deployment of tens of thousands of compact, low-cost sensors for large-scale radiation mapping [46].

Whatever authority Safecast possesses can be characterized as adaptive and fluid, and rooted in the shifting needs of the commons, as opposed to the 'constituted' authority of formal science and its institutions. Nevertheless the possibility of integrating the information produced by Safecast with that of formal science has been demonstrated. Safecast was established as a publicly-generated alternative, but the openness protocols adopted from the outset have made its data available to scientific and political authorities as well. Further, it was recognized from the outset that maintaining high standards for accuracy and reliability was essential. Safecast has never sought the endorsement of official agencies, but nevertheless has been approached with increasing frequency by official bodies who seek to learn more about the group's methods and experience, and to publicize its data. The inclusion of Safecast data in official reports [47, 48] and invitations to speak at expert meetings [18, 19], as well as the wider adoption of the group's innovative measurement methodology referred to above, all suggest a high degree of confidence on the part of the expert community in the quality and significance of Safecast's achievements and a confirmation of the validity of its methodology. Contacts with official bodies have provided the opportunity to familiarize the expert community with the capabilities and functioning of the Safecast system, and to discuss the possible

need for the assistance of citizen scientists to help monitor radiation conditions in the event of future nuclear disasters; the importance of protecting the independence of groups like Safecast is always stressed.

In addition to the educational programs described earlier, increasing interest has been expressed by educational institutions of several types to base new formal curricula on the Safecast hardware and software systems. One of the most successful of these has taken place in France, initially without any input from Safecast itself [49]. In this program, high school students in the Auvergne region, which is known for high natural background radiation levels due to radon, used bGeigie Nanos to map radiation in the region, and overlaid the radiation maps on geologic maps. The students were able to confirm that the areas of high radiation had geologic substrata composed of radioactive granite. The success of this program has led to the purchase of more bGeigie Nano kits to be distributed to high schools across France. Similar educational programs are being planned in other countries. In addition, the American School in Japan (ASIJ) has obtained ten bGeigie Nano kits, and has begun using them in new science courses for middle and high-school students [50]. Finally, Aoyama Gakuin, a leading private college located in the Tokyo area, now offers a course on radiation mapping which is taught by Safecast volunteers, and in which students build and use bGeigie Nanos [51]. With well-supported educational programs under way in several countries, and excellent curricula being developed for students of many age ranges, the Safecast system will become increasingly easy to adopt for educational purposes independent of Safecast itself.

The Safecast project has also been the subject of scholarly study, specifically in the field of sociology. These studies often examine other radiation mapping projects which depend to varying degrees upon citizen participation as well. These comparisons help illustrate the nature and significance of Safecast's activity in terms of impact on communities, in media, and social organization, both within the global citizen science community and in relation to like-minded efforts in Japan. Hemmi and Graham compare the Safecast effort to KURAMA, a government-funded mobile radiation measurement system developed by scientists at Kyoto University and currently used by Japanese government agencies to map radiation in Fukushima and elsewhere [17]. While it has good technical specifications, the KURAMA system is quite expensive (over $10 000 per unit), and the project was never intended to encourage citizen participation. The mapping data is the property of the Japanese government, and while it has been publicized in an increasingly accessible manner, it is not truly 'open' data, requiring instead use agreements and the acceptance of preconditions prior to accessing or downloading it. As Hemmi and Graham point out, KURAMA is an example of development under the conventional 'closed science' model, while open 'hacker' model embodied by Safecast has enabled rapid and adaptive development.

Kawano *et al* contrast the Safecast project to their own 'BISHAMON' project, asserting that data gathered by the latter is more inherently reliable than crowdsourced data like Safecast's, because the data collection can be more closely targeted and controlled [52]. Rather than being a citizen-directed effort, the BISHAMON project is essentially a university-government collaboration which has more in common with government-funded efforts like KURAMA. The BISHAMON detector system, while technically of good quality, is not affordable for the general public, and is more appropriate for use by municipal governments. Importantly, the difference in productivity, social impact, and longevity of BISHAMON and Safecast highlights the strengths of the Safecast's open citizen-science model. Safecast continues to grow in number of volunteers, quantity of data collected, geographic reach, and technical competencies. At the time of this writing, however, no data has been published by BISHAMON since 2014, and several aspects in the planning stage for that project in 2014 had already been realized and deployed by Safecast by late 2011.

Ishigaki *et al* describe the POKEGA system, which they developed as a crowdsourced radiation information system [53]. Like Safecast, this team developed new hardware as well as an online database and mapping system; unlike Safecast, the POKEGA maps are currently only accessible through a custom smartphone application. The low-cost photodiode detector this system uses represents a trade off between reliability, since, as the authors note, it requires long measurement times and is prone to false detections, and cost. Like Safecast, the POKEGA project has made its system plans available under open-source licenses. The most significant difference between POKEGA and Safecast, however, is that the measurement data of the former is not openly available. The data can only be viewed through the associated smartphone application, which requires purchase; that is, it is a paid membership system, albeit with moderate cost, while Safecast's data can be viewed free of charge either on the web on through free applications developed by Safecast. The POKEGA system allows users to share their data with other members, but the default is to protect it as 'private' data. In contrast, while the Safecast system allows users to maintain a certain degree of privacy by viewing but not submitting their measurement data, thus preventing it from entering the public database, the parameters of the system are based on the assumption that users will almost always want to contribute to the open public dataset. Safecast encourages public participation and open sharing at every point.

Plantin provides a useful overview of radiation data mapping efforts following the start of the Fukushima disaster in March 2011, and discusses Safecast in that context [54]. Notably, Safecast is one of the few non-governmental radiation mapping efforts surveyed in 2011 which remains active. Many radiation mapping efforts were prompted by a sense of emergency in 2011, as well as the information vacuum—'…a case of no data and bad data', as the author succinctly puts it. But from the outset Safecast was envisioned as filling needs which would persist even after the Fukushima emergency phase had passed. In particular, the need for an independent global baseline dataset of background radiation levels was recognized, as well as the need for participatory education worldwide on measuring radiation and other environmental hazards. Having identified these and other goals early on has enabled Safecast to continue to grow even though public interest in Fukushima itself has waned. This continued growth and adaptability sets the Safecast project apart from most others. That said, Safecast has been able to share its experience and know-how with individuals and groups who have established other citizen-science based radiation monitoring efforts. These include Our Radioactive Ocean, established by scientists at Woods Hole Oceanographic Institution, and Fukushima INFORM, a collaborative venture based in Canada, both of which provide the means for citizens to take water samples from the Pacific Ocean to be tested by institutional labs for radionuclides [55, 56]. Safecast maintains close contact with these groups, and shares relevant information. Safecast also maintains close contact with the '*Minna no Data'* project ('Everyone's Data'), which publishes a joint online database of independent food and soil measurements from many parts of Japan. Approximately 30 citizen-run radiation testing labs currently participate [57].

The projects described by the authors above each have their strong points, and all have contributed to informing the public. The uniqueness of Safecast in this context lies in its particular implementation of the fundamental principles of open-source, open-data, crowdsourcing, citizen science, and agile development of hardware and software, together with a global vision which extends beyond radiation monitoring to air quality and other environmental challenges. Adherence to this set of principles has allowed Safecast to grow steadily in size and reach, while becoming widely regarded as technically competent and reliable by experts as well as the public. Franzoni and Sauerman outlined the potential benefits of the integration of open innovation and citizen science [3]; Safecast arguably represents a well-realized integration of this type.

Benkler discusses Safecast's impact in the context of 'mutualism' as a response to the failure of institutions, saying:

'*…mutualism has also been used to work around governmental bodies that are reticent to fulfill their role because of the standard failures of government in democratic society—incompetence, political interest, cronyism. Perhaps the clearest example of this to date is Safecast, a response to the failures of the Japanese government and power company to produce reliable information about radiation levels in Japan after the Fukushima incident*' [58].

This points to perhaps the most important result overall of Safecast's activities, which has been to enable people to easily monitor their own homes and environments themselves, and to free themselves in this way from dependence on government. The impact this has had on people is overwhelmingly positive, though the responses that follow depend on individual temperament and circumstances. For some individuals, being able to take reliable radiation readings themselves, and to find radiation levels lower than feared, for instance, brings a sense of relief. For others, their findings serve as reliable confirmation of injustices suffered and risks imposed unnecessarily. Still others consider the results to be objective and useable confirmation of the degree of radioactive contamination they must deal with, supplanting both excessive fear and excessive hope, and enabling them to take informed action appropriate for their situation.

4. Conclusions

While many aspects of the Safecast project align with observations and models proposed by academics studying citizen science, in reality Safecast began without the benefit of academic analysis regarding what citizen science is or could be, or how success would be measured. Rather, consensus regarding the best practices for social involvement, openness, agile development, and other fundamental principles underlying the project was quickly reached, and these ideas were tested in a flexible manner. Compared to typical closed development processes, the less-tightly coordinated process which enabled Safecast to field prototypes rapidly may have appeared somewhat chaotic to outsiders initially. In fact, the overall system can be described as a dynamic interplay of open, overlapping, ad-hoc team efforts, which has allowed striking and enduring results to be achieved.

People's sense of acceptable risk differs tremendously depending on their background, present situation, and knowledge. Notably, despite the group's name, Safecast avoids declarations of what is and isn't 'safe' and instead tries to provide tools and community resources to help people understand the complexities of radiation measurement and to make their own informed decisions. As described above, Safecast's primary information service, environmental radiation data, is intended to be an easily accessible, objective resource. Much of the group's other information-related activity in social media and elsewhere involves locating relevant information sources, summarizing their contents, characterizing any differences of opinion and interpretation that exist, and showing others where to find them. As noted, judgment and experience invariably come into play in this process, but most biases can be identified and guarded against. Nevertheless, despite the group's reluctance to be cast in the role of experts beyond its primary expertise in radiation detection and mapping, citizens in need of expert advice and confirmation often try to force the group into that role in areas such as health, food, or the economics of evacuation.

This highlights the fact that people have many different information needs and different degrees of scientific literacy. While experts frequently contact Safecast to help them locate specific data, on recent water contamination readings at Fukushima Daiichi, for instance, or recent food test results, for lay people the primary question that needs to be answered is, 'Will my children and I be alright living here?' Perceptions and receptivity are shaped by identity, which in turn is shaped by relationships with family and community, and influenced by their needs. It is unlikely that any single source of information, or type of information, will be adequate for all. By listening to people's concerns and fielding many questions over the past several years, Safecast volunteers have been exposed to the doubts and fears of many people, and while the group cannot always provide adequate answers, collectively it has developed a good sense of the questions that average citizens face in the wake of a nuclear disaster such as that in Fukushima, and what it is they need to know.

Initially it was the lack of publicly available information about radiation levels in Japan, and its questionable quality, that prompted the formation of Safecast and guided its priorities. As government efforts improved and more data and maps gradually became available, the primary issue became the insufficient breadth of coverage of data provided by official sources, and the difficulty citizens faced in locating and using it. When enough comparable data had been gathered and published by each side, Safecast readily acknowledged when asked that for the most part Safecast's data matches official data environmental radiation monitoring fairly closely. Nevertheless, in the group's opinion, the granularity of the Japanese government's radiation data, that is, its completeness and detail, as well as the ease with which the public is able to access it, remain wanting. Safecast seeks to set an example of accessibility that it feels should be emulated.

Benkler, quoted above, concludes by saying, '…Safecast is as crisp an example as we have for how mutualism can serve as a successful workaround for failure (whether for lack of capacity or, more likely, for lack of political will) of a public body' [53]. Though groups like Safecast can help fill crucial gaps, ultimately the timely provision of data that citizens need to make informed decisions about their livelihoods and well-being is the government's responsibility. The fact that a group like Safecast proved necessary at all is in itself an indictment of the failures of government and the international system for informing the public of such risks. At the same time the rise of citizen science should be seen as a very positive development, one of the few bright spots that have emerged following the Fukushima disaster. As noted by many researchers, this vigorous emergence suggests that a shift in social expectations and in the balance of information is already happening, from one which favors government and large institutions, to a more egalitarian and democratic relationship driven by citizen access to objective, independent information of high quality which has been generated by the citizens themselves. The technical capabilities occasioned by the open-source and digital fabrication movements are poised to put increasingly sophisticated scientific and communication tools in the hands of average citizens worldwide. This will continue to require social and regulatory accommodation and adjustment as governments and other established stakeholders grow to understand the implications of the changing information landscape and, hopefully, are motivated to reach mutually beneficial accommodation with citizen scientists like those at Safecast. The citizen science genie is out of the bottle, and cannot be forced back in.

Acknowledgments

References

[1] The National Diet of Japan 2012 *The Official Report of the Fukushima Nuclear Accident Independent Investigation Commission* (Executive summary) http://warp.da.ndl.go.jp/info:ndljp/pid/3856371/naiic.go.jp/wp-content/uploads/2012/09/NAIIC_report_lo_res10.pdf

[2] International Atomic Energy Agency 2015 *Fukushima Daiichi Accident, Summary Report by the Director General, Board of Governors* www-pub.iaea.org/books/IAEABooks/10962/The-Fukushima-Daiichi-Accident

[3] Franzoni C and Sauermann H 2014 Crowd science: the organization of scientific research in open collaborative projects *Res. Policy* **43** 1–20

[4] Mansell R 2013 Employing digital crowdsourced information resources: managing the emerging information commons *Int. J. Commons* **7** 255–77

[5] Stodden V 2010 Open science: policy implications for the evolving phenomenon of user-led scientific innovation *J. Sci. Commun.* **9** 1–8

[6] Bonney R, Shirk J L, Phillips T B, Wiggins A, Ballard H L, Miller-Rushing A J and Parrish J K 2014 Next steps for citizen science *Science* **343** 1436–7

[7] Howe J 2006 The rise of crowdsourcing *Wired Mag.* **14** 1–4

[8] Howe J 2008 *Crowdsourcing: Why the Power of the Crowd is Driving the Future of Business* (New York: Crown Business)

[9] Malone T W, Laucacher R and Dellarocas C N 2009 Harnessing crowds: mapping the genome of collective intelligence *MIT Sloan Research Paper* 4732-09

[10] Brabham D C 2012 The myth of amateur crowds: a critical discourse analysis of crowdsourcing coverage *Inf. Commun. Soc.* **15** 394–410

[11] Cross R, Parker A, Prusak L and Borgatti S P 2002 Knowing what we know: supporting knowledge creation and sharing in social networks *Organ. Dyn.* **30** 100–20

[12] Jenkins H 2006 *Convergence Culture: Where Old and New Media Collide* (New York: New York University Press)

[13] Tapscott D and Williams A D 2007 *Wikinomics: How Mass Collaboration Changes Everything* (New York: Tantor Media)

[14] Albors J, Ramos J C and Hervas J L 2008 New learning network paradigms: communities of objectives, crowdsourcing, wikis and open source *Int. J. Inf. Manage.* **28** 194–202

[15] Baym N K 2010 Social Networks 2.0 *The Handbook of Internet Studies* ed M Consalvo and C Ess (New York: Wiley-Blackwell) ch 18

[16] Murillo L F R 2013 New expert eyes over Fukushima: open source responses to the nuclear crisis in Japan *STS Forum on the 2011 Fukushima/East Japan Disaster* https://fukushimaforum.wordpress.com/workshops/sts-forum-on-the-2011-fukushima-east-japan-disaster/manuscripts/session-3-radiation-information-and-control/new-expert-eyes-over-fukushima-open-source-responses-to-the-nuclear-crisis-in-japan/

[17] Hemmi A and Graham I 2014 Hacker science versus closed science: building environmental monitoring infrastructure *Inf. Commun. Soc.* **17** 7

[18] Brown A 2014 SAFECAST: effective use of internet and social media in third- party environmental radiation monitoring after the Fukushima Dai-ichi NPP disaster *Int. Experts' Meeting on Radiation Protection after the Fukushima Daiichi Accident: Promoting Confidence and Understanding (International Atomic Energy Agency, Vienna, 17–21 February 2014)* www-pub.iaea.org/iaeameetings/46522/International-Experts-Meeting-on-Radiation-Protection-after-the-Fukushima-Daiichi-Accident-Promoting-Confidence-and-Understanding

[19] Moross J 2014 Citizen Radiation Monitoring in Japan *Public Seminar: Monitoring Impacts and Communicating Health Risks after Fukushima (United Nations University, Institute for the Advanced Study of Sustainability, Tokyo, 11 November 2014)* http://ias.unu.edu/en/news/news/seminar-explores-lessons-learned-in-communicating-health-impacts-of-fukushima-accident.html#info

[20] Royal Society 2012 *Science as an Open Enterprise* (London: The Royal Society)

[21] Bonner S 2016 Safecast Air Prototypes *Safecast Blog* http://blog.safecast.org/2016/01/safecast-air-prototypes/

[22] Arduino project page 2016 www.arduino.cc

[23] Safecast API page 2016 https://api.safecast.org

[24] Safecast online radiation tilemap 2016 http://safecast.org/tilemap/

[25] Dolezal N 2016 Safecast data processing methodology http://safecast.org/tilemap/methodology. html

[26] Benkler Y 2004 Commons-based Strategies and the Problems of Patents *Science* **305** 1110–1

[27] Florin C 2014 My review of bGeigie Nano from Safecast *Wise Time with Arduino* http:// timewitharduino.blogspot.ca/2014/05/safecast-bgeigie-nano.html

[28] Safecast Blog 2016 http://blog.safecast.org

[29] Safecast Twitter feed 2016 https://twitter.com/safecast

[30] Safecast online discussion group 2016 https://groups.google.com/forum/?pli=1#!forum/safecast-japan (login required)

[31] SLACK product page 2016 https://slack.com

[32] Taira K 2015 The Prometheus Trap (*Purometeusu no wana*) *Asahi Shimbun* 31 p 3

[33] Otori C 2012 Group empowers monitoring of radiation levels for everyone *Nikkei Weekly* p 20

[34] NHK World Newsline 2014 Mapping radiation *Path to Recovery: Three Years On 9 March 2014* www3.nhk.or.jp/nhkworld/newsline/path_to_recovery/r2014030901.html

[35] Krotoski A 2015 The power of privacy (4/5): open data: mapping the fallout from Fukushima *The Guardian Online* www.theguardian.com/media-network/ng-interactive/2015/sep/29/the-power-of-privacy-video-series?video=Dr-zaBDRHsc

[36] Brown A 2015 *Health* v08, revised 10 January 2015 http://www.slideshare.net/safecast/azby-threeyear-sympo- siumhealth-v04

[37] Brown A 2014 *Safecast: Guide to the UNSCEAR 2013 Fukushima Repor*t v05 23 August 2014 www.slideshare.net/safecast/unscear-2013-fukushima-final-report-commentary-v02

[38] Brown A 2013 Decon or con? How is remediation being managed, and how effective is it? *Safecast Blog* 17 August 2013 http://blog.safecast.org/2013/08/decon-or-con-how-is-remediation-being-managed-and-how-effective-is-it/

[39] Safecast 2015 *Safecast Report* vol 1, March 2015 http://blog.safecast.org/the-safecast-report/

[40] Creative Commons license information 2016 https://creativecommons.org/licenses/

[41] Safecast GitHub resource repositories 2016 https://github.com/Safecast

[42] Brown A and Bonner S 2014 Radiation on California Beaches *Safecast Blog* 6 January 2014 http://blog.safecast.org/2014/01/radiation-on-california-beaches/

[43] Alemayehu B 2014 A citizen radiation monitoring workshop at NRDC *NRDC Switchboard* 25 April 2014 http://switchboard.nrdc.org/blogs/balemayehu/a_citizen_radiation_monitoring.html?utm_source=feedburner&utm_medium=feed&utm_campaign=Feed%3A+switchboard_all+%28Switchboard%3A+Blogs+from+NRDC%27s+Environmental+Experts%29

[44] Brown A 2014 bGeigie nano workshops on opposite sides of the world *Safecast Blog* 29 October 2014 http://blog.safecast.org/2014/10/bgeigie-nano-workshops-on-opposite-sides-of-the-world/

[45] Liu A, Wu M, Chandy K M, Obenshain D, Smith M and McLean R 2008 Design Tradeoffs for Radiation Detection Sensor Networks preprint www.cnds.jhu.edu/~dano/IPSN_final.pdf

[46] Tang V 2015 Defense advanced research projects agency SIGMA program information page www.darpa.mil/program/sigma

[47] United Nations Scientific Committee on the Effects of Atomic Radiation 2014 *Effects And Risks of Ionizing Radiation, UNSCEAR 2013, Report Volume I Report To The General Assembly Scientific Annex A: Levels and Effects of Radiation Exposure Due to the Nuclear Accident After the 2011 Great East-Japan Earthquake and Tsunami* (Vienna: United Nations) pp 101,180, 306 www.unscear.org/docs/reports/2013/13-85418_Report_2013_Annex_A.pdf

[48] International Atomic Energy Agency 2015 *Fukushima Daiichi Accident, Summary Report by the Director General, Board of Governors* 4 Annex III, p 23 www-pub.iaea.org/MTCD/Publications/PDF/AdditionalVolumes/P1710/Pub1710-TV4-Web.pdf

[49] Sauvage A 2015 How to measure natural radioactivity? *Radioactivite-Auvergne* (in French) http://radioactivite-auvergne.blogspot.jp

[50] American School in Japan 2015 Environmental Dynamics 1 Strand Map *ASIJ Integrated Science I* http://educhange.com/wp-content/uploads/2015/11/ED-I-Strand-Map.pdf

[51] Aoyama Gakuin University 2015 Topics in Japanese geography II Safecast—state of radiation mapping in Japan *Aoyama Gakuin University School of Global Studies and Collaboration Information for Exchange Students* p 8 www.gsc.aoyama.ac.jp/wp-content/uploads/2015/08/information_for_exchange_students.pdf

[52] Kawano Y *et al* 2012 A map for the future: measuring radiation levels in Fukushima, Japan *2012 IEEE Global Humanitarian Technology Conf. (GHTC) (Seattle, WA, 21–24 October 2012)*

[53] Ishigaki Y, Matsumoto Y, Matsuno Y and Tanaka K 2015 Participatory radiation information monitoring with SNS after Fukushima *ISCRAM 2015 Conf. Proc.—12th Int. Conf. on Information Systems for Crisis Response and Management (University of AgderKristiansand, Norway, 24–27 May 2015)*

[54] Plantin J-C 2011 'The map is the debate': radiation webmapping and public involvement during the Fukushima issue *SSRN Electron. J.* J1926276 http://papers.ssrn.com/sol3/pa- pers. cfm?abstract_id=1926276

[55] Woods Hole Oceanographic Institution, Our Radioactive Ocean project page 2016 http:// ourradioactiveocean.org/

[56] Integrated Fukushima Ocean Radionuclide Monitoring (Fukushima INFORM) project page 2016 http://fukushimainform.ca/

[57] Minna no Data Site project page 2016 http://en.minnanods.net/

[58] Benkler Y 2013 Practical anarchism: peer mutualism, market power, and the fallible state *Polit. Soc.* **41** 213–51