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Citizen Science in the Age of Neogeography: Utilizing Volunteered Geographic Information for Environmental Monitoring

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The interface between neogeography and citizen science has great potential for environmental monitoring, but this nexus has been explored less often than each subject individually. In this article we review the emerging role of volunteered geographic information in citizen science and present a case study of an integrated tool set that engages multiple types of users (from targeted citizen-based observation networks, expert-driven focused monitoring, and opportunistic crowdsourcing efforts) in monitoring a forest disease in the western United States. We first introduce the overall challenge of data collection in environmental monitoring projects and then discuss the literature surrounding an emergent integration of citizen science and volunteered geographical information. We next explore how these methods characterize and underpin knowledge discovery and how multimodal interaction is supported so that a large spectrum of contributors can be included. These concepts are summarized in a conceptual model that articulates the important gradients of Web-based environmental monitoring: the users, the interaction between users and data, and the types of information generated. Using this model, we critically examine OakMapper.org, a Web site created by the authors to collect and distribute spatial information related to the spread of a forest disease, and discuss many of the core issues and new challenges presented by the intersection of citizen science and volunteered geographic information in the context of environmental monitoring. We argue that environmental monitoring can benefit from this synergy: The increased emphasis on a diversity of participants in knowledge production might help to reduce the gaps that have in the past divided the public, researchers, and policymakers in such efforts. *Key Words: citizen science, open source, participatory GIS, sudden oak death, volunteered geographic information, Web GIS.*

新地理和公民科学之间的接口对环境监测有巨大的潜力，但这种关系一直以来相对于每个科目来说较少地被研究。在这篇文章中，我们探讨自愿地理信息在公民科学中的新作用，并呈现一个在监测美国西部森林疾病研究过程中的，多用户参与（从基于定向的公民观测网络，专家驱动的重点监控，到随机人群的举措）的集成工具集。我们首先介绍在环境监测项目中的数据采集的整体挑战，然后讨论周围新兴公民科学和自愿地理信息相融合的文献。接下来我们探讨这些方法如何表征和支撑知识的发现，以及多模式交互是如何被支持，以便包括大范围的贡献者。这些概念概括了一个概念模型，阐明基于网络环境监测的重要梯度：用户，用户和数据之间的相互作用，和产生的信息类型。使用这个模型，我们批判性地研究作者创建的一个用来收集和发布有关的森林疾病蔓延的空间信息的网站 OakMapper.org，并讨论许多核心问题，以及提出了在环境监测中的由公民科学和自愿地理信息的交互所带来的新的挑战。我们认为，环境监测可以受益于这种协同作用：增强在知识生产中的多样性参与者可能有助于减少过去在这种举措中区分的公众，研究人员，和决策者之间的差距。关键词：公民科学，开源，参与地理信息系统，橡树突然死亡，自愿地理信息，网络地理信息系统。

La interfaz situada entre la neogeografía y la ciencia ciudadana reviste un gran potencial para el monitoreo ambiental, aunque este nexo ha sido menos frecuentemente explorado de lo que ha sido cada una de aquellas materias individualmente. En este artículo hacemos la revisión del papel emergente que tiene la información geográfica voluntaria en la ciencia ciudadana y presentamos un estudio de caso de un conjunto integrado de herramientas que involucra usuarios de diversos tipos (de redes de observación centradas en la ciudadanía, monitoreo focal manejado por expertos y esfuerzos oportunistas de diversa procedencia) en el monitoreo de una enfermedad forestal del oeste de los Estados Unidos. Presentamos primero el reto general de la recolección de datos en proyectos de monitoreo ambiental y luego discutimos la literatura que rodea la integración emergente de ciencia ciudadana e información geográfica de voluntariado. Enseguida, exploramos la manera como estos métodos caracterizan y sustentan la adquisición de conocimiento y cómo se respalda la interacción multimodal

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para que se pueda incluir un amplio espectro de contribuyentes. Estos conceptos se resumen en un modelo conceptual que articula los gradientes importantes de monitoreo ambiental basado en la Web: los usuarios, la interacción entre usuarios y los datos, y los tipos de información generados. Mediante este modelo, examinamos críticamente al OakMapper.org, un sitio Web construido por los autores para recoger y difundir información espacial relacionada con la diseminación de una enfermedad forestal, al tiempo que discutimos muchos de los asuntos medulares y nuevos retos asociados con la intersección de la ciencia ciudadana y la información geográfica voluntaria en el contexto del monitoreo ambiental. Sostenemos que el monitoreo ambiental se puede beneficiar de esta sinergia: El énfasis creciente en una diversidad de participantes en la producción de conocimiento podría ayudar a reducir las brechas que en el pasado han dividido al público, los investigadores y los formuladores de políticas en tales esfuerzos. *Palabras clave: ciencia ciudadana, fuente libre, SIG participante, muerte súbita de robles, información geográfica voluntaria.*

The recent proliferation of geospatial technologies, including Web-based mapping tools, Global Positioning Systems (GPS), and smart phones, is transforming the collection, representation, distribution, and use of spatial information. Technologies such as Google Maps and Open Street Map have been embraced by academic geographers but have also been widely employed by a nonexpert community, often referred to as *neogeographers* (Turner 2006; Haklay, Singleton, and Parker 2008). This article considers the emerging roles of volunteered geographic information (VGI, which is generated by the users of these technologies) and of citizen science in research endeavors, particularly for environmental monitoring. We present a hybrid approach to data collection that draws from an array of direct and indirect sources to assemble and share geographic knowledge from both neogeography and expert science sources. Despite their promise, these data pose social and empirical challenges that can proscribe their application, and we consider the utility of VGI and citizen science in this context and in light of these limitations. Nonetheless, we believe that neogeography and VGI complement both citizen science and expert science efforts and here explore the potential of their synergy for environmental monitoring efforts to provide timely detection of large-scale phenomena.

Many of the challenging natural resource problems that the public (this article refers to the public as the nonexpert community of private citizens operating outside of the academy and policy agencies), researchers, and policymakers face today span spatial scales and impact diverse public groups. Addressing these challenges often requires coordinated monitoring, efficient data collection and retrieval, and increased communication and cooperation between scientists and the public (Kusel et al. 1996; Mason and Dragicevic 2006; Lynam et al. 2007; Ban, Picard, and Vincent 2008; Fernandez-Gimenez, Ballard, and Sturtevant 2008; Jacobson et al. 2009). Although there is a long and interesting history of scientists working with private citizens to gather and utilize scientific data (Holland 1996; Kearns, Kelly, and Tuxen 2003; Jennings, Jarnagin, and Ebert 2004; Evans et al. 2006; Parker 2006; Pedersen, Kearns, and Kelly 2007), the ability for these communities to interact can be impeded by interest levels, technical skills, information accessibility, data management, communication barriers, and time requirements. Environmental data sets that are generated and used by communities have commonly utilized the Web as a medium; in this context, geographic location is an intuitive and powerful cataloging structure for many environmental and social data. Such Web-based databases make geotagged data widely available in a visual, dynamic, quickly searchable, and interactive format (Goodchild 1997; Kearns, Kelly, and Tuxen 2003) that builds on many of the design standards from information visualization and cognitive and cartographic research (Tufte 2001; MacEachren et al. 2004; Heer and Agrawala 2008; Balram and Dragicevic 2009).

The recent emergence and broad adoption of information technologies to gather and visualize geographic information have increased the feasibility of conducting large-scale citizen science projects, but these data also challenge the traditional relationships between scientists, the public, and data sets. Examples of VGI and citizen science have become common in biodiversity monitoring and conservation biology (e.g., Danielsen et al. 2005; Lepczyk 2005; Couvet et al. 2008) and early disaster response (Longueville et al. 2010; Poser and Dransch 2010) but are not as common in environmental monitoring. If used in the service of environmental monitoring, VGI and citizen science could embrace the broader social trend that favors citizen involvement in decision making and policy implementation across multiple levels of government (Gouveia and Fonseca 2008; Berkes 2009). Although there has been discussion of the role of these technologies to facilitate participatory efforts and to actively recruit data, less attention has been given to data sourcing from extensive VGI networks that are created independently of formal citizen science projects, and yet are increasing rapidly in number and scope.

This article argues that environmental monitoring projects can benefit from the full spectrum of knowledge producers (from trained scientists to citizen scientists) by bringing in the complete range of VGI (from project-specific data to agglomerative geotagged information on the Web) and providing a multimodal interaction platform for its intentional and unintentional participants. To advance this argument, this article first considers the importance of citizen science and VGI, as supported by the advancement of information technologies, and then details the various modes of interaction that these contributors have with locational information. A conceptual model that maps out the relationships between citizen science (users/producers), VGI (data), and environmental data production (interaction) is presented to help summarize and visualize the core arguments of this article. Finally, the OakMapper.org case study is provided to illustrate how to operationalize this conceptual model. This article concludes with a critical discussion of the implications of VGI and citizen science for environmental monitoring and lessons learned from our experiences with OakMapper.org.

Citizen Science in the Age of Neogeography

The concept of using decentralized groups of nonprofessionals to gather information, which predates the Internet and the term *crowdsourcing*, has long been embraced by citizen science projects. Audubon's Christmas Bird Count, which has utilized volunteers to conduct a census of birds in the Western Hemisphere since 1900 (Butcher 1990), is one of the longest running and best known citizen science projects. Other examples of citizen science have included fish counts, bird biodiversity, water monitoring, and air quality monitoring (Pattengill-Semmens and Semmens 2003; Lepczyk 2005; McCaffrey 2005; Cooper et al. 2007). Scientific data sets are increasingly generated and used by collaborative communities, often virtual, which can include researchers, decision makers, and private citizens (Wulf 1993; Kouzes, Meyers, and Wulf 1996; Cummings and Kiesler 2005; Pedersen, Kearns, and Kelly 2007). The possibilities for enlisting private citizens for scientific research has grown with the spread of the Internet, and many projects have begun to use large-scale public resource computing to distribute data processing to many volunteers (e.g., SETI@home, folding@home, and others; D. P. Anderson et al. 2002). This distributed approach that utilizes the human and technological capital of volunteers can save time and resources as well as increase public knowledge and interest in science (Irwin 1995).

Technological advances have facilitated public participation in expert-guided scientific research, but it has also opened opportunities for informal knowledge sharing and information access beyond the reach of the academy. The production of spatial information in particular has transformed as geospatial technologies provide opportunities for private citizens to participate in activities once relegated to the world of "expert" geographers and cartographers. Web mapping services (e.g., Google Maps, Yahoo! Maps) and digital globes (e.g., Google Earth, NASA World Wind) have increased these opportunities by providing free access to extensive collections of maps and imagery that were previously difficult to obtain and view, and Web developers have responded by producing numerous applications and data sets with these tools. A Web-going public has embraced these opportunities, creating an emerging landscape on the Internet that is geographic in structure, often personal, sophisticated, and highly dynamic. As a result, map making is no longer restricted to the realm of the trained cartographer and there is diminishing distinction among the producer, consumer, and communicator of spatial information (Goodchild 2009). Neogeography, as this informal application of geographical techniques has been coined (Turner 2006; Haklay, Singleton, and Parker 2008), is actualizing the concept of citizen science, which "implies a form of science developed and enacted by citizens themselves—the 'contextual knowledges,' which are generated outside of formal scientific institutions" (Irwin 1995, xi).

The more inclusive role of users in the coproduction of spatial information echoes a broader trend toward developing a more participatory and social Internet, which is called Web 2.0 (O'Reilly 2007; Haklay, Singleton, and Parker 2008; Hall et al. 2010). Definitions of Web 2.0 vary, but O'Reilly (2007) identified common traits that include scalable Web-based services, user-enriched data sources, use of collective intelligence, and lightweight user interfaces. Although developers create the infrastructure, this new digital landscape enlists private citizens as codevelopers and depends on a broad user community to generate content. Neogeographers are supporting a form of crowdsourcing, which utilizes a decentralized network of users to provide content (Howe 2009), to develop geospatial tools and spatial data sets. In the broadest sense, crowdsourcing describes the outsourcing of tasks, which would normally be conducted by an employee, to a fleet of volunteers but more commonly refers to the use of Web 2.0 to facilitate this collaboration. This radical shift in the relationship between use and production of information has led some to refer to participants who take on this dual role as *produsers* (Budhathoki, Bruce, and Nedovic-Budic 2008). Produsers provide content for encyclopedias (wikipedia.com), share videos (youtube.com) and photographs (flickr.com), and publish business reviews (yelp.com). Neogeographers represent a subset of produsers who specifically interact with VGI. Conceptualizing a subset of the Internet users as produsers is important in this article because this term accentuates the agency of these users and distinguishes them from a purely consumptive "mob."

This increased emphasis on the importance of participants in knowledge production is one reason that neogeography, enabled by Web mapping services and applications, might help to reduce the gaps that have in the past divided the public, researchers, and policymakers (Peluso 1995; Bailey et al. 2006; Mason and Dragicevic 2006; Parker 2006; Walker et al. 2007). In producing environmental data, citizen scientists become agents in the decision-making and policymaking process. The desire to utilize geospatial technology for more inclusive environmental decision making and management (Elwood 2006, 2007; Dunn 2007; Dunn et al. 2007) is evidenced in numerous projects, including the areas of habitat restoration, public health, environmental planning, water quality monitoring, and wildland fire management (Sisk et al. 2006; Driedger et al. 2007; Morehouse and O'Brien 2008; Ghaemi et al. 2009). The cited examples seek to use geographic information systems (GIS) to incorporate the opinions of stakeholders into the decision-making process (Obermeyer 1998; Rinner, Kefller, and Andrulis 2008; Simao, Densham, and Haklay 2009), and they illustrate the potential of collaborative tools to actively develop consensus (Dragicevic and Balram 2006; Nyerges et al. 2006). Many of these projects have developed mechanisms that allow data exploration, scenario testing, location-based commenting, or place-based discussion forums (Peng 2001; Rinner, Kefller, and Andrulis 2008); some have also noted the advantages of using free and open source technologies to develop these tools (Greene et al. 2007; Gouveia and Fonseca 2008; Hall et al. 2010). Experiences from researchers in participatory GIS (PGIS) show that GIS can have various benefits for different phases of the decision-making process (Jankowski and Nyerges 2001), but further exploration is still needed to understand the role of VGI in research and environmental monitoring and decision making.

These examples suggest that with the aid of information technologies and Web 2.0 principles, neogeography has actualized a wider range of citizen science opportunities through online Web mapping services and applications. The role and agency of citizens in producing environmental data and engaging in environmental monitoring has been affirmed by an increasing number of citizen science environmental projects. By validating the epistemic position of citizen scientists, the value of environmental data produced by citizen scientists is affirmed by extension. It addresses some of the remaining doubts about this methodology in contrast to the expert-driven knowledge production paradigm. In fact, in a robust citizen science project, the redundancy of data and information can serve as a peer-reviewing, self-correcting mechanism, thus improving the accuracy and reliability of such information. What kinds of data and how are such data produced when citizen science projects take advantage of VGI and Web 2.0? As discussed in the next section, knowledge discovered within this context can be specialized or general, targeted or distributed, and with intentional or unintentional interaction between a user and a project.

VGI and Knowledge Discovery

Examples of PGIS illustrate the epistemic contribution of GIS to participatory models. Many citizen science projects have also benefited from the collaborative environment facilitated by GIS. The realm of VGI shows promise for information gathering and consensus building in citizen science by utilizing broader methods of crowdsourcing. Researchers can use VGI to amass the knowledge of the public, who are often best positioned to provide information that requires indigenous experience, esoteric understanding of a physical environment, or up-to-date information about local conditions (Flanagin and Metzger 2008). The time sensitivity of environmental monitoring efforts often requires rapid action. Local knowledge and crowdsourced skills that manifest in VGI offer particular promise for time-sensitive and emergent phenomena, such as disaster management (Goodchild 2007; Elwood 2010; Longueville et al. 2010; Poser and Dransch 2010). Obtaining timely data can be difficult in these cases, as spatial information is often limited by weather conditions, return rates of sensors, and time demands of traditional geographic methods. In contrast, VGI can be supported by a distributed network of humans functioning as technicians and sensors in real time. Acting in this manner, neogeographers can rapidly create data sets for large areas and develop databases that could support time-sensitive endeavors, such as during disasters (C. C. Miller 2006). Disaster management during recent earthquakes in Haiti has demonstrated the efficacy of VGI to rapidly gather information and leverage volunteers. Following the earthquakes that struck Haiti in January 2010, rescue workers did not have complete or accurate street maps for the area, but neogeographers contributing to OpenStreetMap (OSM), were able to quickly create road maps of the area (http://wiki.openstreetmap.org/wiki/WikiProject_Haiti, last accessed 10 April 2011). Similar applications were used to communicate information during fires in Southern California in the summer of 2008. During these fires, several maps were developed that used collaborative tools in Google Maps to share information regarding locations of fires, road closures, and aid locations (http://googleblog.blogspot.com/2007/10/southern-california-fire-maps.html, last accessed 10 April 2011). Examples from disaster management illustrate the potential of VGI to coalesce crucial information from a diverse public across large areas, even during situations that could hinder information flow.

Despite this promise, the role of VGI within research fields remains narrow, as it mainly focuses on project-specific environmental data directly generated by intentional participants. The prior examples are structured and goal oriented, but VGI often also comes in less organized formats. Although citizen science and environmental monitoring projects often require data gathered in the former manner, others might benefit from an exploratory process of geographic knowledge discovery (GKD), in which data mining methods are used to extract information from spatial databases (C. C. Miller 2006). Such methods might help to distinguish useful information from noise and generate useful data for academic research, including environmental monitoring. Considering this option, researchers can gather VGI in two ways: (1) solicit information for an explicit purpose directly from relevant environmental data produsers or (2) glean the relevant information from alternate sources that are not specific to a particular environmental project. A hybrid approach, which depends on pooled information from multiple sources, could benefit environmental monitoring projects by revealing knowledge in disparate data sets. The following exploration of the many modes by which neogeographers interact with locational information elucidates the different relational structures between produsers and a scientific database, also revealing potential means by which these data can be linked.

Multimodal Interaction with Locational Information

The increasing access to and complexity of spatial technologies has changed the way in which users interact with spatial information, how developers create content, and how researchers compile data. The new modes by which produsers interact with information poses opportunities for researchers to extend citizen science efforts and to reimagine public participation. The array of intuitive Web mapping tools with which the Web-going public has great familiarity has afforded citizen scientists a direct way to produce and contribute environmental data for specific projects. Direct map annotation with points, lines, or areas (in contrast to spatial data collection via paper, digital forms, or traditional geocoding) has sped up VGI considerably (Lee, Quinn, and Duke 2006; Goodchild 2007), particularly in areas that are not on a street network or that do not geocode well. This kind of directed production of data toward a specific project is common in citizen science and can be characterized by produsers' high intentionality. Here, we consider intentionality in terms of a produser's intentions to provide geographic information for a particular end use. Low-intentionality scenarios are increasingly common as interoperability among spatial technologies facilitates the transfer and reuse of spatial content among services. Initially, as with many emerging technologies, the rush to develop Web-based mapping tools led to an array of programming and file structures. The Open Geospatial Consortium (OGC) formed to address these divergent technologies and to create interoperable standards. These standardizations have allowed data of various formats and from many different sources to be shared between both proprietary and open source software and have created opportunities for the greater distribution of spatial information (http://www.opengeospatial.org, last accessed 10 April

2011). This increase in interoperability offers great potential for sharing and reusing data that might not be targeted toward a particular project. For example, a syndicated, geotagged photo stream from Flickr could be reused, after filtering the data, for environmental monitoring purposes without the original user intending to contribute to such a project. Thus, a user of one technology might be unknowingly supporting content elsewhere. This exchange of spatial information has also been supported by open application programming interfaces (APIs). One of the most prominent examples of an open API is the Google Maps API released in 2005, which popularized a new trend of Web applications called *mashups* (C. C. Miller 2006). Google Maps mashups display data from other sources within the Google Maps interface and atop Google's base layers. Although the Google Maps API is only one of the many technologies that have contributed to Web mapping—others include OpenLayers, MapServer, and Yahoo! Maps—it is the most prevalent and is related to the increased focus on the spatialization of information (Skupin and Fabrikant 2003; Crandall et al. 2009) and the increased familiarity with maps among the public.

Although these changes in data standards and software have created new modes of interaction, radical changes in hardware have also supported a growth in VGI. A growing mode of interaction with location information is to use real-time location information via software applications on location-aware mobile devices. Software development kits (SDKs) for location-aware mobile devices, specifically GPS-enabled smart phones, have led to a torrent of location-based services (LBSs) and subsequent VGI. Many LBSs, such as Gowalla and Foursquare, are a form of social media that allow users to communicate locational information to friends. Contributions of location information to these services, however, could also be utilized for marketing services, of which produsers are unaware, in which case they had low intentionality for this application of their VGI. The concept of intentionality can be further differentiated between contributions to geographically explicit projects, which specifically target geographic content, and geographically implicit projects, which gather geographic information without this being the main focus (Antoniou, Morley, and Haklay 2010). As presented here, the lowest degree of intentionality is displayed when a produser submits a piece of Web content with locational information to a geographically implicit service, but this locational information is then used elsewhere. For example, Twitter, which is a social networking and microblogging tool, has recently added a geotagging feature to its service, allowing users to associate their current locations with their messages, or tweets. The mode of interaction is considered to have low intentionality because the location information added to a tweet is simply an extra piece of information attached to these data and not intended to be used in a specific GIS or database. Nonetheless, content from Twitter and Flickr have been extracted and analyzed to explore a range of topics, including public concern surrounding H1N1 (Chew and Eysenbach 2010), and place and event semantics (Rattenbury, Good, and Naaman 2007), and notions of place (Dykes et al. 2008).

These examples display possible applications of LBS and VGI for research endeavors, but these approaches have yet to be applied extensively in environmental monitoring. As this type of locational information becomes more prevalent, it necessitates new methods to mine and filter relevant and useful information for environmental monitoring projects. The locational information produced by neogeographers, in spite of lack of intentionality, is valuable for many applications, and it is already being actively mined for marketing purposes to support a growing interest in location-based advertising. This commercial interest in spatial information is likely to fuel further development and result in a growing pool of information. Thus far, entrepreneurs and technologists have championed development of these technologies and the research community has been slower to adopt them, despite their potential to generate information. The limited examples of research-oriented LBS, which include applications for epidemiology (Aanensen, Huntley, and Feil 2009) and ornithology (eBird), demonstrate that these tools can be useful in providing powerful collaborative tools to researchers and the public. Consideration of these many modes of interaction, in the context of intentionality, content types, and produser background, can help researchers to realize the social and technological promise of neogeography for citizen science. In the next section, we present a conceptual model to link all of these components and to inform design of environmental monitoring projects.

A Conceptual Model of Web-Based Environmental Monitoring

To summarize the complex relationships among citizen science, VGI, and environmental monitoring and the various routes of knowledge production and interaction, and to visualize and explore them with more

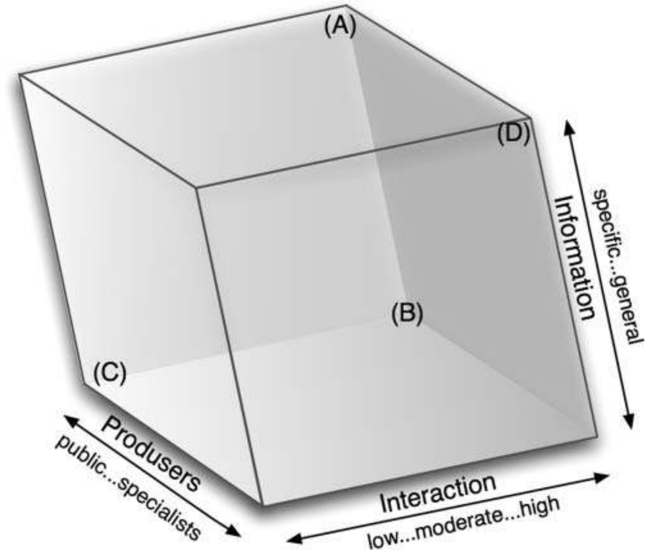


Figure 1. Conceptual model of the intersection between volunteered geographic information, citizen science, and environmental monitoring. Positions on the cube include (A) public citizen science projects with high specificity in terms of data collected and requiring high intentionality and interaction with the database from the produser; (B) public citizen science projects that collect general data; (C) projects that use location-based services on mobile devices and are often anonymous; and (D) expert-driven, targeted environmental monitoring projects not typically broadly accessible outside of their constituent communities.

specificity, we have developed a conceptual framework (Figure 1), refined from both MacEachren's visualization cube (MacEachren et al. 2004) and Dragicevic and Balram's (2006) collaborative GIS cube. Each of these models articulates gradients that help to refine and display the concept in question. The collaborative GIS model focuses on gradients of participation, map usage, and technology; for geovisualization, the model displays gradients of knowledge construction, interaction, and users. Our model (Figure 1) of Web-based environmental monitoring concentrates on gradients of users, information, and interactions. In this model, produsers can be general users or specialists: members of the public, trained and focused volunteers, scientist monitors, or regulatory officials. Users' relative interests can vary, and the information they provide ranges from specific to general for a particular environmental project or issue. Interaction is defined by the degree to which a user intends to contribute to a database for a specified purpose. Intentionality can be very high if the data users provide were directed at a specific database in a particular project, or low, if it was directed elsewhere. A user might simultaneously have high intentionality for one purpose but low intentionality for another; thus, intentionality must be defined in terms of a specific project.

A few examples from the spectrum of citizen science, VGI, and environmental monitoring help to illustrate the model. First, consider a commonly cited example of citizen science in the United States, eBird, which provides an online community for birders to report observations (Sullivan et al. 2009). This is a public endeavor, with high specificity in terms of data collected (e.g., specific bird species) and requiring high intentionality and interaction with the database from the produser. A similar example is provided by the "What's Invasive!" project, maintained by the Center for Embedded Networked Sensing, a research unit within the University of California, Los Angeles. This project is a citizen science campaign that lets anyone with an Android phone help National Park Service rangers find invasive plant species anywhere in the country. This is a public project, supporting the collection of general data (across a range of invasive taxa and species), and with high intentionality. Projects like eBird and "What's Invasive!" are located on Figure 1 in positions (A) and (B), respectively, where most traditional citizen science projects are situated and differentiated by the specificity of information collected.

These examples can be contrasted to several recent developments in LBS on mobile devices, which are largely targeted at individual users but can reveal new information when data are aggregated and analyzed, often in anonymous form (Ratti et al. 2006; Antoniou, Morley, and Haklay 2010; Longueville et al. 2010; Friedland and Choi 2011). For example, Ratti et al. (2006) collected sixteen days of geo-located cell phone activity in the metropolitan area of Milan, Italy, and highlighted urban population flow dynamics during a holiday fortnight, unbeknownst to the phone users. Similar examples are seen in the proliferation of geotagged information available on Twitter, YouTube, Flickr, and Craigslist, which can be easily mapped without the author's knowledge through public APIs. These creative uses of aggregated geotagged data do have a sinister side, highlighted well by Friedland and Choi (2011) and termed *cybercasing*. These agglomerative kinds of activities are located in position (C) on Figure 1.

Finally, some services are designed exclusively for researchers providing specific data to a project. An example of this would be the CAIDA (http://www.fs.fed.us/r5/spf/fhp/fhm/atlas/index.shtml, last accessed 10 April 2011), a database of pest outbreaks across Forest Service lands, for which the data were provided by trained samplers.The information is specific and intentionality is high. Often, projects of this type are utilized to share information in a research community, such as the Berkeley Natural History Museum's Specimen Search (http://bnhm.berkeley.edu/query/index.php, last accessed 10 April 2011), which provides researchers with a means to plot and query the geographic origins of the museum's collection. These kinds of expert-driven, targeted environmental monitoring projects are placed in Figure 1D. These have not typically been made broadly accessible outside of their constituent communities.

Citizen science can take advantage of VGI and merge with expert data collectors, and this synergy will occupy a larger portion of the environmental monitoring space. There are benefits and challenges associated with this synergy, and we present OakMapper as a case study to examine and discuss many of the core issues and new challenges presented by the intersection of citizen science and VGI in the context of environmental monitoring. OakMapper is a hybrid geographic information platform that provides multiple pathways to contribute and to access data about a highly visible invasive forest disease. The system is built using a range of open source and proprietary information technologies that aim to increase our user base, access to information, and general awareness of the disease.

Case Study: OakMapper

In this article, we demonstrate a flexible system in an environmental monitoring context that harnesses the multiple benefits of citizen science and VGI and uses pooled information from multiple sources: public, scientific, and regulatory. We address the resulting benefits and challenges (Table 1) associated with such an approach. The process of monitoring environmental issues in a public context also shares these benefits and challenges, and any framework developed to utilize the public in a Web-based and science-focused monitoring endeavor requires their consideration. The tool set presented here takes advantage of public familiarity with Web mapping and LBS to recruit direct contributions from the public, while also gleaning information from exogenous data sources. Our example, OakMapper.org, is presented to illustrate a collective public–private organizational structure that might be used for other environmental problems that are widespread, visible to the public, and spatial in nature. We review the important features of this project by connecting them back to the data model cube described earlier to concretize and operationalize this conceptual model. Our case study also serves to examine the numerous tensions—the questions of motivation, authority, reliability, and access (Goodchild 2007; Budhathoki, Nedović-Budić, and Bruce 2010; Coleman 2010)—that inevitably arise with VGI and within the context of environmental monitoring.

Table 1. Benefits and challenges raised by the intersection of citizen science and neogeography

Benefits	Challenges
Support development of early warning system	Data credibility, quality, consistency
Ability to leverage volunteers	Metadata standards
Increased scale of coverage	Unpredictability
More informed public	Bias and motivation
Increased cooperation	Perceptions of surveillance
Active consensus building	Reinforced authority and differential empowerment
Community and social networking	Access and the digital divide
Support massive data flows	Technical challenges

OakMapper 1.0 and Study Area

A newly introduced pathogen *Phytophthora ramorum* has caused substantial mortality in several tree species along the coast of California and southern Oregon. The disease, called *sudden oak death* (SOD), presents threats to the ecology, wildlife habitat, and aesthetic value of thousands of hectares of forest (Rizzo and Garbelotto 2003; McPherson et al. 2005). Evergreen and tanoak/redwood forests within the coastal fog belt are the primary habitat, with California bay laurel serving as a vector for disease propagation in wild settings. Infected nursery stock can also influence spread, and susceptible habitat and hosts for the pathogen exist throughout the conterminous United States (Kelly et al. 2007).

The public remains interested in the disease and, early in the infestation, information from active and interested private citizens played an important part in locating new areas of infestation across the state (Kelly and Tuxen 2003). In 2000, a statewide task force called the California Oak Mortality Task Force was formed with membership drawn from government agencies, university researchers, practitioners, and the public, in part to answer the numerous questions about the disease and to coordinate the public and government involvement in monitoring the disease. We created the first OakMapper Web site in 2001 as part of this outreach strategy and developed a Web GIS to coordinate and distribute all SOD spatial data. The earlier OakMapper was developed using ESRI's (2008) ArcIMS and provided interactive mapping technology for users to query data, visualize disease spread, and enter information on likely spots for SOD using a separate Web form, from which volunteered addresses were geocoded individually and added to our databases (Kelly and Tuxen 2003). In this early configuration, each element of the Web site (spatial data, mapped products, volunteered information) existed independently and required routine maintenance to remain up to date. All of these resources were dependent on a project administrator to manually update their source data and reload the content to the Web site on a quarterly basis. This method was not only time consuming but was also susceptible to errors and inconsistencies between resources. Meanwhile, contributors needed to discover our site and were restricted to providing data in a textual format, including geographic information in the form of latitude–longitude, via an online form. The first incarnation of OakMapper was tightly constrained to the upper corners of the data model, as shown in Figures 1A and 1C.

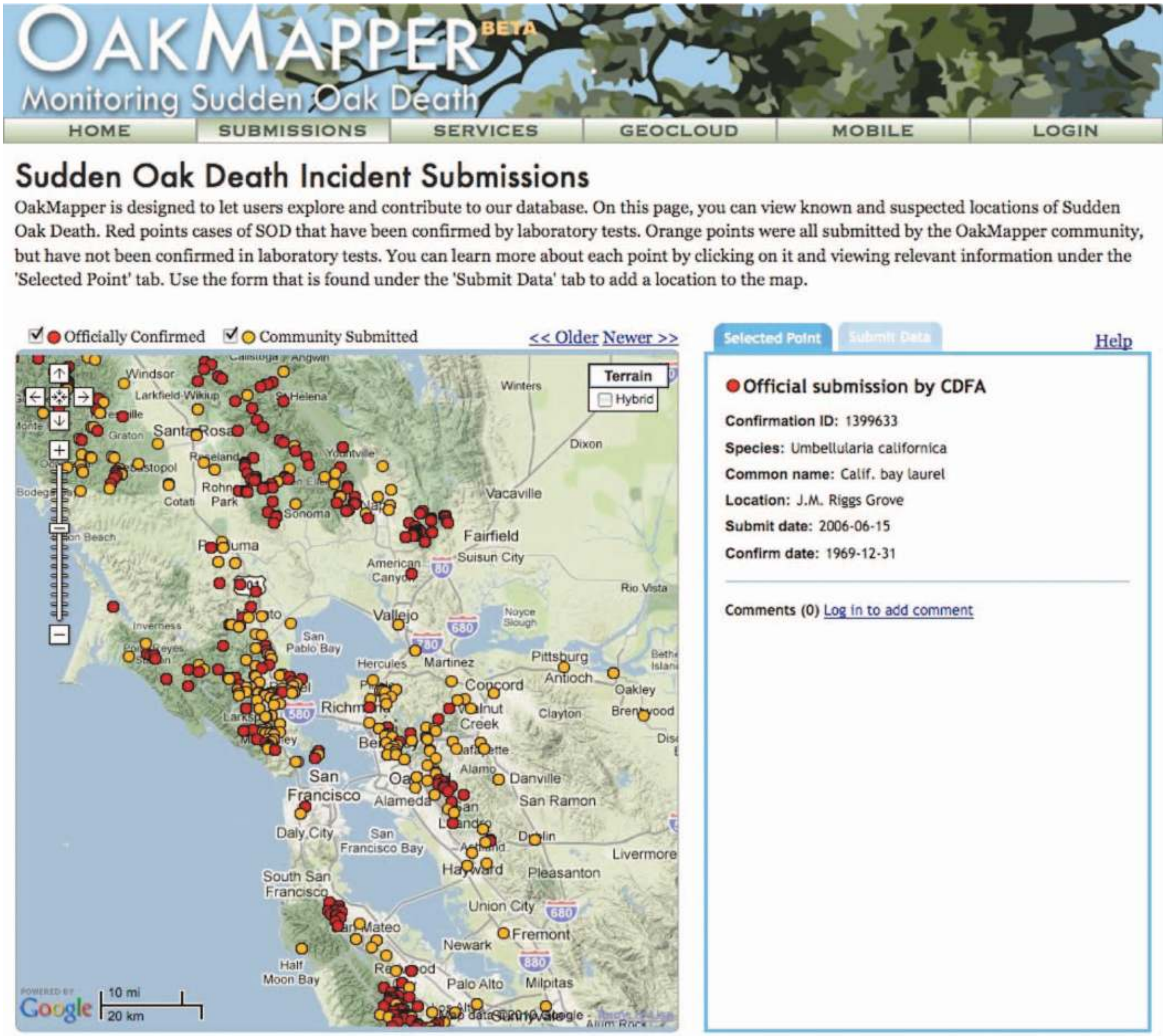
OakMapper 2.0: Harnessing VGI

The new version of OakMapper is intended to fully capitalize on the emergent culture of VGI as well as the advancement in Web and GIS technologies. To fully utilize these resources, we first considered our target user group, the means of interaction with the system, the data set to be supported, and the state-of-the-art for information and geospatial technologies. These objectives all correspond to greater coverage of the model's three axes. We also made the following assumptions about the system from our past experience: (1) a well-designed geospatial tool set can serve the needs of and facilitate communication between the research community and lay persons; (2) vast amounts of spatial information are in constant production on the Web, and some of it is useful for environmental scientists; and (3) private citizens are familiar with and interested in mapping tools and will contribute information with them. Based on these goals and assumptions, we created a Web site to gather and distribute information regarding SOD. From a practical standpoint, we were concerned with the site's *usability* (ease of operation by users with varying levels of GIS or Web experience), *integrability* (ability to interact across multiple applications), and *scalability* (low development cost and ease of future development for growth) and sought to employ practices that addressed these concerns. Above all, OakMapper was designed to utilize new technologies to increase data flow and to enhance produser experience. In the remainder of the article we utilize OakMapper as a platform for discussion regarding neogeography and environmental monitoring. First we highlight some of the basic design elements of OakMapper and their intended benefits for produser experience, then we review our handling of VGI and the supporting technologies, and finally we discuss the implications of these technologies in the context of critical GIS.

Produser-Centered Design

OakMapper 2.0 was designed with a focus on usability and simplicity (Newman et al. 2010), particularly with regard to creating an environment that would ease the creation of geographic content. The user-centered design approach is critical for citizen science projects because users serve as conduits for data. Therefore, users should be able to navigate through OakMapper without any stumbling blocks inherent in the design of the system. As such, we sought to develop tools that would appeal to researchers and scientists, neogeographers with varying degrees of experience with GIS tools, and the general public. Older generations of Web GIS applications targeted GIS experts and maintained the appearance and behaviors of a traditional desktop GIS. More recently, Web mapping tools have developed to serve a lay population. Advanced GIS and Web GIS software serve experienced GIS users in advanced mapping and analysis tasks, but they set a high barrier for novice users. Elwood (2006) acknowledged such technological barriers as a continuing issue of access, by preventing lay people from engaging in participatory GIS. To reduce this obstacle to novice users, we designed tools with simple interfaces to easily access and input data, allowing them to quickly assume the role of produser. We use the term *produser* in these sections mainly for the ease of interchangeability with common expressions that use the word *user* (e.g., user experience), but it should be noted that our main concern is with the subgroup of neogeographers.

The OakMapper Web site is centered on an interactive map, which serves as a portal to a single spatially enabled relational database (Figure 2). The map serves as a powerful tool for data exchange on the Web, providing produser-focused benefits such as visualization and simultaneous access to multiple layers of spatial data. OakMapper utilizes the Google Maps interface



Sudden Oak Death Incident Submissions

OakMapper is designed to let users explore and contribute to our database. On this page, you can view known and suspected locations of Sudden Oak Death. Red points cases of SOD that have been confirmed by laboratory tests. Orange points were all submitted by the OakMapper community, but have not been confirmed in laboratory tests. You can learn more about each point by clicking on it and viewing relevant information under the 'Selected Point' tab. Use the form that is found under the 'Submit Data' tab to add a location to the map.

● **Official submission by CDFA**

Confirmation ID: 1399633
Species: Umbellularia californica
Common name: Calif. bay laurel
Location: J.M. Riggs Grove
Submit date: 2006-06-15
Confirm date: 1969-12-31

Comments (0) Log in to add comment

Figure 2. The mapping page of the OakMapper Web site showing a close-up of the San Francisco Bay Area: Red dots are official confirmations, yellow dots are locations submitted by the community. (Color figure available online.)

and base layers to offer familiar, but customizable, map visualization and tool sets to the public. The Google Maps Viewer also offers rapid rendering of maps, reducing load times that could discourage participation and limit content. To the right of the map, a panel displays data submission forms and location-specific information, such as descriptions of the site characteristics, disease symptoms, and comments. Unlike common map pop-up bubbles, the side panel can easily display greater amounts of information without obscuring the map and allowing the produser to remain in constant contact with the map. The Google Maps interface collects specific data from a range of produsers in a high intentionality environment.

Participation, a hallmark of Web 2.0, is realized on OakMapper as contributions of geospatial information and interaction with map-based content. Integration of our Web site with other services, such as our LBS for iPhone, Flickr, and Twitter, allow for produsers to choose alternate modes of participation, while taking full advantage of hardware, such as cameras and GPS devices that produsers have at their disposal. VGI and mashups challenge traditional concepts of participation by garnering resources from indirect contributions and allowing integration of additional media. Our design is not tailored to the interests of these unknowing contributors, as they are already employing outside tools to contribute SOD-related data. Instead, we focus on the compilation of this information for produsers seeking SOD-related data from disparate sources in a single location.

OakMapper's target audience is comprised of distinct user groups, including scientific researchers, agency officials who provide laboratory-confirmed cases, and the general public. Some of the users are known to have experience with GIS, but the site assumes that most have no or limited knowledge of GIS. The majority of the features on OakMapper are intended to serve all user groups, regardless of background or experience, but some capabilities provide for unique needs of researchers and government agents. We manage the needs of different user groups by creating permissions levels for individual accounts. Users are asked to create a profile when they submit data to OakMapper and to self-categorize their background as public, academic, or government. The OakMapper administrator can grant official status to some users, offering all of the features of community status plus the ability to submit lab-confirmed points. This categorization is also used to catalog points as either community submitted or official-submitted. Discrete separation of data is mainly for the research purposes, as some reporting is concerned exclusively with lab-confirmed points, and to address issues of uncertainty in VGI—this topic is discussed in greater detail in the final section of this article.

User categorization provides additional functionalities that associate a user's activities on OakMapper to his or her personal account. In the My Account section, users can modify their profiles and edit previous submissions and comments. These features were added to allow produsers to develop a relationship with the information that they are providing and to have a record of their personal contributions to the site. Finally, because OakMapper is a live "beta" site, in continual development in response to users' feedback and detection of application errors, we provide an online form for users to send comments or questions.

VGI Gathering and Sharing

Citizen science and VGI both leverage participation of volunteers to gather information and to foster public interest. The ontology of VGI predicates that it is geographic in nature and generated by volunteers; in contrast, citizen science refers to a practice, as opposed to the information itself. All citizen science projects involve volunteers and some have applied spatial tools (Kearns, Kelly, and Tuxen 2003; Delaney et al. 2008). Many of the current mapping tools for citizen science are purely for data display, but citizen science could also benefit from the emergence of VGI for crowdsourcing. OakMapper seeks to capitalize on the intersection between these two realms through application of spatial technologies that are already embraced by neogeographers and have displayed their capacity for collecting data and facilitating communication for nontechnical applications. This potential also exists for scientific endeavors, which can benefit from spatial tools as interfaces for data collection and facilitation of discussion between researchers and the public. One benefit of VGI for scientific research is recognition of different epistemologies through place-based data structures that integrate multimedia data that represent local knowledge through mapping, photography, and writing (Warf and Sui 2010). Some simple advances in technology, such as the addition of tools for produsers to create polygons on maps (as opposed to simply points) coupled with commenting, allow users to express their understanding of space beyond discrete locations.

Following the principles of Web 2.0 and citizen science, OakMapper gives prominence to user contributions of various formats from both official and public sources. Our interactive map at our Web site and in the iPhone application allows users to input point locations and polygons defining locations of suspected occurrences of SOD. Researchers and government officials entering data on official confirmations are distinguished from the general public by their user login and are granted access to an additional form. All users can report suspected cases of SOD in point or polygon format, and researchers and officials can submit data using the official form to identify points that have tested positive for *P. ramorum* in a state-certified laboratory. All of the features from the OakMapper database are displayed atop Google Maps base layers (terrain or hybrid views) and shown in red or orange circles, which indicate official confirmations or submissions from the public, respectively. The classification of points allows the public and researchers to consider authorship and authority when utilizing this data set. This format emphasizes that only official points are known to have SOD, whereas other points are only suspected to be infected. VGI is prone to inaccuracies and imprecision, but this distinction between types of points can serve as an indicator of confidence, such that red points have been validated and there can be a high degree of confidence in nearby orange points.

In addition to submitting points or polygons and information regarding suspected or confirmed cases of SOD, users can comment on previously submitted information. Only registered users in the system are allowed to make comments, so that all comments are traceable to their source. We used this design to encourage community building and help foster trust among the community members (Shneiderman 2000; Ba 2001; Marsh and Dibben 2003). Site-specific commenting facilitates communication between researchers and private citizens and can be used in error checking to flag suspect locations or to affirm the validity of other locations.

OakMapper's database is populated with information that is actively collected from neogeographers directly through the aforementioned tools, as well as VGI regarding SOD from exogenous sources. In doing so, OakMapper has increased draws from a greater area of the data cube, extending into more general and low-intentionality areas. Currently, we mine all photos that have been labeled with the tag "Sudden Oak Death" on Flickr and any Tweets that contain the term "Sudden Oak Death" on Twitter and display all geotagged points on a map. OakMapper draws from these sources to increase data flow and also to function as an information clearinghouse. The content from these sources varies greatly but often contains information that could be useful to researchers. Recently, photos that we have collected from Flickr have included geotagged images of individual symptomatic trees and larger landscapes suspected to be hosting the disease. Twitter posts are less commonly geotagged but often contain a geographic dimension, as they often specify locations within the text. For example, shortly after reports of SOD appearing in the United Kingdom, people began to post tweets regarding this discovery and have since been reporting on specific locations of infection. As discussed earlier, such data are characterized as low intentionality from produsers because its creation was not directed toward the OakMapper project. This low intentionality information is valuable to the OakMapper project because the aggregates of such data can reveal a pattern of public interests and can allow for reuse and centralization of geotagged photos of SOD on the map.

Supporting Technologies

Researchers are faced with the challenge of utilizing a wide array of tools to encourage participation and enhance data flow while also organizing this surfeit of information. OakMapper confronts this challenge by using open technologies, which facilitate software interfacing and data centralization. Open technologies refer to open source software (OSS), open specifications (OS), and open APIs. The term *open source* refers to a set of criteria regarding access to and licensing for software and its underlying code. Licenses for OSS allow the general public to view, modify, and freely distribute the source code and its derived works without including restrictions on the use or distribution of software (G. Anderson and Moreno-Sanchez 2003; Steiniger and Bocher 2009).

Projects meeting these criteria offer several advantages for developing research tools: (1) developers have full access to the working code and can customize it, (2) developers are not restricted to a particular work environment, and (3) free distribution reduces project expense. In addition, many open source technologies have large and passionate followings. Open source software does present several disadvantages, however, including participation and coordination of programmers and quality assurance of code base. If these challenges are not overcome, OSS could be highly susceptible to security breach by malicious hackers who can easily study the source code. Nonetheless, empirical studies show that OSS performs better in terms of software security than its closed counterpart (Payne 2002) through the efforts of communities of open source programmers who audit and maintain the code, as well as online forums and manuals (Von Krogh, Spaeth, and Lakhani 2003). Another potential disadvantage of OSS is the longevity of the software and its community, given that OSS is generally created by a small group of unpaid, dedicated programmers. To address this issue, the OSS chosen for this project, such as Apache, PostgreSQL/PostGIS, CakePHP (a framework for PHP), jQuery (a framework for JavaScript), and HTML/CSS, must have been actively developed, supported, and used for more than five years. Much OSS is experimental by nature, which means that the programs might contain bugs. To access the incremental updates to these software applications, adopters need to perform periodic maintenance updates themselves, which is an additional workload to a project.

Meanwhile, groups such as OGC and the World Wide Web Consortium (W3C) have created markup standards to provide guidelines for encoding spatial data, to increase portability across different applications and platforms, and to ensure interoperability between products (Moreno-Sanchez et al. 2007). Relevant geospatial standards include OGC's Geography

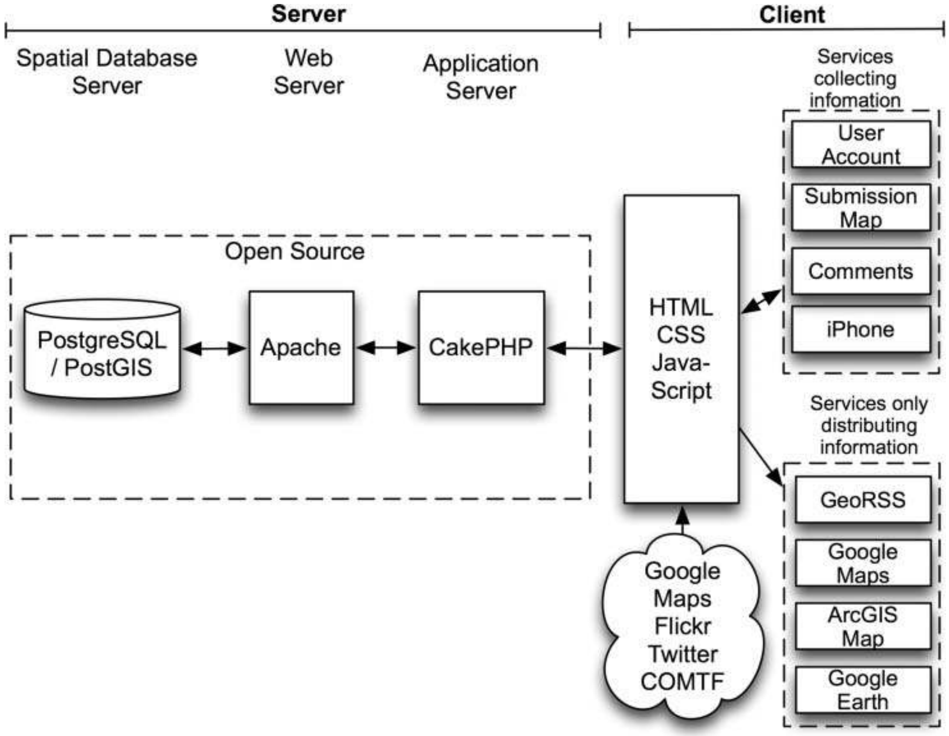


Figure 3. Open source database architecture showing the open source tools.

Markup Language (GML), GeoRSS, and Google's Keyhole Markup Language (KML). Specific OSS used in OakMapper is detailed in Figure 3 and Table 2.

Development of OSS, when coupled with open APIs, has led to the rise of the mashup, the creation of a new Web application or service by incorporating and integrating a number of external Web services. Developers can save time, cost, and resources by using features from other Web applications and services. For Web mapping applications, this provides the additional advantage that developers do not need to locate and catalog multiple cartographic layers, as most common base layers are accessible through APIs and are easily integrated with additional data. This kind of borrowing is also common for embedded objects such as videos, audio, and Flash objects originating in another Web application. Although these embedded objects are usually stand-alone features, they can enrich the presentation of a Web application by providing dynamic and interactive content. Researchers can utilize these tools to tap into other crowdsourced resources and multimedia content to support Web applications. OakMapper draws extensively on object embedding to insert elements provided by other Web services to our site and to create Google Maps mashups with Flickr images and geotagged tweets. These embedded objects also limit the developers' control over site stability, however, as all resources are not based on a single server. As such, it is advisable to only utilize trusted services with proven reliability.

OakMapper organizes SOD submissions (from the Web site and iPhone), Flickr photos, and Twitter feeds in a spatial relational database (Figure 4), in which each record can contain locational data in the form of geographic coordinates and data can be queried and analyzed spatially. The general structure of a relational database allows data to be readily utilized across platforms, with or without spatial information. As a result, a spatial relational database is highly portable and interoperable with many different kinds of GIS and non-GIS applications. Using such databases eliminates the need to manually populate multiple data repositories (e.g., shapefiles, Excel, Access, MySQL, and KML) and increases data consistency between tools while reducing the time spent on database maintenance—compared to maintenance of multiple formats not supported by a common database. A robust spatial database allows researchers to collect the vast amount of VGI from multiple sources in a single location.

OakMapper has also employed the iPhone SDK to create an application that allows users to submit data from the field. Within the framework of the SDK,

Table 2. Technologies discussed in the article

Software	Description	Web address
Web markup and design languages		
GeoRSS	Geographic Web feed language	http://www.georss.org
CSS	Cascading Style Sheet	http://www.w3.org/Style/CSS/
HTML	Web markup language	http://www.w3.org/TR/html
JavaScript	Scripting language	https://developer.mozilla.org/en/JavaScript
jQuery	JavaScript library	http://jquery.com
KML	Keyhole Markup Language	http://www.opengeospatial.org/standards/kml
RSS	Web feed language	http://www.rssboard.org
GML	Geography Markup Language	http://www.opengeospatial.org/standards/gml
Server software		
Apache	Web server	http://www.apache.org
CakePHP	Application software	http://cakephp.org
PHP	Scripting language	http://php.net/index.php
Related Web sites and services		
Flickr	Photography sharing site	http://www.flickr.com
Twitter	Microblogging service	http://www.twitter.com
Google Maps	Google online maps service	http://www.google.com/maps
Yahoo! Maps	Yahoo! online maps service	http://maps.yahoo.com/
Database and geographic information system application software		
PostGIS	DBMS spatial extension	http://postgis.refractions.net
PostgreSQL	DBMS spatial extension	http://www.postgresql.org
OpenLayers	JavaScript library for map data	http://openlayers.org
MapServer	Geographic data rendering engine	http://mapserver.org

Note: All software last accessed 10 April 2011. DBMS = database management system.

developers can access various tools that are built into the iPhone, including its GPS, map functionalities, and camera. Using the phone's built-in GPS, the OakMapper application allows produsers to add locations to our database using their current position. This innovation has powerful implications for citizen science projects because it allows participants to utilize their own phones as a research instrument.

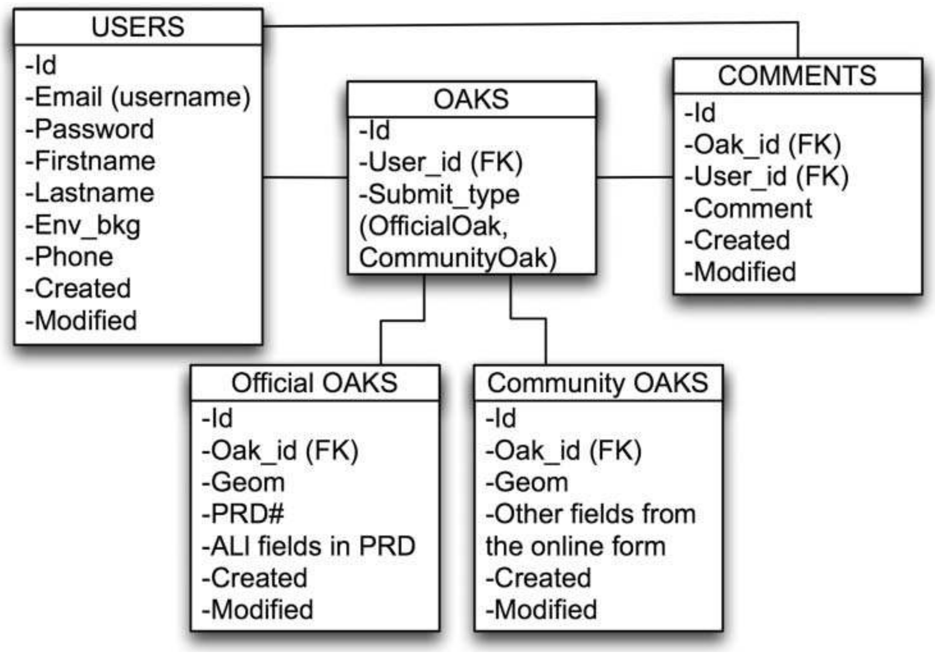


Figure 4. The OakMapper data model.

Current Use

Since its launch in December 2008, OakMapper 2.0 consistently receives about 200 visitors per month. During this period, produsers have given twenty-six submissions of unofficial points and forty-nine have registered at the site, including four government officials. Among the public participants, seventeen did not specify a background, seventeen specified that they are academics, and eleven indicated that they are from other fields. Of the registered users, fourteen have submitted data and three have submitted multiple points. Additional locations were submitted anonymously. Including data collected from the previous version of OakMapper, the database contains a total of 663 unconfirmed community-submitted points and 1,134 officially confirmed points.

OakMapper began downloading Twitter feeds tagged with "Sudden Oak Death" in April 2010 and has acquired 287 Twitter feeds in that short period, including twelve geotagged points. Many of these tweets regard reports of the appearance of SOD in the United Kingdom, which the authors of this article first learned of from these posts. In the same time, OakMapper has downloaded 107 geotagged Flickr photos with the tag "Sudden Oak Death." The majority of the Flickr photos are located in Northern California, but many have also recently appeared in the United Kingdom. Nearly all of the photos depict trees with visible symptoms of sickness, but other photos show restoration efforts and researchers in the field. The iPhone app was released in October 2009 and has been downloaded ninety-four times, but few points have been submitted using the application.

These differences in activity from each channel display the possibility for data integration. Even as the OakMapper site has seen a slower rate of contributions, we have been able to extract information from Flickr and even greater activity around SOD has occurred on Twitter. If we treat this information as a potential data source and combine it with contributions to the OakMapper site, we are able to increase our data set for understanding the spread of SOD. This information is also valuable to better characterize public interest and target outreach efforts. Twitter and Flickr users are unknowing contributors to OakMapper but could also be actively recruited to the OakMapper community to increase the number of direct contributions.

Our external data resources have not yet been applied for analysis, but the OakMapper Web site and the database have been used for a variety of scientific purposes. The OakMapper database and Web site have been mentioned in a number of recent scholarly articles, largely in two areas of research. First, the OakMapper database has been used as inputs to environmental niche models to predict the current and possible range of the pathogen *P. ramorum* (Guo, Kelly, and Graham 2005; Kelly et al. 2007; Kluza et al. 2007; Magarey et al. 2008). Second, the Web site has been used as an example of emerging technology in support of participatory forest management (Kelly, Tuxen, and Kearns 2004; Ward and Johnson 2007).

Future Directions

The previous sections highlighted the technical and conceptual underpinnings of OakMapper and introduced some of the critical issues surrounding their implementation. Further development of OakMapper will focus on increasing the functionality of these tools and increasing their specific utility for citizen science, remaining attentive to issues of access, representation, epistemology, and power. The current design of OakMapper is intended to be flexibile and expandable. In a practical sense, this will mean developing new tools that are readily accessible to larger portions of the public and making efforts to reduce impacts of information gleaning.

We envision the addition of several other features in the future to provide increased access and an improved produser experience. Given the diversity of groups interested in SOD, OakMapper would also benefit from developing new pathways for transmission of data. The centralized database is capable of serving and receiving information from additional platforms, such as other mobile devices or ArcGIS (ESRI 2008). Since its inception, OakMapper has provided researchers with shapefiles of SOD locations. Our new design could enable researchers to connect directly to our server within ArcGIS or other GIS packages to obtain the most up-to-date data sets. To enable a greater number of users to partake in the LBS side of OakMapper, we could also utilize Short Messaging Service (SMS) to receive data and expand access beyond the iPhone to other smart phones, such as those with the Android OS, by creating applications for these devices or creating mobile-specific Web-based applications.

Given the often personal nature of photography and blogging, we are exploring means of opting out of data collection. When data are obtained from an outside source, an automated message could be sent to the creator to inform them of this reuse. An alert system such as this could also have the added benefit of outreach; produsers could be introduced to OakMapper through this alert, and some might choose to add more content or place relevant tags on more of their content. The statistics on usage for OakMapper indicate that the site must make greater outreach efforts to build its user base.

Discussion

In this article we have lauded VGI and citizen science for their ability to foster participation and in turn to generate important data across broad spatial scales for scientific endeavors. There are important issues to consider regarding the data itself, however, such as who is involved in its creation and who controls its use. We discuss these issues in this section to consider limitations to the use of VGI and to foresee challenges that practitioners will face. Within this context, we then consider how issues of access and representation might affect the content captured by VGI and explore the motivations of participants. Throughout the discussion, we critically assess the case study.

Citizen science poses a unique set of challenges regarding accuracy and uncertainty, particularly when data are collected by an untrained public. VGI is particularly susceptible to error and can result in inaccurate or imprecise spatial information (Flanagin and Metzger 2008; Goodchild 2008; Seeger 2008). This can be due to technology, training, or intention. Neogeographers might accidentally misrepresent information due to lapses in memory or misinterpretation of maps or intentionally misrepresent information for personal purposes. The accuracy and origins of VGI and underlying data can be difficult to discern due to a lack of metadata standards common to traditional data sets. Data produced in this environment might also be prone to misregistration due to inaccuracies in the base layers, such as a known datum shift in Google Maps (Goodchild 2007). Thus, there is a need to understand the role of data screening and assessment in applying VGI for research purposes. Many of the previously identified challenges facing PGIS, including the need for evaluation and effectiveness (Sieber 2006), are relevant to applications of VGI for citizen science. Nevertheless, these issues of accuracy are irrelevant without participation, and researchers must actively recruit the public's contributions to ensure consistent data flow (Peng 2001). When accessing multiple information channels, potential trade-offs exist between data flow and accuracy, which must be addressed for individual projects.

These differences in accuracy are increasingly recognized as characteristic of VGI (Girres and Touya 2010; Haklay 2010; Haklay et al. 2010). Goodchild (2007) mentioned this in the context of the new map "patchwork" paradigm, in which the accuracy of each piece of the patchwork, and the frequency with which it is updated, can be determined by local need. Thus, solutions to issues of quality control will depend on the needs of a project and the applications of the data set and can vary within the project itself, across space or user. For example, OakMapper separates laboratory-confirmed points, which are held to a higher degree of scrutiny, from other points (no matter the user's status). In this manner, we can have different quality expectations for each data set and each can be used for different purposes. With our current data flow, site administrators can easily monitor for and remove blatant inaccuracies and keep track of comments that indicate suspect points. Given a critical mass of participants, accuracy assessment could take on a wiki approach, where produsers collaboratively identify and remove inaccurate information.

For projects that require highly specific information, the accuracy of the data might be affected by the experiences and education levels of the produsers. Delaney et al. (2008) found a correlation between level of education and accuracy of reporting from citizen scientists identifying an invasive crab species, with 95 percent accuracy from participants with two or more years of college education. This relationship between education and accuracy creates a possible conflict of project goals: It is desirable to have university-educated individuals participate if they are more likely to provide accurate data, but we wish to engage a diverse segment of the public in citizen science, regardless of education levels. Greater recognition of different epistemologies might help us to find a compromise between these seemingly conflicted interests. Integration of other ways of knowing from VGI, such as narrative data and photographs, could reveal broader environmental and social impacts of SOD. In this manner, citizen science can learn from the efforts of PGIS to create new roles for the public in gathering spatial information (Weiner and Harris 2003; Elwood 2006) that extend beyond quantitative forms of knowledge that are most easily translated into a GIS format (Pickles 1995). In doing so, scientists must also consider the goals of the data and continue to discriminate between data that are suitable for spatial modeling, or other quantitative tasks, and other types of information, which could broaden the understanding of a phenomenon. Ultimately, these goals will determine the level of specificity of the information that researchers gather. Specific information might be easier to evaluate for accuracy and allow for a higher degree of scrutiny than general information.

Our proposed hybrid approach to data collection poses issues beyond accuracy, which must be carefully considered. Issues of access, power, and control of information addressed by critical GIS (Harris and Weiner 1998) have gained new relevance with the growth of VGI and are particularly relevant to these methods. Despite the perceived democratization of information with Web 2.0, concerns over access and biased representation in spatial information persist. Although 70 percent of households in the United States have access to the Internet (Watson et al. 2008), general usership displays a heterogeneous pattern with great variations in adoption by race and area (Chakraborty and Bosman 2005). Similar disparities are apparent in the spatial distributions of posts on Google Maps, which have revealed a bias toward high-income locales and tourist destinations (Crutcher and Zook 2009). This bias echoes the arguments in critical GIS that socioeconomic forces regulate the flow of spatial information even when information control is divested from centralized institutions. The research community must consider these concerns while exploring applications of these methods and addressing the need for GKD methods (H. J. Miller 2010). Although VGI offers the promise of democratizing GIS by engaging large numbers of public contributors, issues of access remain relevant. These issues are well-documented in the Web GIS and participatory GIS literature (Sieber 2003; Chakraborty and Bosman 2005), but they merit mention with regard to emerging mobile technologies and in the context of citizen science. Smart phones in general represent about 23 percent of the mobile market, with iPhones representing about 5 percent of the entire mobile market (Comscore 2010). Our iPhone application has yet to be implemented on any other devices, posing technological and financial barriers to participation. Thus, we might want to explore SMS as an additional means for cell phone users to submit data from the field. Unequal access is particularly important for citizen science, as it will also affect sampling and ultimately limit the applications of a data set.

The phenomenon of corporate control of spatial data acquisition devolving to a more distributed model, exemplified by OpenStreetMap, is discussed at length within arguments about neoliberalism and political economy (e.g., Goodchild, Fu, and Rich 2007; Coleman 2010; Zook et al. 2010). Few have asked what these trends mean in the context of environmental monitoring and questions necessarily arise. What are the benefits and challenges raised when the role of monitoring something like a forest disease devolves from federal entities to a more distributed VGI model that includes scientists, regulators, and the public? What are the necessary checks and controls on data acquisition and distribution in such a framework, and how are clear monitoring objectives, necessary for any successful environmental monitoring program, developed in a participatory model? There are few examples in the United States, other than SOD and OakMapper, of participatory models for monitoring regional or continental-scale forest diseases (e.g., bark beetles, pitch canker, Pierce's disease, Dutch Elm disease, etc.), so broad answers to these questions are difficult to come by. OakMapper's flexible VGI-based environmental monitoring system that incorporates motivated participants, sensing devices, and back-end information infrastructure—what Gouveia and Fonseca (2008) called the backbone of participatory monitoring—provides a starting point to examine these questions. In this example, the motivated participants include scientists, regulators, and private citizens with different inspirations, and the data they generate require different levels of validation and carry different expectations about quality, but there is something to be gained by having them juxtaposed.

Neogeographers are challenging traditional roles for data creation and circumventing the authority of the cartographer, yet even with this shift, questions of power and motivations persist. Tulloch (2008) offered a detailed assessment of the relationship between PGIS and VGI and concluded that contributors to VGI and PGIS display an interest in participating in a larger project, but each realm differs in part because of motivations of participants. PGIS focuses on social outcomes and development of democratic processes, but VGI projects are far more diverse and their motivations will vary greatly. Similarly, citizen scientists and neogeographers are both contributing to a larger effort, but citizen scientists can be distinguished by their intention to contribute to research endeavors. Drawing from literature on the motivations of contributors to Wikipedia and OSS projects (e.g., Lakhani and Wolf 2005; Cook 2008; Schroer and Hertel 2009), Coleman, Georgiadou, and Labonte (2009) create a taxonomy of neogeographers and identified eleven distinct motivations for contributors to VGI, which operate within four areas of context:

market-driven, social networks, emergency reporting, and civic and governmental. OakMapper's services are intended to attract the full spectrum of users identified by this taxonomy, from neophytes to expert authorities, operating within a civic and governmental context. Meanwhile, our data gleaning efforts are intended to draw information from interested amateurs and expert amateurs who are operating within social networks. Produsers from the civic and governmental context are likely to be motivated by professional or personal interest, intellectual stimulation, and protection or enhancement of a personal investment (in this case oak trees and property). At the same time, there will be produsers who are motivated by agendas (e.g., preserving or diminishing real estate values or promoting landscaping services).

We can further situate VGI-driven citizen science projects within the context of a macro–micro participatory decision strategy (Jankowski and Nyerges 2001). According to this framework, participatory decision making involves three macro phases that include intelligence about values and objectives, design of options, and choice about recommendations. At each of these macrolevels, participants first gather information, then organize said information, then select from it, and finally review and assess it to move onto the next phase. OakMapper has only been involved with the first macro phase and has not yet extended into the design and choice phases of environmental decision making. There is the potential for OakMapper to straddle the fields of participatory decision making and citizen science by invoking tools that simultaneously serve data collection and decision support.

OakMapper is very different from traditional expert-driven models of environmental monitoring because of its coupling of data from interested publics and opportunistic utilization of the geocloud. Enhancing our understanding of VGI will open opportunities for researchers to take advantage of this constant flow of information, and new Internet tools, such as Google Fusion Tables, provide greater options for distribution of interactive visualizations. OakMapper is utilizing tweets, which are produced at four times the rate of our current contributions, although these are not all geotagged. The regular contributions of SOD-related information through outside channels reveals the public's continued interest in the topic and shows the potential of popular media to gather related data, even when contributions to a topic-specific site are low. VGI from outside sources is quite useful as a gauge of public interest and can also be utilized to time and target outreach activities for scientific projects. Outreach efforts can also be directed specifically to the produsers who are reporting on SOD in these forums, to recruit them to OakMapper. Currently, we only extract information from these channels, but feeding information into them might improve public outreach and attract more participants. Any photos submitted directly to OakMapper could be automatically uploaded to Flickr and appropriately tagged.

In this article, we show one example of a Web application designed in an open source, produser-centric framework, but tools founded on these elements could take many forms and could borrow from both open source and proprietary software solutions. For example, at one end of the spectrum, some might prefer to work with in an entirely open source environment, creating maps in OpenLayers and using base layers from OpenStreetMap and open source Web design frameworks, such as WordPress. Such a reliance on open source technologies might necessitate a certain level of programming skill, as the more complex and interoperable designs often require extensive programming. Developers are also dependent on a dedicated open source user base for documentation and development, making it difficult to locate information about some technologies. Furthermore, new versions and necessary updates of products might experience infrequent releases. More popular open source technologies with many users, however, are often supported by extensive documentation on the Web and online user forums that quickly answer questions. In utilizing OSS, researchers might also display greater neutrality in their scientific endeavors, as they can divest from corporate interests associated with commercial software (Curry 1998).

Conclusions

The inclusion of private citizens in large-scale and complex environmental challenges will undoubtedly continue, whether through regulation—such as in the National Environmental Protection Agency process that requires public participation in many federal environmental activities—or fed by the spirit of volunteerism. We argue here that environmental monitoring can benefit from accessing a larger spectrum of produsers and an array of data created with different intentions, as illustrated in our conceptual model. Despite the challenges, we show that an integrated geospatial tool set can provide a logical, flexible, and intuitive framework for soliciting, storing, analyzing, and visualizing such volunteered spatial data across information domains. To support this argument, we provide an example of a user-driven project, supported by open source technology, with a scalable database for environmental monitoring. Our example, the OakMapper project, is part of a long-term and collaborative venture where both researchers and private citizens gather and share environmental data at multiple geographic scales over time. The project is intended to help realize the potential of Web mapping and citizen science for environmental monitoring by taking advantage of freely available technologies and robust design principles while paying attention to user experience and having an inclusive view on data sources. The Web mapping technologies presented in this article can quickly gather and disseminate information from multiple streams in an organized and easily interpreted format.

The Web site is a hybrid, uniting several characteristic types of VGI and citizen science: targeted citizen-based observation networks, expert-driven focused environmental monitoring, and opportunistic crowdsourcing efforts (Figure 1). The benefits of our blended approach to monitoring are clear: OakMapper is the one place where all official data on the spread of this disease are available; it has been able to gather spatial information on potential SOD from the length of California from a diverse community; and we have engaged broadly with an interested public about a regional-scale environmental problem. The challenges to this approach have also been considerable, and we are still working through them. Issues of data quality, differential motivation, surveillance and decision-making power between parties, all discussed in this article, remain of concern as we seek to utilize new technologies. Such activities can be reviewed in terms of their balance between "external" and "internal" values. External values are those that have usefulness for the public in a specific decision-making context, whereas internal values are those that relate to learning and personal development; these are subjective and specific to each participant (Lawrence 2010). Often, participatory tools are forced to be dichotomous, with either transitional or instrumental objectives, but the benefit and utility of such tools are often more mixed, with multiple audiences with myriad responses and values.

This argument is also useful in the context of information. The benefit of projects such as OakMapper is their hybrid approach to information gathering that solicits information from a range of users—from the regulatory and scientific users who supply specific data on tree infection to the distributed community that includes submissions from the geocloud and submissions from a focused public. This blended approach to citizen-based environmental monitoring enhances data flow and taps into exogenous data sources. We believe that this model might be beneficial and well utilized in other cases of highly visible environmental problems that have an engaged public, a scientific framework, and a broad spatial range.

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