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The art and science of multi-scale citizen science support

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ABSTRACT

Citizen science and community-based monitoring programs are increasing in number and breadth, generating volumes of scientific data. Many programs are ill-equipped to effectively manage these data. We examined the art and science of multi-scale citizen science support, focusing on issues of integration and flexibility that arise for data management when programs span multiple spatial, temporal, and social scales across many domains. Our objectives were to: (1) briefly review existing citizen science approaches and data management needs; (2) propose a framework for multi-scale citizen science support; (3) develop a cyber-infrastructure to support citizen science program needs; and (4) describe lessons learned. We find that approaches differ in scope, scale, and activities and that the proposed framework situates programs while guiding cyber-infrastructure system development. We built a cyber-infrastructure support system for citizen science programs (www.citsci.org) and show that carefully designed systems can be adept enough to support programs at multiple spatial and temporal scales across many domains when built with a flexible architecture. The advantage of a flexible, yet controlled, cyber-infrastructure system lies in the ability of users with different levels of permission to easily customize the features themselves, while adhering to controlled vocabularies necessary for cross-discipline comparisons and meta-analyses. Program evaluation tied to this framework and integrated into cyber-infrastructure support systems will improve our ability to track effectiveness. We compare existing systems and discuss the importance of standards for interoperability and the challenges associated with system maintenance and long-term support. We conclude by offering a vision of the future of citizen science data management and cyber-infrastructure support.

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1. Introduction

Citizen science and community-based monitoring programs are emerging as significant providers of ecological data. These programs measure and monitor streams, lakes, birds, fish, invasive species, biodiversity, climate change, air quality, water quality, macroinvertebrates, astronomy, and even earthquakes (Bonney et al. 2009b, Cochran et al. 2009, Newman et al. 2010, Silvertown 2009a, b). As the number and breath of these programs increase, so does the volume of ecological data they generate (Bonney et al. 2009b). Creating and maintaining online data management systems capable of supporting the varied nature of these data is difficult for most programs. Programs fortunate enough to have their own data management systems still face user interface challenges (Newman et al. 2010) and struggle when their needs grow beyond the specificity of their current data management system.

Program-specific systems are limited to a particular domain (e.g., streams) and may not incorporate data standards or controlled vocabularies necessary for efficient data sharing or system interoperability. The benefits of integrating data from one program with another are often overlooked. For example, meta-analyses to determine climate change effects or species distributions cannot easily be conducted if data standards are not used between all programs measuring similar species and/or attributes. Additionally, given the importance of social interaction for volunteers (Bell et al. 2008a,b), systems focused solely on data entry and storage may overlook important features that facilitate communication, marketing, and social interaction among citizens, volunteer coordinators, and stakeholders (Newman et al. 2010) or that support data analysis and visualization.

Citizen science programs are created for many purposes. Examples include: long term monitoring; scientific research; community networking; social empowerment; science literacy improvement; environmental education; youth career development in science, technology, engineering, and mathematics; community service; and the preservation of traditional ecological knowledge. Citizen science program objectives are equally varied. Examples include: contributing quality data, helping scientists answer questions, informing local decisions, engaging in social networks, and/or offering opportunities to enjoy nature. Meeting these objectives requires data management systems with many capabilities. For example, effective systems must announce training events, offer educational materials, perform automated data quality checks, provide tools for metadata support, automate summary statistics, create reports, enable data uploads and downloads, offer tools for analysis and modeling, exchange data with other databases, and provide decision support capabilities. End users demand flexible systems capable of integrating data across domains and scales while also accommodating diverse needs. Bonney et al. (2009b) articulate these challenges clearly: "… as citizen science [programs] grow in scope, …innovative tools in database management, scientific analysis, and educational research [will be needed], … networking technologies and… database solutions [will be] imperative, [and] computationally efficient geospatial analysis and imaging techniques [will be needed] … to handle … massive amounts of monitoring data … collected across vast geographic scales." Thus, we sought to: (1) briefly review existing citizen science approaches and data management needs; (2) propose a framework for multi-scale citizen science support; (3) develop a cyber-infrastructure designed to support citizen science program needs; and (4) describe the lessons we learned. We compare existing systems and discuss the importance of standards for interoperability and the challenges associated with system maintenance and long-term support. We conclude by offering a vision for the future of citizen science data management, informatics, and cyber-infrastructure support.

2. Existing approaches and data management needs

At the forefront, it is important to review various citizen-based approaches and summarize their respective data management needs. Unfortunately, terminology remains confusing (Table 1) and includes phrases such as Community-Based Monitoring or Citizen-Based Monitoring, Citizen Science, Decision Support Systems, Environmental Decision Support Systems, Environmental Collaborative Monitoring Networks, Volunteered Geographic Information, Participatory Geographic Information Systems, Participatory Monitoring Networks, Public Participation Geographic Information Systems, Indigenous Mapping, Community Networking, Participatory Action Research, and, more recently, Public Participation in Scientific Research. These approaches can be categorized as contributory, collaborative, or co-created (Table 1; Bonney et al. 2009a). For the purposes of this paper, we use the term citizen science broadly to encompass all of these approaches.

Citizen science represents scenarios in which citizens participate in the scientific process along with professionals (Bonney et al. 2009b). Citizen science programs require significant oversight, coordination, protocol development, protocol refinement, training, data management infrastructure, and financial support (Bonney et al. 2009b, Cohn 2008a, b). Some programs focus on public engagement, with goals and objectives less data collection oriented and more policy oriented (Powell and Colin 2008), while others enlist citizens to "volunteer" their personal computers for causes such as monitoring seismic activity (Cochran et al. 2009), celestial bodies (e.g., Galaxy Zoo), or posting disaster information online (Laituri and Kodrich 2008). Preeminent North American examples include the programs coordinated by the Cornell Lab of Ornithology, including Project FeederWatch, PigeonWatch, NestWatch, NestCams, Great Backyard Bird Count, eBird, Celebrate Urban Birds, CamClickr, BirdSleuth, and Birds in Forested Landscapes (Bonney et al. 2009b, Cornell Lab of Ornithology 2008) while exemplar European programs include iSpot for citizen-based nature sharing (McAndrew et al. 2010) and OpenStreetMap for community-based street mapping (Haklay and Weber 2008).

In addition to these notable large-scale programs, however, are countless smaller efforts, including 115+ programs listed in the Citizen Science Central registry (Cornell Lab of Ornithology 2008) and 272+ listed at scienceforcitizens.net (scienceforcitizens.net 2011). Small programs (e.g., programs with less than 100 active volunteer members and a support staff of 10 or fewer) often lack the internal capacity to develop their own online data management system and may benefit most from cyber-infrastructure support. Regardless of situation or size, the data management needs of citizen science programs encompass data beyond mere species observations, such as auxiliary environmental data, participant information, volunteer hours, land manager contact information, training event schedules, species attributes, site characteristics, and user preferences for alerts related to new observations. Citizen science programs require features that support communication; teach field skills online; store field data collected by citizens; offer analysis and reporting capabilities; and collect, store, and analyze standardized program evaluation data in a single comprehensive system.

Table 1
Categorized citizen-based approaches, definitions, and data management needs.

Citizen based approach	Category*	Data management needs
CBM — Community Based Monitoring** (Whitelaw et al. 2003a,b) Focus: issues of common community concern	Collaborative	• Long term visualization • Analysis and synthesis • Login/registration • Automated reports
CBM — Citizen Based Monitoring** (Stepenuck 2010a,b) Focus: citizen advocacy	Collaborative	• Long term visualization • Analysis and synthesis • Login/registration • Automated report
CS — Citizen Science (Bonney et al. 2009b, Cohn 2008a, b, Silvertown 2009a,b) Focus: answer scientific questions raised by researchers	Contributory	• Easy data entry • Communication • Volunteer management • Program evaluation
DSS — Decision Support Systems (Argent et al. 2009a,b) Focus: decision support and artificial intelligence	Supportive	• Analysis and synthesis • Login/registration • Data integration • Geo-visualization
EDSS — Environmental Decision Support Systems (Guariso and Werthner 1989, Haagsma and Johanns 1994a,b, Cortes et al. 2000a,b, Poch et al. 2004a,b, Poch et al. 2004a,b) Focus: software to assist environmental decision makers	Supportive	• Decision support • Analysis • Geo-visualization
ECMN — Environmental Collaborative Monitoring Network (Gouveia and Fonseca 2008a,b) Focus: networks of sensors	Collaborative	• Social networking • Wireless sensors • Open source code • Data management
VGI — Volunteered Geographic Information (Goodchild 2007a,b) Focus: geographic information contributed by volunteers	Contributory	• Geospatial data storage and visualization • Performance • Features to support fast vector and raster data display
PGIS — Participatory Geographic Information Systems (Rambaldi et al. 2006a,b) Focus: community empowerment through integrated applications of geospatial technologies	Co-created	• Geospatial analyses • Web mapping features • Infrastructure availability • Access
PMN — Participatory Monitoring Network (Bell et al. 2008a,b) Focus: volunteer data collection	Contributory, Collaborative	• Data management • Social networking
PPGIS — Public Participation Geographic Information Systems (Aberley and Sieber 2002a,b, Craig et al. 2002a,b, Sieber 2006a,b) Focus: social justice through GIS implementations	Collaborative, Co-created	• Geospatial analyses • Web mapping features • Infrastucture availability • Access
IM — Indigenous Mapping (Chapin et al. 2005a,b) Focus: Traditional Ecological Knowledge	Co-created and Collaborative	• Cultural relevance • Language translation • Unit conversions • Innovative features for different data representations
VM, CS, PAR — Volunteer Monitoring, Community Science, and Participatory Action Research (Cooper et al. 2007a,b, Cornwall and Jewkes 1995a,b, Ely 2008a,b, Lawrence 2006a, b, Wilderman et al. 2004a,b) Focus: scientific research and action	Contributory, Collaborative, and/or Co-created	• Metadata • Research question, hypothesis, and methods information storage • Analysis
CN — Community Networking (Longan 2007a,b) Focus: social networking	Collaborative	• Social networking • Photo sharing • Blogs
PPSR — Public Participation in Scientific Research (Bonney et al. 2009a) Focus: informal Science Education (ISE)	Contributory, Collaborative, or Co-created	• All of the above

*Categories as defined by Bonney et al. (2009a) with the addition of the supportive category.
**These terms are often used synonymously.

3. A framework for multi-scale citizen science support

Given these various citizen science approaches and respective data management needs, we developed a framework to situate programs based on their scope, scale, and activities (Fig. 1) and improve the design, development, and effectiveness of cyber-infrastructure systems built to support them. The proposed framework includes different program aspects and acknowledges that each aspect has

	Aspect	Tension / Continuum	
Scope	Purpose	Perform services	Influence policy
	Domain	Focused	Broad
	Objectives	Create/Act	Learn/Change
	Audience	Lay public	Scientists
	Accessibility	Marginalized	Elite
	Data Quality	Low	High
Scale	Spatial	Local	Global
	Temporal	Short	Long
	Social	Individual	Community
Activities	Research question	Bottom up	Top Down
	Protocol	Pre-existing	Newly Created
	Recruitment	Targeted	Non-Targeted
	Training	Pragmatic	Conceptual
	Volunteer Management	Cursory	Intensive
	Data Management	Loose	Restricted
	Data Dissemination	Local	Global
	Program Evaluation	Formative	Summative
System Approach	Level of Engagement *	Category I	Category V
	Service Provided	Production	Experimental
	Funding Mode	Maintenance	Innovation
	Developer Motivations	User requirements	Design Intents
	Research Model	Development	Research

Fig. 1. Framework for multi-scale citizen science support. The framework includes the scope, scale, and activities for citizen science programs. Each aspect of multi-scale citizen science has associated continuums and tensions. Many tensions listed represent tensions between cyber infrastructure developers (right side; tend to operate in domains that are broadly focused, in a global spatial extent, where research questions are top–down) and citizen scientists (left side; tend to operate in focused domains where the spatial extent is local and where research questions are bottom–up). * The level of engagement categories are from Danielsen et al. (2009): Category I represents "externally driven, professionally executed monitoring" and Category V represents "autonomous local monitoring."

associated tensions and continuums (Fig. 1). It is important for citizen science programs to define these aspects for their own program (intra-program dimension) and between their program and other programs (inter-program dimension). By using the framework to characterize programs based on these aspects, citizen science programs can better ensure their effectiveness, refine their data management needs, and help guide the development and/or selection of data management systems appropriate to their needs.

3.1. Intra-program dimension

Citizen science programs must determine their own scope, scale, activities, and level of required system support (Fig. 1). Effective programs must: (1) choose or define their research question, (2) gather information and resources, (3) develop hypotheses or possible explanations, (3) design data collection methods, (4) collect data, (5) analyze data, (6) interpret data and draw conclusion, (7) disseminate results, and (8) discuss results and ask new questions (Bonney et al. 2009a). Deciding how to approach these planning aspects and where on each continuum a program may reside (Fig. 1) is critical to the overall success of a program and to the design, development, and/or selection of an effective data management system. Mismatches in the relative positions of a program on each continuum can lead to tensions between group goals, data quality, and program outcomes (Nerbonne and Nelson 2008) and to an over- or under-designed data management system. For example, a program designed to foster child experiences with nature would require different features than a program focused on scientific data collection and analysis. The data collected by children whose goals and objectives are to experience nature may result in simple species observations, whereas more professional efforts may result in data containing geospatial coordinates complete with accuracy, precision, and additional measured attributes such as percent cover, height, life stage, sex, or weight (Table 2). A data management system built specifically for species observations may be limited in use for more detailed data collection and analysis, depending upon the schema used. Some schemas may be appropriate for data collection and dissemination (steps 4 and 7 above), but may lack support for online presentation of the research question being asked (steps 1 and 3 above). We developed the framework (Fig. 1) to provide program coordinators with a means to decide where on each continuum their program may reside and to help guide the development and/or selection of data management systems flexible enough to suit a variety of program needs.

3.2. Inter-program dimension

Inter-program planning refers to the degree to which programs coordinate with other programs and involves defining the purpose, goals, and objectives of such coordination along with the desired outcomes. For example, a program may have a goal to exchange data with other programs monitoring the same species in a different region locally, regionally, nationally, or globally to foster early detection and rapid response. Effective data management systems will make data sharing easier for citizen science programs already strapped for limited resources. Inter-program activities for data sharing include collaborative meetings, standardized data exchange protocols, data standards, methods to address data sensitivity and authorship, and evaluation data related to data sharing efforts. Examples of

Table 2
Supported attributes by category.

Name	Description	Value Type	Unit Type
Organism Data Attributes			
Dominant species	Dominance ranking based on most cover or basal area for all plant species present	Lookup	
Height	Height above ground, average height for groups	Float	Distance
Percent cover	Percent of area covered by this individual or organism	Float	Percent
Vigor		Lookup	
Infested area		Float	Area
Length		Float	Distance
Sex		Lookup	
Life stage		Lookup	
Tag ID		Integer	
Born wild		Integer	
Weight	Dry weight for plants, live weight for animals, in kg.	Float	Mass
Number of individuals		Integer	Count per area
Gross area	Area covered at least in some part by the species	Float	Area
Presence	Presence or absence of species at for a visit	Lookup	
Depth	Depth below water level	Float	Distance
Nitrate		Float	Parts Per
Derived biomass	Biomass calculated from other data collected	Float	Mass per area
Measured biomass	Biomass directly measured from organisms collected	Float	Mass per area
Canopy area	Area covered by the canopy (by individual or species)	Float	Area
Density per meter squared	Number per meter squared	Float	Count per meter squared
Voucher collected	True if a voucher specimen was collected	Lookup	
Count of individuals	Area-independent count of individuals	Float	Count
Dominant species	Dominance ranking based on most cover or basal area for all plant species present	Lookup	
Location Data Attributes			
Difficulty	Trail or route difficulty of travel (Theobald & Linn)	Float	
Allowed uses		Lookup	
Start elevation		Float	
End elevation		Float	
Elevation change		Float	
Length	Trail length etc.	Float	
Accessibility	How accessible for disabled persons	Lookup	
Surface type		Lookup	
Search time	Total search time for this location		
Soil Type Attributes			
Sand	% sand	Percent	
Silt	% silt	Percent	
Clay	% clay	Percent	
Soil texture	General soil texture categories	Lookup	

measurable evaluation benchmarks could include the amount of data exchanged annually and the degree to which data were used by practitioners to address problems. Data management systems designed to store, analyze, and disseminate evaluation data in addition to ecological data will be better poised to promote and market the value of data sharing and data integration.

4. Cyber-infrastructure for multi-scale citizen science support

We created a cyber-infrastructure for ecological data management (Graham et al. 2007) and used this system to develop a website designed specifically for multi-scale citizen science support (CitSci.org; www.citsci.org). The website uses an enterprise-level SQL Server 2008 relational database management system in conjunction with numerous open source libraries and tools, including: PHP, Java (Sun/Oracle), GeoTools, the Java Topology Suite (Vivid Solutions), Proj4 (US Department of the Interior or USDOI), Nad2Nad (USDOI), MaxEnt (Phillips et al. 2006), R (R Development Core Team 2008), and fpdf. It makes use of the widely used Google Maps Application Programming Interface (API) as a free map service, but uses a custom Java application for dynamically rendering clustered map tiles overlaid on top of standard Google Maps background tiles instead of the Google Maps Javascript API for placing “pins” on top of these background images. Traditional HTML, JavaScript, and CSS files are used for page presentation. The system uses the standard OGC-compliant Well Known Binary format for spatial data and simple XML-based RESTful web services (see Fig. 2 for overall system architecture).

Our aim was to support the inter- and intra-program data management needs of collaborative, co-created, and contributory citizen science programs. We realized upfront that it would be cost-prohibitive to create systems specific to each program. Thus, we allow organizations to create and customize *their own* CitSci.org projects using a simple web-based Graphical User Interface. Currently, the CitSci.org website serves 28 citizen science programs that have collectively reported over 5196 species observations. Most of these programs are contributory in nature and make use of both standard and non-standard attribute data.

4.1. System features

The CitSci.org cyber-infrastructure system stores volunteer data, project data, spatial data (point, line, and polygon), location data, organism data, attribute data, metadata, evaluation data, environmental data, visit data, and website-specific data (Fig. 2). Its schema relies on a least common denominator set of core data common to most programs, including a simple quartet consisting of an *object* found at a *location* at some point in *time* along with *measured attributes* (Fig. 2). This object-oriented approach (Kamath et al. 1993) supports a wide-range of an ever-increasing set of attribute data collaboratively driven by various program needs (Table 2).

The website enables citizen science organizations to create their own online projects that are managed by volunteer coordinators (project managers) who in turn manage project members. These projects form online social communities (Longan 2005) which ensure that only project members with permission may contribute data to a given project in what could be called “controlled crowd-sourcing.” Website features include: registration; login/logout; a “My Profile” page; an email alert system; a map application that allows users to add species to view, add new locations spatially using the map, get information about species locations, and change the color of species layers; the ability to search and query for projects and species; the ability to view information about species on “Species Profile” pages; features to support sensitive data (Jarnevich et al. 2007); the ability to upload photos; and the ability for project managers to create their own “Project Profile” pages along with their own data entry forms for their members to use to contribute new observations (Table 3). The ability of project managers to create their own data entry forms is unique in that it allows project managers to select from any organism in the system (the system uses the International Taxonomic Information System dataset) and then select attributes from a vetted, yet growing list of available attributes suggested by users. Similarly, it allows project managers to select from a vetted and growing set of site characteristics (e.g., soil pH, water salinity, etc.) and treatments (e.g., control agents categorized as biological, mechanical, or chemical). The system also contains an integrated online defect tracking system.

We augmented the system with 22 standard environmental raster data layers that can be used by land managers and scientists re-using

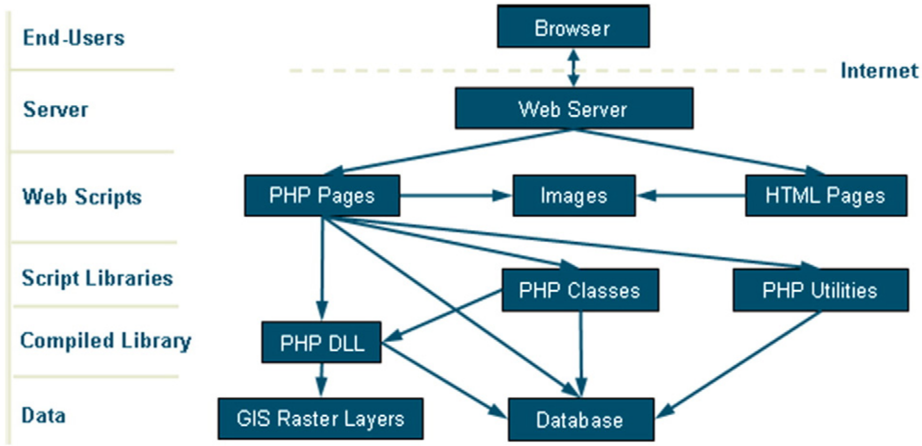

Fig. 2. High-level system architecture.

citizen-contributed data for online environmental niche modeling and species distribution modeling (Graham et al. 2010). Photo management tables support the social networking objectives of the collaborative, co-created, and contributory programs focused on volunteer social interaction. Core data and ancillary data are assigned to projects to organize them and user preferences are assigned to registered users. Finally, a web service API delivers dynamic maps for citizen science organizations who wish to embed maps into their own website along with a web service data exchange protocol for those wishing to exchange core data regionally and globally (currently in development).

5. Lessons learned

5.1. More features are required to support program activities and social interaction

We have learned much in developing the CitSci.org system. Although the current CitSci.org system allows program managers and approved project members to customize their online citizen science experience (e.g., managers can create their own data entry forms and project members can customize their own alerts and

Table 3
A comparison of existing cyber-infrastructure systems and their current features.

	System[a]											
System features	CitSci	EB	EM	FS	IS	NM	NN	OP	OSM	PBB	WM	Z
Login/logout	X	X	X	X	X	X	X	X	X	X	X	X
Register	X	X	X	X	X	X	X	X	X	X	X	X
My profile	X	X	X	X	X	X	X	X	X	X	X	X
Personal photo		X	X		X			X	X		X	X
My favorites					X			X			X	X
My locations of interest	X	X							X	X	X	X
My alerts	X	X	X									
My saved maps	X											
My saved analyses												X
Social networking**		X	X				X			X	X	X
User roles, permissions	X	X	X						X	X		X
Projects	X		X									X
Observation photos	X	X			X				X	X	X	
Events calendar					X			X				
Interactive id keys		X			X			X				
Interactive maps	X		X	X	X	X	X	X	X	X		X
Point data support	X	X	X				X		X	X	X	X
Polyline data support	X								X		X	
Polygon data support	X										X	
Click-on map data entry		X							X		X	
Mobile application			X							X		
Data QA/QC review			X							X		X
Long term visualization		X			X		X					
Online analysis	X	X			X					X		X
Dynamic charts, graphs	X	X			X							
Automated reports		X										X
Customizable forms	X											
Customizable surveys	X											
Customizable attributes	X								X			
Data integration	X	X	X		X	X	X	X	X	X	X	X
Blogs		X	X		X			X	X	X	X	X
Analysis features		X										
Animated results		X										
Language translation		X							X		X	X

[a] Note — system abbreviations include: EB: e-Bird; EM: EDDMapS; FS: FieldScope; IS: iSpot; NM: NatureMapping; NN: Nature's Notebook; OP: OPAL; OSM: Open Street Map; PBB: Project BudBurst; WM: WikiMapia; and Z: Zooniverse. Note: Some systems were regularly new when evaluated and system features change regularly.

maps), more development needs to be done to support the full suite of citizen science program needs. For example, when creating their own project, managers must also be able to enter their own research questions, create their own automated reports by selecting which summary statistics they want automatically generated, create their own program evaluations, or select from standardized national assessments (National Science Board, 2008). Additional features to support social interaction between volunteers, project managers, and scientists are needed. The CitSci.org system has not yet fully leveraged the existing web 2.0 social networking capabilities. However, decisions must be made regarding the pros and cons of having separate systems for volunteers to use and keep track of, creating mash-ups that combine various widgets, and systems that integrate these features directly into the cyber-infrastructure to minimize the number of systems volunteers must learn and keep track of.

5.2. Attributes must be able to be suggested collaboratively online, yet remain vetted

Currently, the CitSci.org cyber-infrastructure system consists of a backend that allows system administrators to add suggested attributes to be measured for *different things* of interest to end users, such as organisms, locations, abiotic site characteristics, information about a specific observation made in time (visits), and *things done* (treatments) during a particular visit. Table 2 shows the current suite of supported attributes. For each suggested attribute, we work with program managers to discuss standardized protocols and/or controlled vocabularies already in use prior to approval. In this way, the attribute data are decisively more comparable across programs where possible. This helps managers avoid measuring the same attributes that others are measuring under a different name which can impede cross-studies comparisons. However, we add the unique attributes suggested under unique circumstances when needed. By showing managers upfront what others are already measuring, it helps them decide whether they need to measure a different attribute using a different protocol, or whether they can measure the same attribute using the same protocol that others are already using.

For example, the City of Fort Collins Natural Areas Program has volunteers measure the intensity of amphibian calls heard at local ponds to help inform state herpetologists about the presence/absence of various amphibians and their relative abundance (City of Fort Collins Natural Areas Program 2009). A collaborative search by our team and their staff discovered the standardized amphibian call index (Nelson and Graves 2004). By adopting this standard protocol, other citizen science programs in other regions of the country with similar objectives using the same protocol can collect data that then can be used for cross study comparisons and/or meta-analyses.

5.3. Small programs lack the capacity for custom programming

Free and Open Source Software programming efforts facilitate system customization and provide good support via forums and email lists (Steiniger and Hay 2009). However, these efforts often have a small user base, lack up-to-date documentation, and require programming and API familiarity that can make them largely inaccessible to most small citizen science programs. Small programs do not typically have the capacity to set up a web server; learn an open source web-development Content Management Systems (e.g., Drupal; http://drupal.org/); download, install, and customize APIs similar to the CitSci.org system approach (e.g., indicia; http://code.google.com/p/indicia/), and, ultimately, create, design, and maintain their own website to support their own citizen science program needs. The mash-ups that most programs do leverage (if they have their own website and/or web team) use simple API plug-ins that are easily integrated into their own website such as the Google Maps API or the Facebook/Twitter/Flickr social network APIs. Most small programs simply do not have their own internal resources to support their own website system.

5.4. Web skins can improve system usability and focus

Our underlying cyber-infrastructure serves a family of related web skins that currently are created by the system administrators using a simple back-end Graphical User Interface requiring no programming. This interface allows administrators to create their own web skins, add menu items, change navigation layout (e.g., top navigation, left navigation, or both), alter web skin width, change menu links, and modify the color palette (e.g., CSS code) for a given web skin. Future development aims to expose these capabilities to project managers. Each of our current web skins share a common theme: they all rely on participation from stakeholders to keep data current in real-time. In this sense, they are examples of Web 2.0 applications that facilitate interactive information sharing, interoperability, user-centered design, and collaboration (Lake and Farley 2007). Examples include web-based communities, web applications, social-networking sites, video-sharing sites, wikis, blogs, content management systems, and mash-ups. A Web 2.0 site allows users to interact with other users or to change website content, in contrast to non-interactive websites that allow only a passive view of information (Lake and Farley 2007). We have developed web skins to ease usability by focusing features to specific program needs. For example, we have developed web skins for Buffelgrass (e.g., the Southern Arizona Buffelgrass Coordination Center; www.ibis.colostate.edu/sabcc), for trails mapping (e.g., COTrails; www.cotrails.colostate.edu), and, more recently, for Pika monitoring (e.g., the Front Range Pika Project; www.pikapartners.org; currently in development). By targeting a specific species, the Graphical User Interface can bypass complex species searching and make it easier for species observations to be made.

6. Discussion

We developed the CitSci.org cyber-infrastructure system to begin to tackle the challenges associated with developing a system for multi-scale citizen science support. We devised a framework to help program coordinators situate their own program's scope, scale, and activities in the context of other programs. The framework helps cyber-infrastructure developers determine the breadth of scenarios systems may be confronted with and suggests a spectrum of use cases that systems may need to support. The existing frameworks related to citizen science focus on program evaluation. The Framework for Evaluating Impacts of Informal Science Education Projects (Friedman 2008) emphasizes five Informal Science Education impact categories, whereas others address empowerment by combining four catalysts (information, process, skills, and tools) with two social scales (individuals and communities) (Corbett and Keller 2005). Empowerment within our framework relates to the aspects of training, data collection, data management, and level of customization. Similar to our framework's intra- and inter-program dimensions, Bell et al. (2008a,b) found that social interactions occur within and between participatory biodiversity monitoring networks. The authors found that these networks must "…strike a … balance between recruitment and retention; bringing in new volunteers while consolidating existing [members]" and that to expand and sustain participation, networks must engender enthusiasm "…by providing an inspiring environment where trust, respect, recognition, value and enjoyment can flourish" (Bell et al. 2008a,b). Engendering this type of enthusiasm will require data management systems that allow a greater degree of customization by end users.

6.1. Existing system comparisons

There are several systems being developed similar to the CitSci.org system. The indicia project (http://code.google.com/p/indicia/) is an open source toolkit supported by the National Biodiversity Network and the Open Air Laboratories (OPAL) that simplifies the construction of new wildlife websites and allows data entry, mapping, and reporting of wildlife records (http://code.google.com/p/indicia/). This system is not a finished online website. Instead, it is more akin to a kit car versus a manufactured car where you "…get the wheels, engine, and all the important tricky bits ready-made, but you still have to assemble the parts" (http://code.google.com/p/indicia/). Like the CitSci.org web skins, the indicia toolkit allows developers to create their own web skins (websites). Websites currently using this open source cyber-infrastructure toolkit include the North East Cetacean Project (http://www.northeastcetaceans.org.uk/) and the MNHNL Data Portal (http://data.mnhn.lu/). Our experiences with working with the 28 current citizen science programs using CitSci.org thus far indicate that most small programs do not have the capacity to develop their own web system based on an open source framework such as indicia.

In contrast, another existing system (iSpot) allows any registered user to make simple specie observations. It is a consortium of crowd-source enabled identification resources that collaboratively make and verify species observations to share nature with the world. However, although more features are on the horizon, this system does not yet support polygon mapping or the contribution of attributes about each species observation as does CitSci.org. Another similar system, OpenStreetMap is a powerful and widely used open source initiative to enable citizen participation in mapping streets. Wikimapia is broader in scope – mapping the world – and has advanced the collaborative attribute approach; users can create categories of places that end up being selected as a set of open-ended vocabularies. However, it may be difficult to conduct meta-analyses if the categories representing similar things are labeled differently. Meta-analyses making use of wikimapia data may require a more sophisticated semantic interpretation.

There are many benefits to open forums (e.g., see the popularity and success of Wikipedia, Wikimapia, and OpenStreetMap; Haklay and Weber 2008) and free and open source software shows great promise for fields such as landscape ecology (Steiniger and Hay 2009). However, stakeholder concerns over data quality and developer concerns over longevity, reliability, documentation, and performance require a balance between Web 2.0 alternatives and traditional software development solutions. For example, preliminary robustness testing of the Google Maps client-side JavaScript API shows that the ability to zoom, pan, and get information on species locations can become slow and unresponsive under scenarios of greater than 5000 locations when not using clustering algorithms (Graham, unpublished data). Like other development teams, we must ensure reliability, performance, usability, data quality, daily use satisfaction, system longevity, and data sensitivity specific to stakeholder needs (Jarnevich et al. 2007, Ribes and Finholt 2009).

There are other cyber-infrastructure systems that focus on specific domains such as plant phonological observations (Project BudBurst, www.budburst.org), astronomical observations (Zooniverse websites, www.zooniverse.org) and Bird observations (e-Bird, www.ebird.org) and those that focus on professional ecological data curation, storage, analysis, and visualization, such as the Data Observation Network for Earth system (DataONE; www.dataone.org/), the Global Biodiversity Information Facility (GBIF; www.gbif.org), or the Data Basin system (www.databasin.org). Some systems are also beginning to emphasize more flexible online analysis capabilities (e.g., FieldScope, www.fieldscope.us). Although focused more on specific domains or professional datasets, these systems guide the development of data standards that the more general systems such as CitSci.org can adopt. A comparison of several existing systems is shown in Table 3.

Our experiences in developing the CitSci.org system underscore the importance of a flexible architecture. Knowing up-front what level of cyber-infrastructure support is needed by a citizen science program and how a given program fits within the broader context is critical. Such knowledge can determine if a program's needs are best suited to a project within a multi-project website such as CitSci.org, if a species observation network such as iSpot may be best, if a domain specific system such as e-Bird is best, or if a specific data management system created and maintained by program staff may be best. Regardless, effective systems for citizen science data management must improve the way they handle, store, and exchange data and increase their ability to communicate metadata about citizen-collected data to ensure effective reuse by ecologists and land managers for science-based analyses, modeling, and decision making. Although most systems make use of user levels and project roles for system security, an approach similar to that of Poch et al. (2004a,b) who advocate for user profiles with different privileges and responsibilities, successful systems for sharing citizen science data will succeed not only because of security, but also on account of the metadata they provide and the level of standardization they afford.

6.2. Standards for multi-scale interoperability

Data standards facilitate data exchange through web service protocols. Without standards, data may still be exchanged in meaningful ways through semantic markup languages and metadata, but these approaches require significant technological expertise. Data standards link disparate data. They bridge boundaries between heterogeneous communities, but they may also create and reinforce them (Ottinger 2010). For example, data standards can establish scientific authority among experts and help those reusing data determine credibility (Ottinger 2010). If data are to be effectively integrated and reused across programs (i.e., in the inter-program dimension), trust and an understanding of how the data were collected must be able to be discerned from merged datasets. Standard data collection protocols may not be adequate indicators of data quality; the ability to *understand* data collected by others may be more critical to subsequent reuse (Zimmerman 2008).

Standards also play an important and often hidden role in shaping the uneven terrain between citizen scientists and web developers (Ottinger 2010). Data standards may establish some knowledge as authoritative and some communities as credible data generators, while marginalizing alternative knowledge production processes (Ottinger 2010) such as those emerging from citizen science. Some advocate that citizens develop standards through the emergent processes of Web 2.0 social networks such as in OpenStreetMap or WikiMapia where volunteer citizens themselves create pseudo-controlled vocabularies. Should plant life form options be labeled as "grasses, forbs, and shrubs"or "herbaceous and woody?" The answer may emerge through, and be decided by, those using the system. These processes allow for self-policing; according to the founder of OpenStreetMap, "The best data quality control [may be] no quality control at all" (Coast 2010; personal communication).

6.3. Maintenance and long-term support

Despite the hubris surrounding new technical solutions for effective data standards, data sharing, and cyber-infrastructure development, this excitement may mask complications experienced by developers (Ribes and Finholt 2009). Novel platforms may not meet the needs of citizen science programs. These exciting solutions may not offer the functional stability required by daily use. They may not simultaneously promote both knowledge seeking and data contribution motivations (Phang et al. 2009) and they may lack human resources to maintain and upgrade technology (Ribes and Finholt 2009). The steadfast reality is that developing a cyber-infrastructure requires long term funding and support. Developers must primarily be concerned with motivating contributors, aligning end goals, and designing systems focused on use (Ribes and Finholt

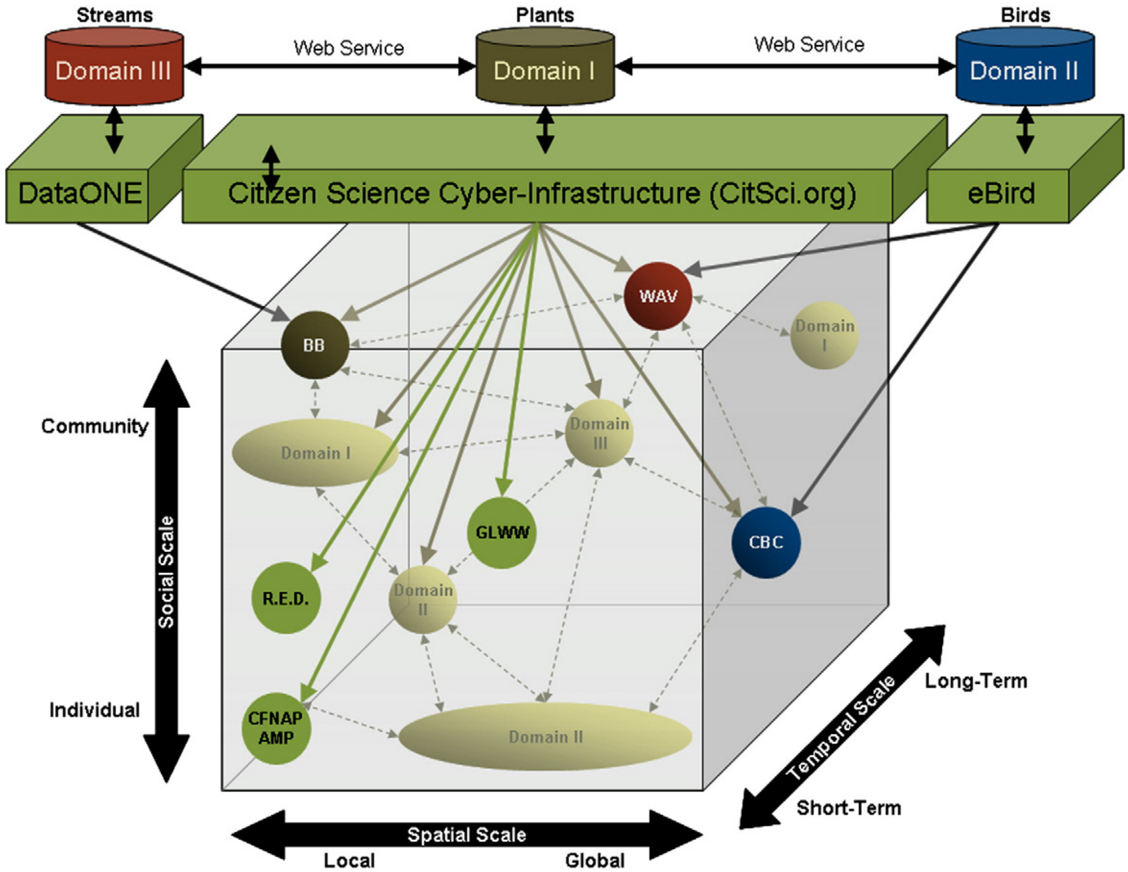

Fig. 3. Vision of the future of cyber-infrastructure support for multi-scale citizen science programs. There may be many instances of citizen science programs in Domain I (plants) that are situated in different spatial, temporal, and social spaces. For example, the Soapstone Prairie Bio-Blitz was a community event that occurred over a short time scale (a weekend during spring 2009) on a local scale. The Water Action Volunteers program (WAV; streams) is a statewide community-oriented program operating over many years (long term). The Christmas Bird Count (CBC; Birds) is a national, long term, individual affair occurring annual on Christmas day. Each citizen science program interacts with each other (dashed lines) and is supported by cyber-infrastructure systems (solid lines). There may be several domain-specific databases (canisters) that interoperate and exchange data between each other and other cyber-infrastructure systems through web services. Example programs such as the Great Lakes Worm Watch (GLWW); Project Riverine Early Detectors (R.E.D.); and City of Fort Collins Natural Areas Program Amphibian Monitoring Project (CFNAP AMP) are supported by a cyber-infrastructure system such as CitSCi.org rectangular box along the top). Ideally, there would be numerous cyber-infrastructure support systems (additional rectangular boxes along the top; not shown for simplicity) that in turn exchange data with each other.

2009). We dealt with this reality by relying on a flexible database architecture, using object-oriented design, adhering to "make versus buy" analyses, creating a system that supports online projects that can be created by our users themselves, using a "train the trainer" approach, making use of open source libraries where feasible, using third party APIs where appropriate, and integrating a web skin module into our cyber-infrastructure.

7. Conclusions

We conclude by offering a vision for the future of citizen science data management, informatics, and cyber-infrastructure support (Fig. 3). We anticipate that there will be many citizen science programs in a given domain (e.g., Domain I; plants; Fig. 3) that are situated in different spatial, temporal, and social spaces. For example, the Soapstone Prairie Bio-Blitz was a community event that occurred over a short time scale (a weekend during spring 2009) on a local spatial scale. The Water Action Volunteers program (WAV; Fig. 3) is a statewide community-oriented water quality monitoring program operating over many years (long term). The Christmas Bird Count (CBC; Fig. 3) is a national, long term, individual affair occurring annually on Christmas day. We envision a scenario where each citizen science program interacts with each other (dashed lines) and is supported by cyber-infrastructure systems such as CitSCi.org, iSpot, or DataONE. There may be several domain-specific cyber-infrastructure systems that interoperate and exchange data between each other and other systems through web services. Meanwhile, numerous small-scale citizen science programs (examples include: Great Lakes Worm Watch, GLWW; Project Riverine Early Detectors, R.E.D.; and City of Fort Collins Natural Areas Program Amphibian Monitoring project, CFNAP AMP) symbolized by ovals in Fig. 3 are supported by existing cyber-infrastructure systems (Fig. 3).

This vision (presented conceptually in Fig. 3) may only be achieved by finding a balance between supporting the specific needs of individual citizen science programs while also meeting the needs of those wishing to integrate and synthesize data across many programs. There is a tension between supporting specific program needs, while simultaneously encouraging sharing and standardization between programs. This tension will need to be addressed to improve data management approaches. Better use of shared and vetted controlled vocabularies, standardized protocols, and standardized evaluation measures will better integrate these networks and leverage their assets in creative ways. Such integration may enable more effective and easily accomplished meta-analyses across programs and ensure minimal duplication of effort locally, regionally, and nationally. However, improved data sharing may not necessarily lead to improved dissemination and understanding; it may only increase issues related to "information over-abundance."

The volumes of data now generated by citizen science programs and by professionals alike may create a situation in which land managers and decision makers are drowning in data. They may become threatened by a tyranny of data on the one hand, and inefficient and costly means to managing existing data on the other. Future cyber-infrastructure support systems will need to offer value-added data analysis and synthesis services to reach their full potential and better serve citizen science program needs. Automated summary reports and statistics using integrated datasets will help complete the data dissemination lifecycle — bringing meaningful results back to land managers, decision makers and citizen volunteers alike. Integrated program evaluation capabilities will help cyber-infrastructure systems better assess program outcomes essential to future funding support. Increased and appropriate use of Web 2.0 features such as RSS feeds and social networking may improve communication among citizen science programs and the volunteers, coordinators, and scientists that comprise them.

Nevertheless, pressing questions remain. What are the capabilities and capacities of those using cyber-infrastructure? What is required to support traditional ecological knowledge provided by participants from different cultures? What programs are in place to educate and train the next generation of users of online scientific exploration tools and cyber-infrastructure applications? Does cyberspace represent the next frontier for scientific analysis tied to community-driven social needs? How can we fund the development and long-term maintenance of support systems?

Resources supporting the cyber-infrastructure system development and maintenance are sparse. Despite this reality, we aim to improve the social networking, analysis, visualization, program evaluation, and customization of the CitSci.org system. Future citizen science program success may hinge on the flexibility and adaptability of these multi-scale cyber-infrastructure support systems. The practical work of developing long-term cyber-infrastructure system development supporting multi-scale citizen science will not be not easy. It will require sustainable technology, persistent human arrangements, stable institutional resources, and innovative system design to accommodate and adapt to citizen science program requirements (Ribes and Finholt 2009). The real and anticipated benefit of citizen-contributed data lies in data integration with other datasets and the subsequent analysis and use of these data to help solve problems, make science-based decisions, and answer ecological questions.

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