FEATURE

Crowd-Sourced Databases as Essential Elements for Forest Service Partnerships and Aquatic Resource Conservation

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Published 2018. This article is a U.S. Government work and is in the public domain in the USA
DOI: 10.1002/fsh.10083

High-quality information is needed for conservation and management of aquatic resources on lands administered by the U.S. Forest Service (USFS). Information is ultimately derived from data, so the USFS maintains a series of databases that are used to describe the status and trends of aquatic habitats and biota. The databases are spatially explicit and are crowd-sourced, meaning that distributed networks of professionals and technicians operating throughout the National Forest System collect stream and biological measurements, which are stored in central repositories. How those databases are developed is evolving and ranges from agency-specific endeavors to collaborative projects that involve dozens of natural resource organizations and extensive user-communities throughout the USA. The rate of data collection is accelerating and databases now often encompass millions of records, so proper archiving and maintenance by information technology specialists are necessary to maximize the utility of data for natural resource planning. Here, we describe several of the aquatic databases maintained by the USFS, applications arising from novel syntheses of databases, and the increasingly important roles databases play in collaborative partnerships and cost-effective stewardship of aquatic resources.

The need for good information is common to all topics in this special issue of *Fisheries*. Whether U.S. Forest Service (USFS) managers, cooperators in other agencies, and partner organizations are trying to understand how fish and other aquatic species are distributed on public lands or how habitat and populations are affected by management activities (e.g., grazing, timber harvest, and road construction) or new threats (e.g., climate change and larger wildfires), information at many scales is essential for resource stewardship of complex ecosystems (Loftus and Flather 2012; Penaluna et al. 2018, this issue; Roper et al. 2018, this issue). The USFS, as a land management agency founded on the principle of scientifically based multiple-use management set forth by Gifford Pinchot (Egan 2009), relies on numerous databases compiled at forest, regional, and national scales to store, summarize, and analyze many types of measurements that are pertinent to aquatic species and their habitats. These databases are crowd-sourced in the sense that distributed networks of professional biologists, hydrologists, and technicians operating throughout the National Forest System collect data, which are then stored in central databases for use during the course of Forest Plan revisions and status assessments, National Environmental Policy Act analyses, Endangered Species Act consultations, and a variety of research endeavors. Some of these databases are accessible primarily to USFS personnel, but a new generation of databases is making use of information technologies to broaden the scope of those who contribute and use the data to include professionals from state, tribal, and other federal agencies; universities; consulting firms; and nongovernmental organizations. That evolution parallels the agency's move toward accomplishing fisheries conservation through a growing emphasis on collaborative partnerships (Gillespie et al. 2018, this issue; Shively et al. 2018, this issue). Key to fostering those partnerships are transparency and data access so that a common understanding of complex conservation issues and potential remedies can form the basis for collective actions (Hampton et al. 2015). The goal of this article is to describe several aquatic resource databases maintained by the USFS, highlight examples of their use, and clarify database roles in resource management.

TRADITIONAL AQUATIC DATABASES

The corporate data management system accessible to USFS employees for most resource information is Natural Resource Manager (NRM). The NRM system consists of more than 60 applications built on an Oracle platform housed at the U.S. Department of Agriculture's Enterprise Data Center in Kansas City, Missouri. Those data and applications inform field-level resource inventories, natural resource projects, timber sales, permit issuance, recreation use, resource analyses, and decision-making processes as directed by a variety of legal requirements and agency mandates. The diversity of data types associated with NRM reflects the agency's multiple-use mission, but the subsets of data most relevant to aquatic resources are centralized in the Aquatic Surveys (AqS) application of NRM. The application includes modules for data related to aquatic species occurrence, abundance, and habitat conditions in stream–river, lake–pond, and spring–wetland environments; surveys of aquatic organism passage at natural and constructed barriers; water and air temperature monitoring; and valley-segment-scale assessments of geomorphic and hydrologic variables (Table 1). Metadata describing data collection protocols and methods are captured to provide context for data quality. The number of records varies by data type and region depending on the concerns of local managers, the prevalence of USFS lands, and corporate data management practices. For example, the number of lake, pond, and amphibian surveys from the Pacific Southwest (Region 5) greatly exceeds those from other regions because emphasis has been placed on data collection for several endangered species of amphibians (Table 1). Surveys for aquatic organism passage, in contrast, are more uniformly distributed among regions because habitat fragmentation at forest road crossings is an issue throughout the country. The data in NRM-AqS are usually entered by personnel at individual national forests but can be summarized for reports or analyses at regional or national levels when needed. In circumstances where a large backlog of data develops and overwhelms available personnel time for uploads to NRM-AqS, additional resources may be directed toward data archiving (Box 1). In some instances, historical data sets may exist only as paper records, and digitization is required before database storage is possible.

To be useful for resource management, data must be spatially explicit (i.e., associated with accurate geographic coordinates) so it can be combined with other data sets for reporting and analysis. That requirement was recognized early in the development of NRM-AqS, which relies on the 1 : 24,000-scale National Hydrography Dataset (NHD) to provide a geospatial framework that is consistent throughout the full extent of the National Forest System (Moore and Dewald 2016; Viger et al. 2016). Each stream reach in the NHD has a unique identifier, is attributed with topological information, and is georeferenced in a cartographic projection system. When aquatic data are entered into one of the NRM-AqS modules, geographic coordinates are also entered and can be used to associate the data with the appropriate stream reach as well as other data previously entered into NRM-AqS for the same location. Nationally consistent data sets of reach descriptors (e.g., elevation, slope, watershed area, etc.) have also been developed that link to NHD

Table 1. The Aquatic Surveys application within the U.S. Forest Service's (USFS) corporate data management system (Natural Resource Manager) contains seven submodules hosting data for the types of surveys that are most frequently conducted by agency biologists. A survey consists of a discrete sampling event at one point in time. Most survey data are from the last 20–30 years, but some surveys date back to the 1960s and may be especially valuable for descriptions of historical conditions. Variability in the amount of data reflects differences in local management concerns and the prevalence of USFS lands throughout the country.

USFS region	Amphibian	Lake–pond	Stream–river	Spring–wetland	Passage	Temperature	Valley segment
Northern (Region 1)	0	848	20,566	0	5,034	9,280	0
Rocky Mountain (Region 2)	695	102	4,774	0	400	519	116,877
Southwestern (Region 3)	85	16	1,358	11	20	152	0
Intermountain (Region 4)	57	305	15,057	0	2,941	3,199	0
Pacific Southwest (Region 5)	20,635	16,231	18,083	262	2,172	7,160	0
Pacific Northwest (Region 6)	0	32	23,505	0	2,149	17,779	0
Southern (Region 8)	0	0	10,333	0	339	0	0
Eastern (Region 9)	0	354	19,114	0	10,561	3,042	0
Alaska (Region 10)	0	192	7,058	0	6	438	0
Total	21,472	18,080	119,848	273	23,622	41,569	116,877

BOX 1
MIGRATING DATA FROM DESK DRAWERS INTO DATABASES

Cold stream temperatures are critical for many species of concern in the U.S. Forest Service's Pacific Northwest Region, so agency personnel conduct extensive temperature surveys at thousands of sites on national forest lands (Table 1). Those surveys are usually performed using inexpensive sensors that record hourly temperatures for continuous periods spanning weeks, months, or years. Many surveys were conducted prior to the development and widespread adoption of the Aquatic Surveys (AqS) application in the Natural Resource Manager (NRM) system, which meant that large amounts of data had accumulated on scores of different computers at offices throughout the region. The lack of a central database made it difficult to efficiently summarize and share data within the agency or with state and regional partners where assessments at large spatial and temporal scales were needed. The availability of NRM-AqS to store data, the increasing need to conduct climate change vulnerability assessments on national forests, and the emergence of the Northwest Stream Temperature project (Isaak et al. 2017b) as a comprehensive interagency temperature database catalyzed efforts to organize and centralize disparate data sets into a single database.

The first step in organizing the Pacific Northwest Region's large legacy temperature data sets was defining the scope of the required effort. A simple questionnaire was provided to staff across the region to estimate the number of surveys that had been conducted, the number of different sites visited, and survey dates. Next, a data migration guidebook was developed to provide detailed procedures for (1) prioritizing and preparing data for entry into NRM-AqS, (2) defining specific temperature surveys with unique locations and monitoring time frames, (3) importing data into NRM-AqS, (4) identifying potentially erroneous data using a quality assurance/quality control algorithm, (5) editing and deleting data, and (6) visualizing data via tables, graphs, and maps. After the migration procedures were developed, online training was provided to specialists from each of the 17 national forests in the Pacific Northwest Region, and the specialists then worked to import temperature data sets into NRM-AqS.

Organizing and migrating the large amount of legacy temperature data (48 million temperature recordings from 14,000 sites spanning decades of monitoring) into NRM-AqS were accomplished over 4 years with a US$250,000 investment in personnel time. This cost-effective effort resulted in a robust resource that is available now and in the future for various analyses to inform resource decision making at a broad range of spatial and temporal scales. After this project, stream temperature monitoring efforts have been better coordinated, and reuse of existing data for multiple purposes increased the efficiency of conservation efforts and impact assessments. Moreover, the concerted effort to properly archive temperature data helped to foster a culture of improved data stewardship while ensuring that the data are available to future generations of resource stewards as they continue the work of conserving and managing aquatic habitats and biota.

reaches based on the unique identifiers (McKay et al. 2012; Hill et al. 2016). Those descriptors can be used to attribute measurements taken within reaches, to query networks, and to visualize results within geographical information systems (GIS) and can serve as covariates in predictive models (Isaak et al. 2017a).

The condition of aquatic habitats on USFS lands and the effects of management and restoration on those habitats have long been an agency focus. To meet those needs, two flagship stream monitoring programs—the PACFISH/INFISH Biological Opinion (PIBO) and the Aquatic and Riparian Effectiveness Monitoring Program (AREMP)—were established in the northwestern USA to inventory and assess stream habitats in watersheds with significant federal ownership by the USFS and Bureau of Land Management (Kershner et al. 2004a; Reeves et al. 2004; Roper et al. 2018, this issue). The monitoring programs span dozens of national forests and five state Bureau of Land Management offices and were implemented with random sampling designs to ensure their representativeness. Summer field crews use standardized habitat measurement protocols and annually resample several hundred of the more than 2,500 stream sites encompassed by the programs (Figure 1). The resultant databases include extensive measurements of stream substrates, channel units, bank conditions, large wood, temperature, riparian vegetation, and macroinvertebrate communities (Kershner et al. 2004b; Al-Chokhachy et al. 2010; Lanigan et al. 2012). The PIBO and AREMP databases are available online and in summary reports that describe the status and trends of stream and watershed conditions for planning purposes (PIBO: http://fsweb.r4.fs.fed.us/unit/nr/pibo/index.shtml; AREMP: https://reo.gov/monitoring/reports/watershed-reports-publications.shtml).

COLLABORATIVE INTERAGENCY DATABASES

Concerns about climate change, particularly its potential effects on coldwater fishes like the trout, salmon, and char that occur extensively throughout USFS lands, spurred development of the Northwest Stream Temperature (NorWeST) database for the western USA (Figure 2A; Chandler et al. 2016; Isaak et al. 2017b). The NorWeST database is crowd-sourced but marks a departure from previous USFS databases because it includes data contributed by multiple agencies that monitor stream temperatures in the region. Data from NRM-AqS, PIBO, and AREMP constitute a large proportion of the NorWeST database but were integrated with data contributed by more than 100 state, federal, tribal, commercial, and non-governmental organizations to form a comprehensive archive for broad use by the aquatic conservation community. Also noteworthy were the funding and science data-team models used in the NorWeST project. The expertise of USFS scientists and database professionals, as well as collaborating scientists at universities and other federal agencies, were used as in-kind contributions to leverage small grants from many sources that were interested in developing stream temperature databases for different portions of the western USA. Most of the grant funding was then used to support a team of two to four people that focused exclusively on aggregating and organizing data from contributing agencies. Quality assurance/quality control procedures were applied to create a standardized database of stream temperature records that is probably the largest in the world (220 million hourly temperature recordings from 23,000 stream and river sites) and would require US$10–15 million to replicate but was developed at a fraction of that cost. To provide access to the database, a custom Web site was designed and hosts temperature data sets and climate scenarios in user-friendly Excel, Adobe, and ArcGIS file formats, which are also

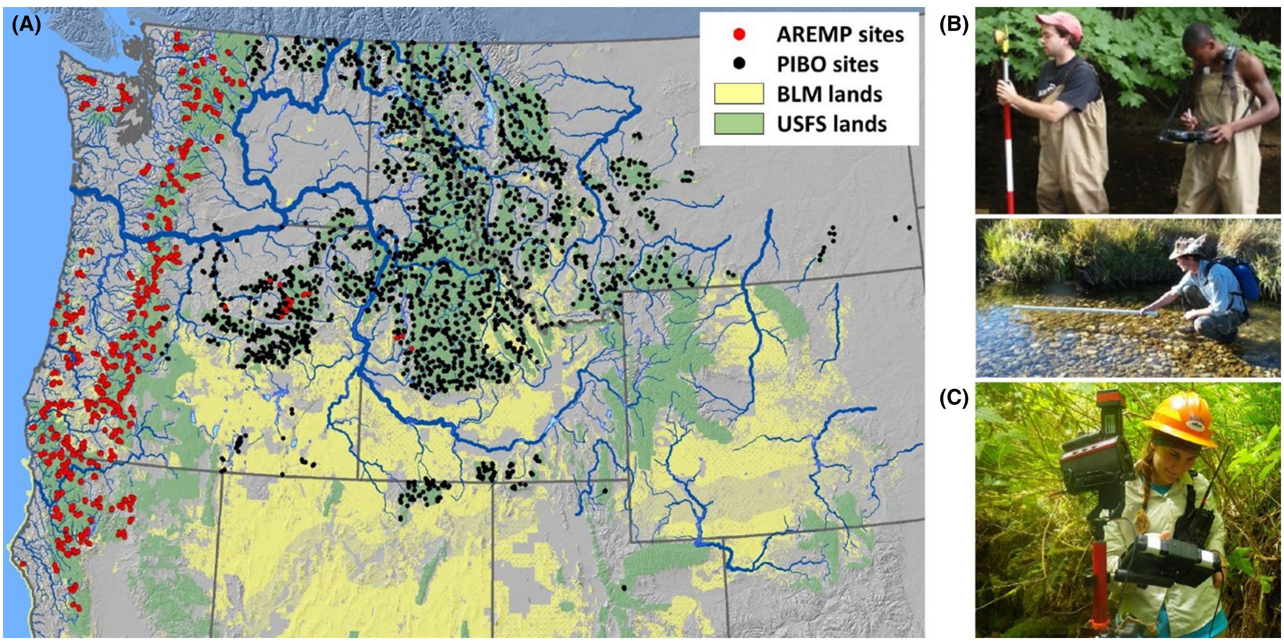

Figure 1. **(A)** An extensive network of more than 2,500 stream sites throughout headwater watersheds in the northwestern USA are monitored by the U.S. Forest Service (USFS) and the Bureau of Land Management (BLM) to describe the status and trends of stream fish habitats and to understand the effects of land management activities (AREMP = Aquatic and Riparian Effectiveness Monitoring Program; PIBO = PACFISH/INFISH Biological Opinion). **(B)** Standard protocols are used at each site by technicians to collect data that are **(C)** recorded with field computers to minimize errors and expedite downloads into a database after crews return to the office. Photo credits: C. Hirsch and D. Isaak.

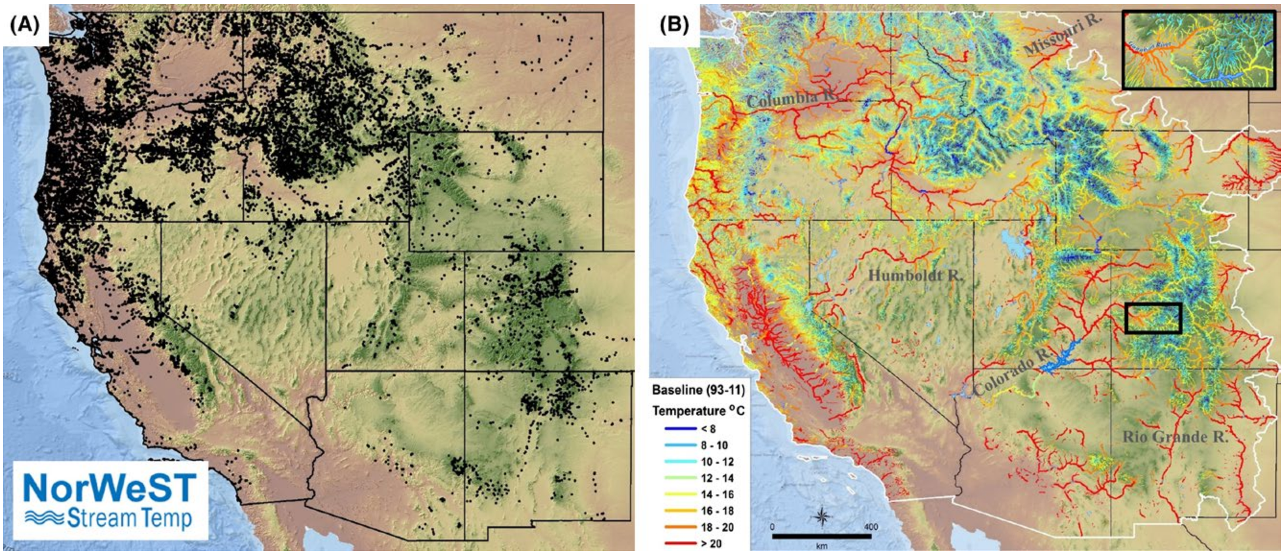

Figure 2. **(A)** Locations of 23,000 sites in the western USA where stream and river temperature data were compiled from over 100 natural resource organizations to create the Northwest Stream Temperature (NorWeST) database. **(B)** The database is accessed by a large user-community through a project Web site and is used for many purposes, including the development of accurate temperature scenarios for rivers and streams.

integrated with NHD streamlines (https://www.fs.fed.us/rm/boise/AWAE/projects/NorWeST.html). The NorWeST Web site serves a broad user community that downloads hundreds of data products annually for purposes that include species' climate vulnerability assessments, interagency coordination of temperature monitoring networks, and research on temperature regimes and thermal ecology (Williams et al. 2016; Isaak et al. 2017b).

Among the key data products from NorWeST are high-resolution, 1-km modeled climate scenarios of historic and future stream temperatures for all rivers and streams and 101 national forests in the western USA (Figure 2B; Isaak et al. 2016). Combining those scenarios with large fish and amphibian occurrence data sets from NRM-AqS and state agency partners (Idaho Department of Fish and Game; Montana Fish, Wildlife, and Parks; and Wyoming Game and Fish Department) provided descriptions of thermal niches for aquatic species and a broad view of the thermal risks posed by climate change (Isaak et al. 2017c). For two coldwater species of concern (Cutthroat Trout *Oncorhynchus clarkii* and Bull Trout *Salvelinus confluentus*), their apparent vulnerability to climate change stimulated development of the Climate Shield species distribution models to forecast which streams are most likely to serve as long-term climate refugia and might therefore be cornerstones in species conservation efforts (Figure 3; Isaak et al. 2015). Similar to NorWeST, a custom Web site was developed for the Climate Shield project to host the fish database used in model development as well as precise maps of current and future trout distributions in user-friendly file formats to assist managers with site-specific planning (https://www.fs.fed.us/rm/boise/AWAE/projects/ClimateShield.html).

PROACTIVE INTERAGENCY DATABASES

The NorWeST and Climate Shield databases were developed from post hoc organization of existing data sets, which was relatively inefficient because agencies often unnecessarily resampled many of the same sites prior to the development of shared databases. A better approach would be to first design a database that is tailored to a specific project, coordinate data collection efforts that efficiently populate the database, and provide the data back to the user-community in a timely fashion. That proactive approach forms the basis of the latest generation of crowd-sourced databases being developed for aquatic environmental DNA (eDNA) samples collected in partnerships with the USFS National Genomics Center for Wildlife and Fish Conservation (NGC; https://www.fs.fed.us/research/genomics-center). Scientists at the NGC have developed robust field sampling and laboratory protocols for collecting and analyzing aquatic eDNA samples (Carim et al. 2016; McKelvey et al. 2016) that are used by hundreds of biologists from dozens of organizations to sample thousands of stream, river, wetland, pond, and lake sites annually throughout North America. Results from those samples, with permission from the original data collectors, are passed to USFS scientists at the Aquatic Sciences Laboratory in Boise, Idaho, for integration into the eDNAtlas database (Young et al. 2018) and distribution through a project Web site (https://www.fs.fed.us/rm/boise/AWAE/projects/aquatic-eDNAtlas.html). As the eDNAtlas database has grown to include thousands of sample sites, it provides spatially precise information about the distribution and abundance of many species throughout their ranges on and near national forests. Those data are essential for basic status and trend assessments (Loftus and Flather 2012) as well as research projects to model and understand species distributions and the constraints imposed by environmental and habitat conditions (Elith and Leathwick 2009). Importantly, by developing and sharing the contents of the eDNAtlas among numerous agencies and users as it is populated, redundant sampling is minimized and cost effectiveness is maximized.

Integral to the eDNAtlas is the Rangewide Bull Trout eDNA Project, which has crowd-sourced an inventory of the species' potential habitats in numerous streams (Young et al. 2015). The project's proactive database illustrates the powerful synergies that emerge from the integration of databases with new information technology. The GIS data sets

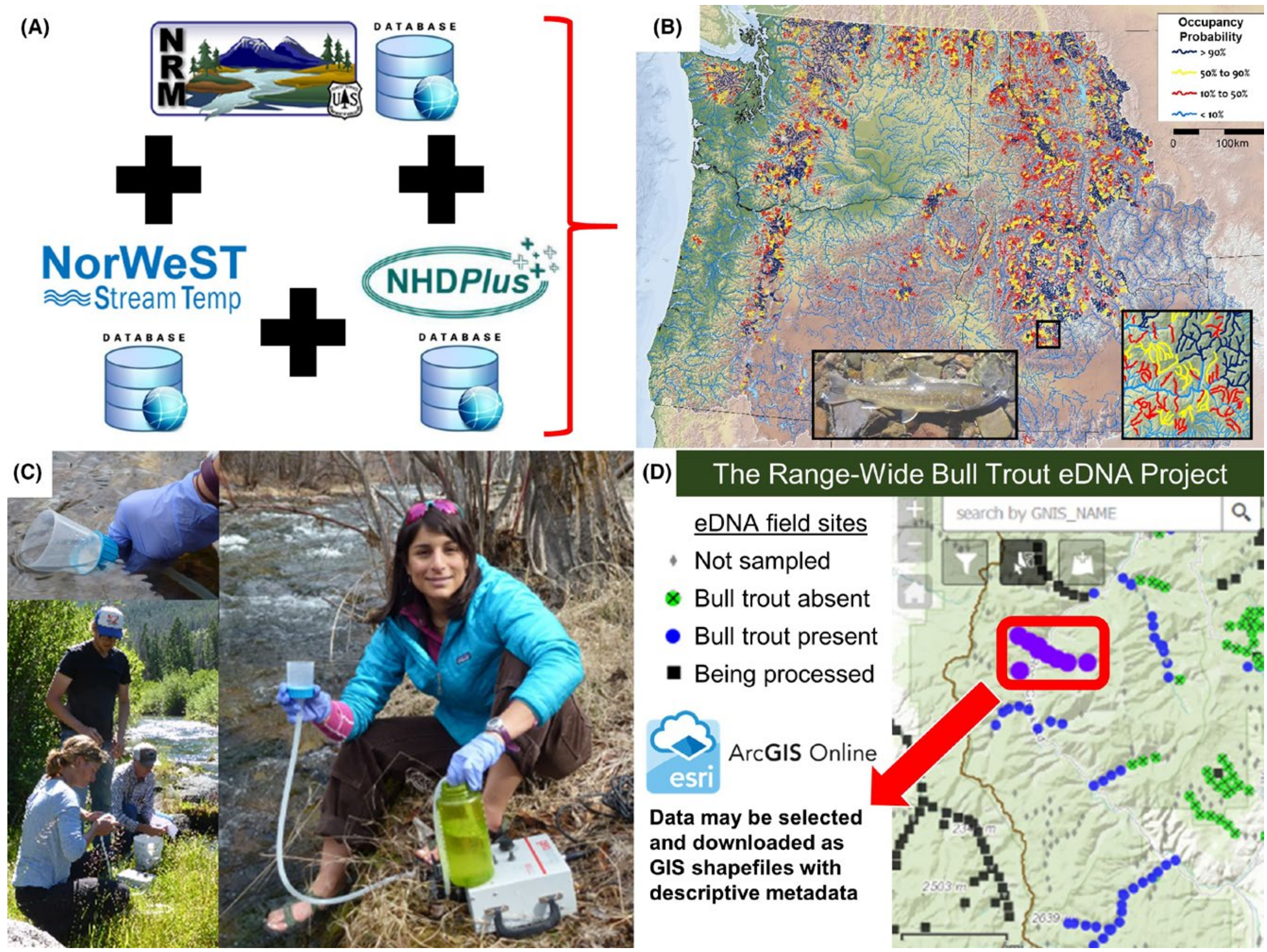

Figure 3. Integration of existing databases, scientific models, and new information technology that enables dynamic online data distribution creates powerful synergies. In this example, **(A)** fish survey data from the Aquatic Surveys application in the Natural Resource Manager (NRM) system were combined with Northwest Stream Temperature (NorWeST) scenarios and National Hydrography Dataset (NHD) stream reach habitat variables to develop **(B)** the Climate Shield species distribution model that predicts where potential Bull Trout *Salvelinus confluentus* habitats occur throughout the species' range. **(C)** In streams where biologists are uncertain about whether a Bull Trout population occupies a potential habitat, environmental DNA (eDNA) surveys are used with modeled maps of habitat locations to conduct efficient field surveys, and **(D)** the data results are shared publicly through a dynamic ArcGIS Online tool at a project Web site.

of modeled habitat maps developed in the Climate Shield project guide eDNA sampling efforts by dozens of volunteers from multiple agencies and nongovernmental organizations in streams where Bull Trout distributions are poorly understood (Figure 3). The volunteers navigate to predetermined stream sites using Global Positioning System receivers, collect eDNA samples following the NGC protocol (Carim et al. 2016), and mail samples to the NGC laboratory for processing. In the first year of the project, eDNA samples were collected at 3,000 stream sites across a five-state area, and results were distributed through a project Web site (https://www.fs.fed.us/rm/boise/AWAE/projects/BullTrout_eDNA.html). An ArcGIS Online tool allows users to dynamically query the master database and download Bull Trout eDNA survey results in digital file formats accompanied by descriptive metadata (Young et al. 2017). Results have provided managers with definitive information for conservation decision making at many stream locations (Box 2). The value and cost effectiveness of developing the interagency database were recognized immediately and spurred additional interest in the project, which continues to coordinate sampling efforts among professional biologists and citizen scientists throughout the Bull Trout.

GROWING DATABASES, PARTNERSHIPS, AND SYNERGIES

As the preceding examples illustrate, coordinated monitoring and databases are integral to aquatic resource stewardship on USFS lands. The size and quality of databases continue to increase, and these trends are accelerating as data's inherent value is recognized, synergies emerge, and the technical proficiency of user-communities grows (Hampton et al. 2017). Challenges exist with regard to digitizing and migrating legacy data sets that remain common throughout the National Forest System, as well as maintaining or developing teams of scientists and information technology specialists who are capable of managing large databases and developing useful information from these rich sources, but the future trajectory is clear (Hampton et al. 2013). Efficiency and utility grow rapidly once databases are created and user-communities are engaged—the latter readily achieved through the use of inexpensive

BOX 2
ENVIRONMENTAL DNA SAMPLING TO DESCRIBE RANGEWIDE BULL TROUT DISTRIBUTIONS

Bull Trout *Salvelinus confluentus* are widely distributed in the northwestern USA, where they occur on portions of 33 national forests but have declined significantly from historical abundances. Bull Trout are listed as threatened under the U.S. Endangered Species Act, so their occurrence has an important influence on land and water management and planning. Because the species is often present at low densities and in remote locations, it is difficult to sample by using traditional methods like snorkeling and electrofishing, and many potential habitats have been sampled infrequently or not at all. The high detection efficiencies and reduced logistical requirements of environmental DNA (eDNA) sampling (Wilcox et al. 2016) led the U.S. Forest Service and the U.S. Fish and Wildlife Service (USFWS) to adopt its use to resolve uncertainties about Bull Trout distributions in species recovery planning (USFWS 2015). To comprehensively address that need, the Rangewide Bull Trout eDNA Project was initiated and coordinated by the National Genomics Center for Wildlife and Fish Conservation. A reliable and inexpensive field protocol (Carim et al. 2016) was used to sample systematically throughout streams that were predicted by the Climate Shield model to have some probability of Bull Trout occupancy or in locations designated as critical habitat by the USFWS. Project collaborators rapidly resolve the aforementioned distributional uncertainties (Figure 3) while also resolving the headwater extent of many Bull Trout populations in basins previously known to be occupied in downstream areas. Especially exciting has been the discovery of new Bull Trout populations as well as the rediscovery of populations that had not been detected in recent decades. Some of these populations were unexpectedly found above historical fish barriers, such as waterfalls, which is leading to a better understanding of the diversity of Bull Trout life histories and the amount of habitat required to support populations. Just as valuable has been the confirmation that Bull Trout are absent from many locations, which has reduced the administrative requirements associated with local project planning and regulatory compliance. The eDNA samples have also revealed temporary use of cold microrefugia by Bull Trout during peak summer temperatures and extensive movements by itinerant individuals. The crowd-sourced, open-access Bull Trout eDNA database has grown rapidly and is popular with the user community. The project Web site received about 6,000 visits in its first year, which led to downloads of hundreds of data products and the recruitment of new volunteers to continue sampling streams throughout the distribution of this species of concern.

communication media, such as Web sites, blogs, webinars, and e-mail chat. As a network of information flow is created among researchers, managers, planners, and regulators, a positive feedback cycle emerges wherein new data are collected more efficiently and existing data are frequently reused. Making databases accessible through Web sites also provides public accountability and facilitates the trend toward open science, which empowers more scientists to develop new models and better information more rapidly and inexpensively than has historically been the case (Hampton et al. 2015). Finally, because the NHD provides a nationally consistent geospatial framework that is used by most natural resource agencies, the integration of multiple databases with similar kinds of data to create metadatabases becomes possible. As the number of available databases grows, they may be used with geospatial tools to conduct synthetic analyses (sensu Poisot et al. 2015) that yield valuable new information, as was the case with the Climate Shield models and subsequent eDNA survey efforts.

Although the crowd-sourcing approach to database compilation and use is not exclusive to the USFS in this era of big data and citizen science (Hampton et al. 2013, 2015; Prudic et al. 2017), the agency is uniquely positioned to capitalize on these trends. An extensive land base, a dedicated workforce distributed across those lands, and a research branch that exists to assist managers in conservation management are key elements. Equally important, the aquatic habitats on national forest lands support some of the strongest populations and largest blocks of habitat for high-profile aquatic species of concern (Hudy et al. 2008; Penaluna et al. 2016; Roper et al. 2018, this issue), so these lands often form the de facto backbone of regional conservation efforts and provide a logical nexus around which collaborative partnerships can be built (Isaak et al. 2015; Shively et al. 2018, this issue). Shared databases developed collectively will be integral to cementing those collaborations and ensuring that the agency rises to the future's new challenges in aquatic resource conservation.

ACKNOWLEDGMENTS

John Rothlisberger and Dan Shively led efforts to develop this special issue of *Fisheries* and provided us with the opportunity to make this contribution. An earlier draft of the manuscript was improved by comments from Mary Barczak, Gary Curtis, and an anonymous reviewer. There is no conflict of interest declared in this article.

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