ARTICLES

Delineating Climate Refugia for Native Aquatic Species with Big Crowd-Sourced Databases

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Topographic diversity is the essence of mountain environments in western North America, a diversity that manifests itself hydrologically in a host of forms—rivers, streams, lakes, wetlands, and springs—that constitute habitats for a wealth of fish, amphibians, mussels, and insects. Some of those taxa, such as species of salmon and trout, are well studied icons of the region, whereas others are known only to dedicated naturalists or have yet to be described by science. Climatic controls on the distribution and abundance of aquatic taxa are of longstanding interest to aquatic ecologists and researchers given the aridity of much of the western U.S. and the strong environmental gradients driving biodiversity patterns from headwaters to lowlands. In fact, some of the first global research predicting how anthropogenic climate change could affect popular cold-water trout species occurred in the Rocky Mountains more than 20 years ago (Keleher and Rahel 1996). Early estimates of the potential habitat losses that warming could cause were a source of widespread concern and have stimulated ongoing research ever since. Most recently, historical resurvey efforts have confirmed that distributions of trout species are shifting coincident with warming (Eby et al. 2014), and these have heightened interest in identifying habitats that may serve as climate refugia for species preservation.

More Precision, Please

One limitation of early bioclimatic models that often persists to the present is their coarse resolution. That is, the models may be accurate in predicting an unbiased representation of species distributions and climatic conditions but are based on sparse underlying datasets that require extensive interpolation among observations to create the continuous prediction surfaces and maps that represent conditions during different climatic periods. The result is local imprecision that makes it difficult to use the information for guiding site or project-level climate adaptation responses and conservation investments. Compounding matters for many aquatic climate assessments is that air temperature has often been used as a surrogate for water temperature because data on the latter were lacking in many areas.

At about the same time that climate change awareness was dawning for aquatic professionals in the 1990s, inexpensive temperature sensors were developed, marketed, and adopted by many natural resource agencies as a basic habitat monitoring tool because of temperature's importance to ectothermic organisms. Temperature monitoring in the two decades since has occurred for many purposes but increasing climate concerns, combined with an accumulating mass of data, provided a need and an opportunity to develop a central database that would service the needs of multiple agencies and that could be used to develop precise climate scenarios across broad areas. Beginning with seed grant funding from the Landscape Conservation Cooperatives, the NorWeST (Northwest Stream Temperature) project was initiated in 2011 and recently completed scenarios for all flowing waters in the western U.S. (Fig. 1; Isaak et al. 2017). The database consists of >220,000,000 hourly recordings at >23,000 unique sites and was crowd-sourced from data collected by professional biologists and hydrologists with more than 100 state, federal, tribal, municipal, and private resource organizations. Geostatistical models for data on stream networks were fit to the temperature data and used to interpolate summer climate scenarios with 1-km resolution that are distributed as ArcGIS shapefile formats through the NorWeST website (https://www.fs.fed.us/rm/boise/AWAE/projects/NorWeST.html). Open access to the scenarios and database via a central repository has proven popular among resource professionals who visit the website >12,000 times annually, download hundreds of data products, and use the information in climate vulnerability assessments to improve the efficiency of new temperature monitoring, and for new research on water temperature and thermal ecology.

Climate Shield Native Trout Refugia

Developing more precise stream and river temperature scenarios was an important means but not the end of delineating climate refugia at an extent and grain sufficient for conservation planning. The thermal information still needed to be integrated with species ecology, so in 2014 we repeated the crowd-sourcing process but focused instead on compiling a biological database

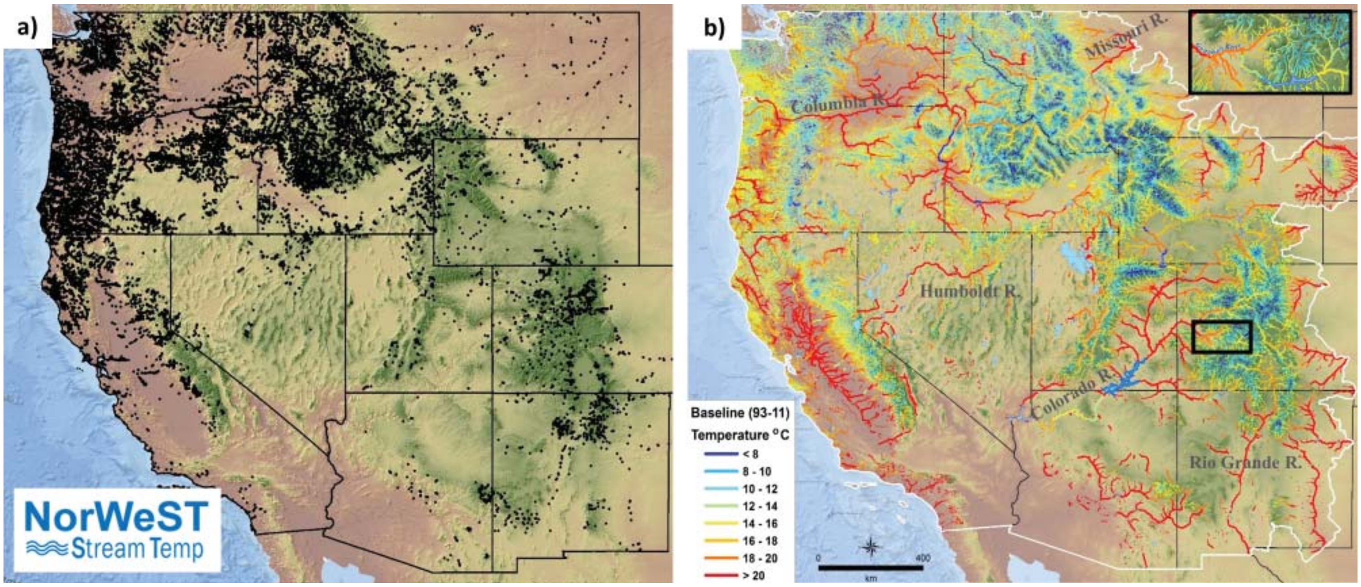

Figure 1. Locations of 23,000 sites in the western U.S. where stream and river temperature data were crowd-sourced from professionals working for more than 100 natural resource organizations to create the NorWeST database (a). The database is accessed by a large user-community through a project website and is used for many purposes, including the development of high-resolution temperature scenarios for rivers and streams (b).

of species occurrence records for two native trout species—bull trout and cutthroat trout—that are of conservation concern in the West. Here again, thousands of observations were available and professionals from state and federal biologists from management agencies were willing to share the data to develop a larger database. Once the database was complete, it was used to develop species distribution models that predicted the probability of trout occurrence as a function of the NorWeST scenarios and other environmental covariates that were obtained from regionally consistent geospatial datasets. Not surprisingly, temperature was a strong predictor of where trout populations occurred, the overall predictive accuracy of the models was good, and the modeled relationships were used to map probabilities of species occurrence for different climate scenarios throughout all streams within the geographic ranges of bull trout (Fig. 2; ~5,000 streams) and cutthroat trout (~20,000 streams).

Those probability maps are powerful tools for assessing the relative quality of current and future habitats throughout the ranges of these fishes. The maps show that not all habitats are created equal, nor do they decline at identical rates with future warming given the local nuances that arise from different combinations of habitat size, geomorphology, and temperature regimes. Most promisingly, some streams were predicted to have high probabilities of supporting trout populations even under the most extreme climate change scenarios, and therefore could serve as long-term climate refugia. Similar to the NorWeST project, all the data and scenario probability maps were organized into user-friendly digital formats and are distributed through a custom website for the Climate Shield project (https://www.fs.fed.us/rm/boise/AWAE/projects/ClimateShield.html). The information is broadly used by many agencies for bull trout and cutthroat trout conservation planning done in association with National Forest plan revisions, endangered species consultations, NEPA analyses, and climate adaptation projects (Isaak et al. 2015; Isaak et al. 2016; Young et al. 2018).

eDNA Opens the Way

Ongoing climate change means that information similar to that provided by the Climate Shield project is needed to delineate refugia for many taxa. Unfortunately, relatively few data exist for most aquatic species in the western U.S. that are not sport-fishes such as trout and salmon, and even information for those taxa is rarely collated into broad databases readily accessible to users. Both shortcomings need to be addressed to position society for informed management of aquatic taxa.

The primary limitation to gathering data on the distribution of aquatic species is methodological. We often rely on specialized techniques that only work for a handful of species in particular environments e.g., backpack electrofishing is suitable for describing small-stream fish communities, but little else. Learning about the presence of many species generally requires multiple visits, different techniques, and wide expertise, and rapidly becomes cost-prohibitive. A recent advance in aquatic species monitoring, however, may revolutionize our ability to sample across the taxonomic spectrum. Because all organisms release DNA into the surrounding environment, detecting that DNA can serve as a tool to infer species presence. This is the

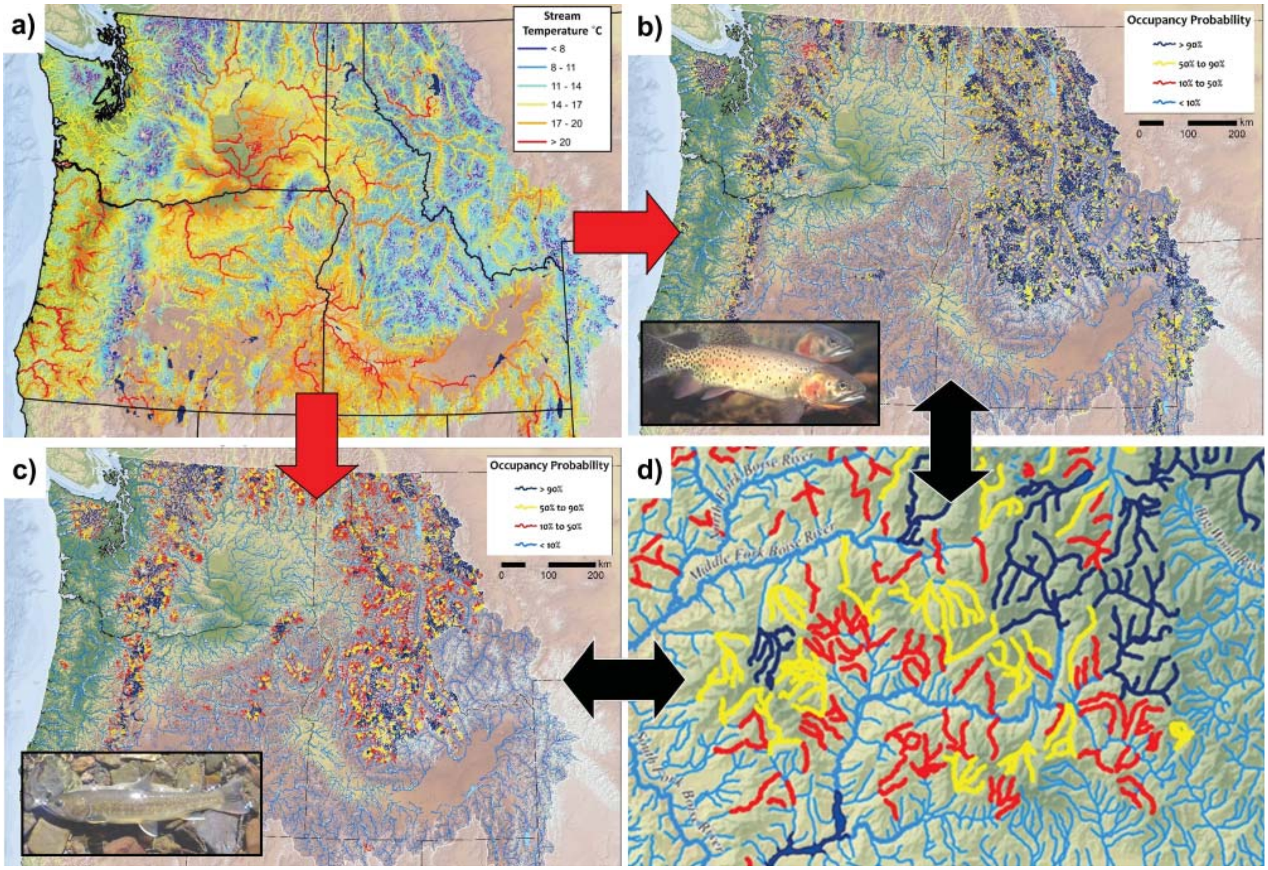

Figure 2. NorWeST temperature scenarios (a) were used with other environmental covariates from geospatial datasets to develop the Climate Shield species distribution models and predict the probabilities of habitat occupancy for cutthroat trout (b) and bull trout (c) throughout their ranges. Climate refuges are identified as those streams which retain high probabilities of supporting local populations during future climate change conditions (d).

premise of environmental DNA (eDNA) sampling, and interest in the field has exploded since its first application late in the last decade (Ficetola et al. 2008).

Much of the ongoing research into eDNA sampling has been in mountain environments in the western U.S. for taxa as diverse as amphibians (Goldberg et al. 2011), fishes (Wilcox et al. 2015), invasive snails, and even a mammal (Padgett-Stewart et al. 2016). Increasingly, this work is directed at characterizing the effectiveness of eDNA sampling relative to traditional methods, and many studies are concluding that eDNA sampling offers several-fold higher detection rates at lower costs (Wilcox et al. 2016). These advantages have led to a number of field applications, particularly to detect the distribution of species of conservation concern, whether rare native taxa or introduced invasive species (Carim et al. 2016a; McKelvey et al. 2016). Among the broadest approaches is the attempt to delineate the distribution of bull trout in natal habitats throughout their entire U.S. range (Young et al. 2017; https://www.fs.fed.us/rm/boise/AWAE/projects/BullTrout_eDNA.html), and similar efforts are underway for other species. And the value of these broad-scale surveys is not limited to the species they are targeting. Each sample from a site has the potential to contain the DNA of all the taxa present at or upstream from that site, and these samples can be archived indefinitely. In essence, eDNA samples constitute a biodiversity archive that can be interrogated now to answer pressing questions about extant species, and stored to address questions that may arise in future decades.

As in any rapidly emerging field, there are growing pains. One is a concern about the comparability among projects, but this can be overcome if clear, straightforward sampling methods are adopted (Carim et al. 2016b). Perhaps a more pressing issue, however, is to raise consciousness among the community of professionals about those locations that have already been sampled (to avoid redundancy and redirect efforts to unsampled locations), and to make those existing data readily available to scientists, managers, and decision-makers. To foster that data sharing, we are developing the eDNAtlas (https://www.researchgate.net/project/The-Aquatic-eDNAtlas-for-the-American-West), an open-access online database that displays the site-specific results for all eDNA samples analyzed by the National Genomics Center for Wildlife and Fish Conservation (a prototype ArcGIS Online database tool can be seen here: https://www.fs.fed.us/rm/boise/AWAE/projects/BullTrout_eDNA/SurveyStatus.html). A key feature is that users can filter the data for any species or location, and download that information in a variety of customizable formats. Although primarily focused on the West, for which there are data on over 8,000 samples, the eDNAtlas will expand to the rest of U.S. in 2018 as samples arrive from throughout the country.

Our future efforts, and those of the eDNA sampling community, are being directed at a broader species pool—which will include a number of birds, mammals, pathogens, macroinvertebrates, and plants—and expanding into other environments e.g., snow and soil, as well as developing cost-effective methods to simultaneously analyze a host of species from each sample. Our overriding motivation, however, is to combine the increasingly sophisticated and comprehensive geospatial databases reflecting climate and hydrology with the growing eDNA databases to build more precise, accurate, and spatially specific models of species distributions, understand their responses to a changing climate, and map those areas which will serve as climate refugia for conservation planning and species preservation.

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