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STREAM NOTES

To Aid in Securing Favorable Conditions of Water Flows

Rocky Mountain Research Station

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Stream Temperature Monitoring and Modeling: Recent Advances and New Tools for Managers

by Daniel J. Isaak

Stream thermal regimes are important within regulatory contexts, strongly affect the functioning of aquatic ecosystems, and are a primary determinant of habitat suitability for many sensitive species. The diverse landscapes and topographies inherent to National Forests and Grasslands create mosaics of stream thermal conditions that are intermingled with strong gradients from headwaters to lowlands. Alteration of these thermal regimes has traditionally been associated with anthropogenic effects on stream flows and riparian shade or natural disturbances related to wildfires and debris flows. Climate change could exacerbate many of these factors, but is also expected to cause warming through global air temperature increases.

The responses of individual streams to future climate change, however, will be spatially variable and contingent on geomorphic context, local climate trends, and management responses (Hari et al. 2006; Kaushal et al. 2010). In some cases, especially where degraded riparian areas or other stream conditions have contributed to past thermal gains, restoration efforts could successfully offset a significant amount of future warming. Understanding and predicting current and possible future thermal characteristics for 100,000's of stream kilometers on National Forests and Grasslands will be needed to help prioritize restoration efforts and to think more broadly about strategic allocation of conservation resources for aquatic systems. It sounds like a daunting task, but recent advances in the ability to accurately and inexpensively monitor and model stream temperatures could largely meet this need in the next 5 to 10 years. Here, I describe the current state of affairs with regards to stream temperature research, a variety of new tools for managers, and outline a vision for future stream temperature work that could ultimately expand to provide fundamentally improved spatial data for many stream attributes.

Measuring Stream Temperatures

The last decade has seen rapid development of new sensor technologies for measuring thermal conditions in streams. These technologies vary in cost and the specific applications to which each is best suited. Forward

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Looking Infrared Radiometry sensors mounted on aircraft or fiber optic Distributed Temperature Sensor cables can provide high-resolution, spatially continuous thermal profiles at scales ranging from 1 to 100 kilometers. Both technologies are relatively expensive to use, however, and are generally limited in application to those streams or reaches of streams where management issues are especially pressing. A less expensive alternative for thermal profiling involves mounting a temperature sensor on a small raft or other mobile device that is linked to a global positioning system. The user then walks or floats the sensor downstream while simultaneously recording the locations of temperature measurements. Thermal profiles serve a variety of useful purposes, including identifying specific locations with strong groundwater inputs or thermal gains and studying the physics of stream heat budgets.

In most cases, stream temperature applications on National Forests and Grasslands require monitoring over extended periods of time at one or more sites. These needs can be addressed using small digital temperature sensors (Dunham et al. 2005) that are left in place for the duration of the monitoring assignment. These discrete sensors are inexpensive ($20 to $120), portable, have programmable recording intervals, and memories and battery lives than enable continuous deployments spanning 1 to 5 years. Until recently, it was common practice to measure temperatures with these sensors only during a few summer months when mountain streams are most accessible and low flows ensured that the sensor could be retrieved. Monitoring in this fashion is extremely inefficient, however, because it requires two site visits each year and yields data for a small subset of the year.

Permanently installing temperature sensors in streams would improve temperature monitoring efforts considerably, but requires durable installations that are capable of withstanding large annual snowmelt floods. In the past, such installations involved using intrusive materials such steel cable or fence-posts, and failure rates remained high. A low-tech solution, developed in the last year, is the use of underwater epoxies to simply glue sensors to large boulders in streams (Isaak and Horan 2011). The techniques has been extensively field tested and validated to: 1) find the best performing epoxy, 2) assess sensor loss rates relative to floods, and 3) confirm that temperature measurements were not biased by attachment to boulders. In all cases, the epoxy technique has proven reliable and is being adopted by many agencies that are deploying temperature sensor networks across the western U.S. and other parts of the country (fig. 1). A detailed visual guide for installing temperature sensors with underwater epoxy has also been developed (Isaak et al. 2010a) and is available for download through the U.S. Forest Service, Rocky Mountain Research Station, Boise Aquatic Science Lab Stream Temperature webpage (http://www.fs.fed.us/rm/boise/AWAE/projects/stream_temperature.shtml).

Stream Temperature Monitoring Designs

The portability and potential for lengthy deployments of temperature sensors makes them ideal for establishing monitoring networks across individual National Forests or other wildland settings where logistical access to remote streams is often challenging. And in fact, the ease with which temperature data can now be collected is leading to rapid expansion of such monitoring efforts in many parts of the country. At the scale of the typical National Forest or Grassland, implementing a monitoring network is also surprisingly affordable, requiring only $5,000 to $10,000 of equipment (mostly for temperature sensors), a few weeks of technician time for sensor installations, and a few weeks in subsequent years to retrieve and process data.

As interest in monitoring networks grows, it also leads to questions regarding sampling designs and choosing specific locations where temperature sensors should be placed to provide the best information. Many monitoring designs are possible and none are best in all cases because the motivations for monitoring, idiosyncrasies of individual river networks, and available resources vary widely and will ultimately dictate the sort of design that is implemented. There are, however, general principles and readily available tools that can be applied to assist in customizing monitoring efforts for most river and stream networks. We can categorize sampling designs as experimental designs; sit-specific, project-level designs, regression designs; or ecologically motivated designs:

Experimental designs

Temperature monitoring locations are placed randomly and spread in space to obtain a representa-

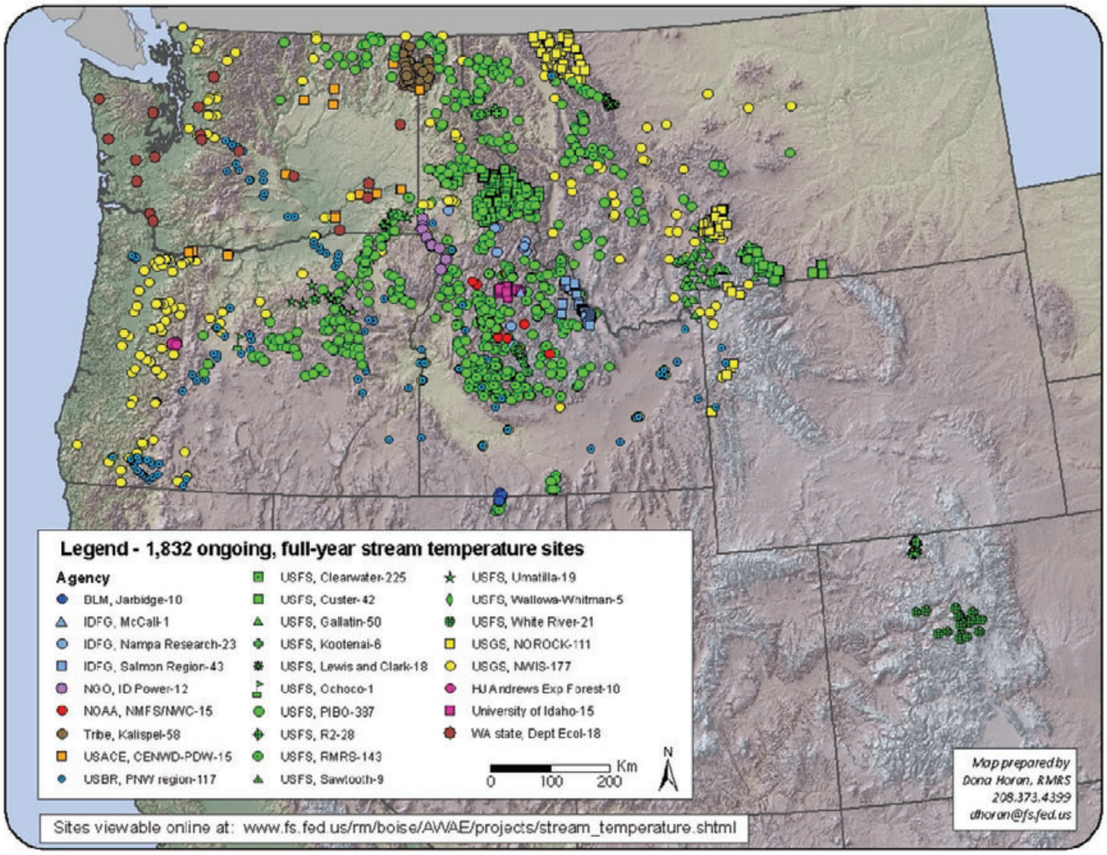

Figure 1. Sites in the western U.S. where full-year stream temperatures are currently monitored by different agencies. Many of the U.S. Forest Service sites were established by agency biologists and hydrologists in 2010 using the underwater epoxy technique. It is anticipated that another 500 to 1,000 full-year stream temperature monitoring sites will be added to this growing monitoring network by different agencies in 2011.

tive sample while minimizing spatial correlations among the sites. Large regional monitoring programs like EMAP, AREMP, and PIBO use experimental design based sample allocations. The information provided by these designs is mainly used for descriptive purposes.

Site-specific, project-level designs

Small-scale, local monitoring efforts associated with individual projects to assess temperature responses to habitat restoration, grazing abatement, or recovery from a wildfire. Although typically of limited spatial extent, project-level temperature monitoring efforts sometimes consist of long-term datasets that may also be useful for assessing climate-related trends. Where many years of stream temperature data already exist, it is important to maintain these monitoring efforts because so few long-term stream monitoring datasets exist.

Regression designs

Monitoring locations are spread evenly along major environmental gradients that affect stream temperatures to collect data useful for building predictive models and deriving spatially continuous temperature maps to represent historic or future climate scenarios. In mountain environments, this usually means elevation and stream size or slope are referenced as the important gradients when selecting temperature sensor sites.

Ecologically motivated designs

Placement of temperature sensors is motivated primarily by biological considerations. Sensors are placed in areas of a stream network that are near the edge of a species distribution or in habitats associated with a particular life stage (e.g., natal habitats, migratory habitats). These designs are useful for accurately defining the thermal characteristics that affect the distribution and abundance of individual species.

The above descriptions are only the most basic and many additional details need to be addressed when implementing any design. For a thorough discussion of these details and guidance regarding useful procedures and GIS tools for establishing temperature monitoring networks, interested readers are directed to Post #8 of the Climate-Aquatics Blog (http://www.fs.fed.us/rm/boise/AWAE/projects/stream_temp/stream_temperature_climate_aquatics_blog.html).

Coordinating Stream Temperature Monitoring Among Agencies

The convenience and cost-effectiveness of modern temperature sensors has greatly increased the amount of stream temperature monitoring in the last decade. In the northwest U.S. alone, somewhere between 15,000 and 30,000 summers of stream temperature measurements exist. Exact figures are not known because the data are scattered within and among dozens of different state, federal, tribal, and private resource organizations. Temperature data collection, especially during the summer, is so common that it is not unusual to encounter sensors placed by other agencies when trying to establish new sensor sites. To minimize the redundancy of new efforts and to maximize the potential for data sharing and coordination among agencies, a Google map tool has been developed to display the locations of full-year temperature monitoring sites (fig. 2). The tool can be accessed through the Boise Aquatic Sciences Lab Stream Temperature Website (http://www.fs.fed.us/rm/boise/AWAE/projects/stream_temperature.shtml) and makes it possible to dynamically query maps like the one shown in fig. 1, to zoom in and out of specific monitoring sites, and to obtain information about sensor site locations and local data stewards. The initial version of the tool was geographically limited in scope, but it has recently been expanded to include most of the western U.S.

Stream Temperature Data Applications

A range of applications useful to managers of aquatic ecosystems can be developed from stream temperature databases. Some of these applications

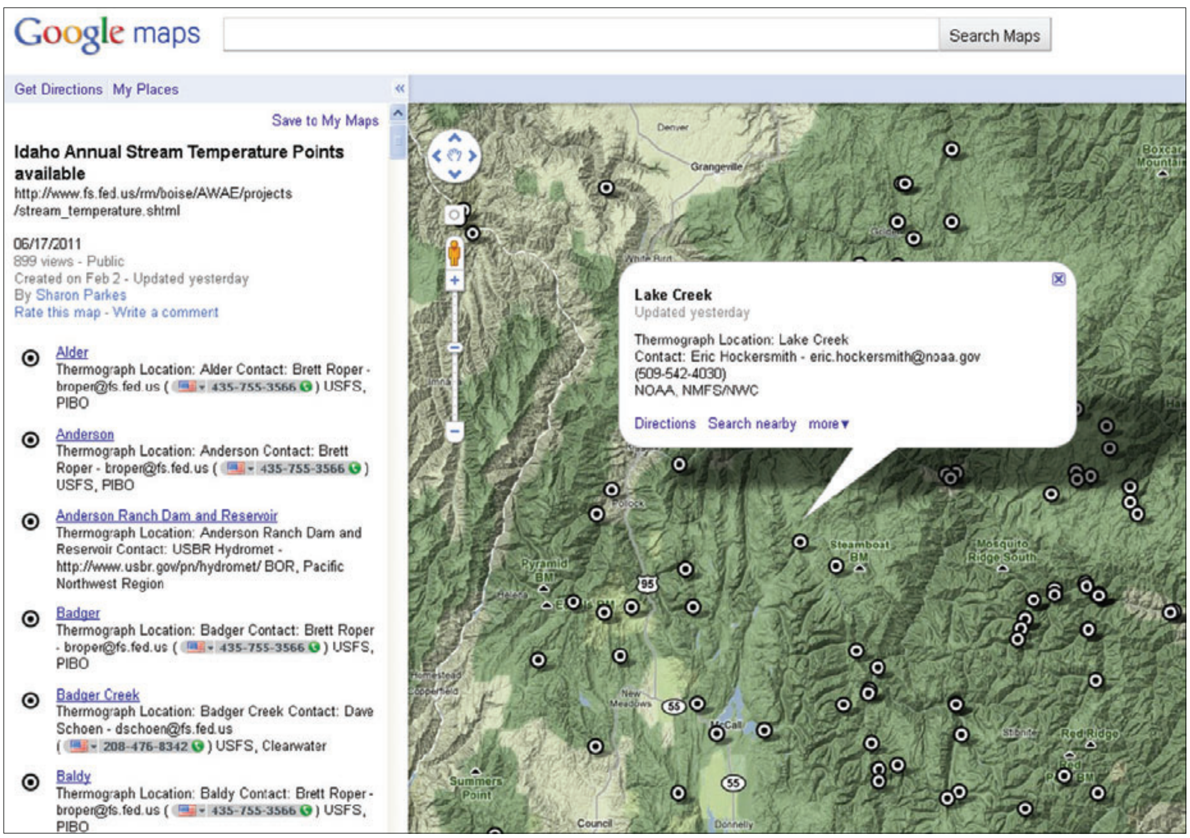

Figure 2. Example view from the Google map tool developed for the western U.S. to show locations of full-year temperature monitoring sites. The tool makes it possible to dynamically query maps like the one shown in fig. 1 so that redundancy can be minimized among agencies when new monitoring sites are established. The tool also lists the contact information for the local data stewards to facilitate sharing of existing data.

are easily implemented by those with basic spreadsheet, statistical, and GIS skills; whereas others require more involved database and analytical procedures that research partnerships may provide. Below I discuss a few of the more popular applications and additional resources for their pursuit.

Sensitivity analysis

In this analysis, differences in stream temperatures between years are calculated for individual sensors that have monitored the same sites for at least two years. These differences are examined across many sensors to describe the amount of concordance among sites and to highlight those stream locations that changed either more rapidly or more slowly than others. These changes can then be related to the physical attributes of a site (e.g., elevation, stream size, riparian condition) or type of habitat (e.g., spawning, migratory) to better understand which areas of a river network may be especially sensitive to climatic variation.

Trend summaries

At stream sites where temperatures have been monitored for long periods of time, simple examination of these time-series may provide valuable insights regarding inter-annual temperature variation, the effects of climate cycles (e.g., El Nino or the Pacific Decadal Oscillation), and responses to wildfires or other factors that affect riparian conditions. The development of digital temperature sensors in the early 1990's made collection of temperature data more common at that time and in instances where these monitoring efforts have been continued, the time-series now extend 15 to 20 years in length. It is these longer-term monitoring efforts that are too often lacking and present a significant gap in our understanding regarding how trends associated with climate change have been affecting mountain stream temperatures. Whenever possible, therefore, these long-term monitoring temperature time-series should be continued indefinitely and new trend monitoring started in additional areas.

Predictive stream temperature models

Although considerable stream temperature data have been (and will be) collected in many areas, the vast extent of stream and river networks that drain National Forests and Grasslands (literally 100,000's of kilometers) mean that temperature measurements will never exist in all, or even most, areas. Predictive modeling tools are needed to interpolate between locations with measurements and to fill these gaps. Once a predictive model has been developed from a local temperature database, it can be used to provide spatially continuous maps of thermal conditions throughout an entire river network or National Forest. These maps serve a variety of useful purposes, including: highlighting sections of stream where regulatory temperature criteria are met or exceeded, predicting where thermal habitat exists for sensitive species, improving monitoring designs for biological or temperature sampling, understanding how the terrestrial landscape affects stream temperatures, and conducting climate change assessments.

Predictive temperature models can be developed using a variety of techniques, but one of the most commonly and easily applied is a statistical approach called multiple regression analysis. Multiple regression temperature models work by relating measured stream temperature values to a variety of landscape, riparian, and climatic factors using mathematical relationships. Once these relationship are developed, predictions can be made at sites without temperature measurements using the values of the predictive factors at those sites. Detailed, step-by-step instructions for model development are provided in association with the "multiple regression stream temperature model" project on the Boise Aquatic Sciences Lab Stream Temperature Website (http://www.fs.fed.us/rm/boise/AWAE/projects/stream_temperature.shtml).

Although traditional multiple regression and predictive models provide much useful information, they also fail to account for the unique spatial structure of stream networks like directional flow, branching at network junctions, and abrupt changes in stream size at these junctions. Recently, however, a new type of spatial statistical model has been developed that accommodates this network structure to greatly enhance the amount of information that can be extracted from data arrayed on stream networks (Peterson et al. 2007; Ver Hoef and Peterson 2010). The following example illustrates the utility of these new spatial models using an *ad hoc* stream temperature database that consisted of 780 summers of stream temperature measurements collected from 1993 to 2006 by resource

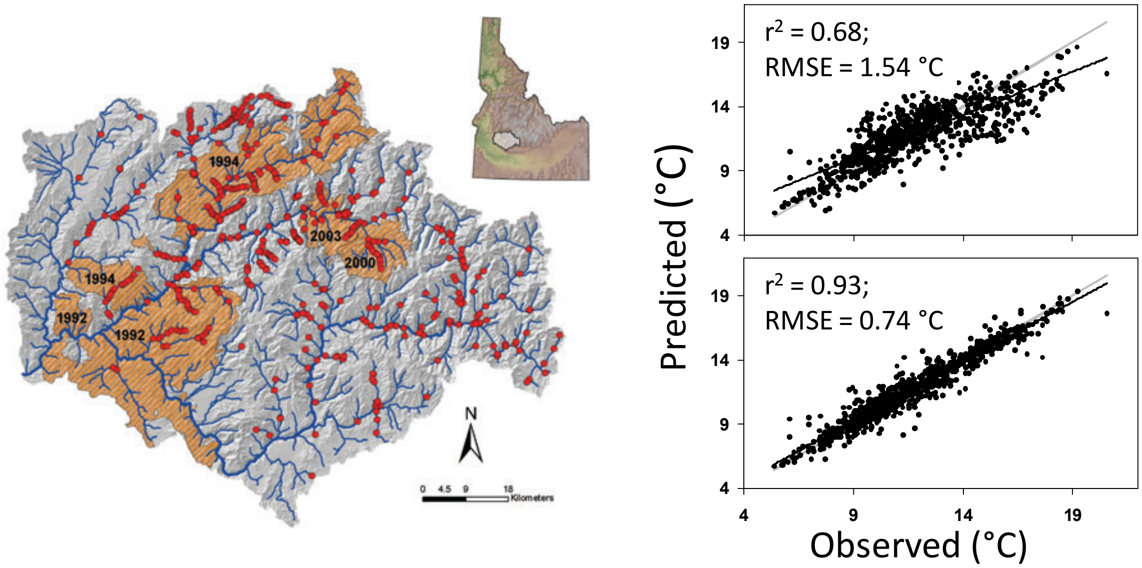

Figure 3. Locations of 780 summer stream temperature measurements in an interagency database developed for the Boise River in central Idaho. Comparison of summer mean stream temperatures predicted from a traditional multiple regression model fit to these data (upper graph) and predictions from a new type of spatial statistical model that accounts for the structure of stream networks (lower graph; Isaak et al. 2010b).

agencies within the Boise River basin of central Idaho (Isaak et al. 2010b; fig. 3). Application of the spatial model to these data accounted for almost 93% of the variation in summer mean temperatures and average prediction errors were only 0.74 °C, which were both dramatic improvements over a traditional multiple regression model. This accuracy ensured more precise results when the model was subsequently used to make spatially continuous thermal maps throughout the river network for quantifying the basin-scale effects of climate change and wildfires on temperatures and thermal habitats (fig. 4). Additional details regarding this study are in Isaak et al. (2010b) or the "spatial statistical stream temperature model" project on the Boise Aquatic Sciences Lab Temperature Website (http://www.fs.fed.us/rm/boise/AWAE/projects/stream_temp/spatial/spatial_temp_model.shtml).

Conclusions

Thermal regimes are a fundamental attribute of stream ecosystems and the ability to monitor and models these regimes are rapidly advancing. As technological costs continue to decrease, and concerns over climate change ensure ongoing interest in the subject of stream temperatures, it is an exciting time to be working in this arena. Moreover, the U.S. Forest Service is in a unique position among resource and land management agencies to do cutting edge science and integrated management relative to stream temperatures and risk assessments for aquatic biotas. Our agency already has some of the world's best stream temperature databases and a highly skilled and committed workforce distributed across an extensive land-base that is intent on doing more.

The modeling and monitoring infrastructures that are today being built to increase our knowledge of stream temperatures across National Forest lands will yield fundamentally better spatial and temporal information regarding this important attribute in future years. Many aspects of these infrastructures will also have equal utility for developing better spatial information about other attributes of streams, including aquatic biotas, water quality parameters, and physical habitats. Efforts to address questions surrounding stream temperatures, therefore, may well yield significant dividends regarding the quality and quantity of stream data that are someday available to managers. Although it will take time, the future holds tremendous potential, as we just now in the initial stages of broad application of spatial information technology to stream databases. This process will ultimately generate significant amounts of valuable and accurate information regarding streams, facilitate strong partnerships between research and management, and contribute to better understanding and management of aquatic ecosystems on National Forests.

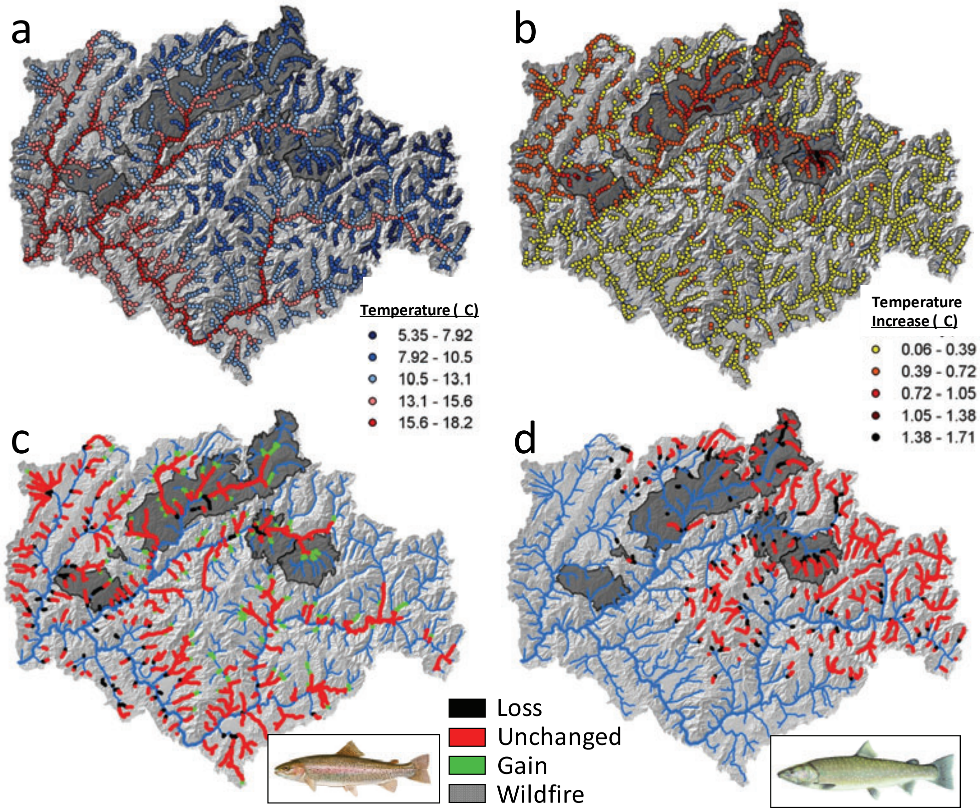

Figure 4. Example outputs from the spatial statistical stream temperature model for the Boise River basin. Maps of summer mean stream temperatures in 2006 (panel a), change in summer mean temperatures from 1993 to 2006 associated with long-term climate trends and wildfires (panel b), and shifts in thermally suitable habitat for rainbow trout and bull trout from 1993 to 2006 (panels c and d).

Additional Information

For a more in-depth discussion and complete list of references on these various stream temperature topics, please refer to the following websites: http://www.fs.fed.us/rm/boise/AWAE/scientists/profiles/AWAIsaak.shtml and http://www.fs.fed.us/rm/boise/AWAE/projects/stream_temp/stream_temperature_climate_aquatics_blog.html.

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