

APPLIED ECOLOGY

Socioeconomic resilience to climatic extremes in a freshwater fishery

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Heterogeneity is a central feature of ecosystem resilience, but how this translates to socioeconomic resilience depends on people's ability to track shifting resources in space and time. Here, we quantify how climatic extremes have influenced how people (fishers) track economically valuable ecosystem services (fishing opportunities) across a range of spatial scales in rivers of the northern Rocky Mountains, USA, over the past three decades. Fishers opportunistically shifted from drought-sensitive to drought-resistant rivers during periods of low streamflows and warm temperatures. This adaptive behavior stabilized fishing pressure and expenditures by a factor of 2.6 at the scale of the regional fishery (i.e., portfolio effect). However, future warming is predicted to homogenize habitat options that enable adaptive behavior by fishers, putting ~30% of current spending at risk across the region. Maintaining a diverse portfolio of fishing opportunities that enable people to exploit shifting resources provides an important resilience mechanism for mitigating the socioeconomic impacts of climate change on fisheries.

INTRODUCTION

Ecological heterogeneity is critical for ecosystem resilience and the reliability of ecosystem services (1), especially under accelerating climate change and increasing frequency and intensity of extreme events. Biological and physical complexity within ecosystems and across landscapes (e.g., genes, populations, species, and habitats) have been shown to enhance ecosystem productivity (2), stabilize population dynamics (3–5), and mitigate against abrupt change in natural resource economies (6). In freshwater ecosystems, such heterogeneity interacts with changing environmental conditions to shift productive habitats across space and time, stabilizing the production of biological resources (i.e., fish) at the scale of entire landscapes (1). However, it remains unknown whether people using and benefitting from these dynamic resources adaptively track them across a range of spatial scales and whether such behavior translates to socioeconomic resilience in human communities reliant on fisheries for livelihoods and well-being.

Freshwater fisheries (commercial, subsistence, and recreational) have enormous social, ecological, and economic importance worldwide (7, 8), yet the natural systems that support them (e.g., climate, weather, and ecosystems) are being rapidly transformed by global climate change (9, 10). Shifts in species distributions in response to climate change have been documented for a broad range of organisms (11), especially ectothermic species like fishes that are strongly tied to water temperature (12). Such climate-induced range shifts may change the distribution of fishing opportunities across landscapes, requiring fishers to adapt by catching different species or fishing in new locations (13–15). Globally, extreme climatic events (e.g., droughts, storms, heat waves, and wildfires) are increasing in frequency and severity and may also affect fishing opportunities by affecting fishers' decisions on where and when to fish (16, 17). Although these climatic changes may have important ecological impacts on freshwater

fisheries (18, 19), how these dynamics influence the reliability of fishing opportunities and associated revenues has never been empirically quantified.

Here, we provide an empirical assessment of the impacts of climate change and climatic extremes on freshwater fisheries using an inland trout fishery as a case study. Trout (Salmonidae)—a group of cold-water fishes with substantial ecological and socioeconomic importance—are highly prized by fishers in many parts of the world (20). Fishers travel long distances to pursue trout in streams, rivers, and lakes, often generating substantial revenues for local and regional economies. The northern Rocky Mountains in Montana (USA) support some of North America's most popular trout fisheries, valued at more than US\$750 million year⁻¹ (21) representing more than 20% of the spending by tourism in the state (22). This economic value is primarily driven by nonresident fishers who spend, on average, US\$690 fisher-day⁻¹ compared to US\$90 fisher-day⁻¹ by resident fishers (21). However, the cold-water fisheries that support this substantial tourism industry may be at risk as this region warmed at twice the global average rate over the past century (23), contributing to warmer water temperatures (24), lower summer streamflows (25), and increasing frequency and severity of drought events. These climatic changes are shifting the abundance and distribution of trout species across the region (26–28). The combined effects of these climatic changes may significantly affect popular trout fisheries by shifting both fish and fishers across space, with potentially severe socioeconomic consequences. Therefore, understanding how climate change will affect social, economic, and ecological components of cold-water fisheries will be critical for enhancing resilience and adaptation of fisheries and local communities.

We used an extensive spatiotemporal dataset from more than 5000 km of popular trout rivers in the northern Rocky Mountains (1983 to 2017) to quantify trends and spatial patterns in fishing pressure in response to changing climatic conditions. First, we leveraged historical drought, temperature, and streamflow data to estimate how climate drivers directly affected fishing pressure at the river reach scale (8 to 190 km). We used dynamic factor analysis (DFA) (29) to account for common patterns in resident and nonresident fishing pressure over time that may be due to aggregate social and economic

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drivers while simultaneously estimating the interannual effects of past environmental conditions. Second, we quantified whether aggregating heterogeneous fishing pressure dynamics across river sections stabilized fishing pressure and spending at larger spatial scales (i.e., portfolio effects) (30). Third, we quantified the importance of cold-water habitat by comparing fishing pressure in river sections dominated by cold-water species (i.e., trout) to sections where fish communities were transitioning to cool-water species (e.g., black bass *Micropterus* spp. and walleye *Sander vitreus*). We then used predictions of current and future summer stream temperatures in 2040 and 2080 under an A1B emissions scenario [similar to the Representative Concentration Pathway (RCP) 6.0 emissions scenario] (31) to project how the spatial distributions of cold-water habitat may change and the potential effects on fishing pressure. Last, we estimated the potential economic impacts of future climatic change by combining estimates of current fisher spending with estimated changes in fishing pressure due to the combined impacts of future droughts and losses in cold-water habitats. Our analyses incorporate the direct impacts of climate drivers on fishers (i.e., streamflow and temperature) and the indirect effects of changing temperature on species distributions to comprehensively understand the potential consequences of climate change for these fisheries.

RESULTS

Growth in freshwater trout fisheries

Fisheries across the region experienced rapid growth over the past three decades (Fig. 1A). From 1983 to 2017, total fishing pressure doubled from 0.8 million fisher-days year⁻¹ to more than 1.7 million fisher-days year⁻¹. This growth was primarily due to changes in non-resident fishing pressure, which increased from 0.2 to 0.8 million fisher-days year⁻¹ (280% increase), and, to a lesser degree, resident fishing pressure, which increased from 0.6 to 0.9 million fisher-days year⁻¹ (50% increase). These increases in fishing pressure were not distributed evenly across the region, varying considerably within and across major rivers (Fig. 1, B and C). Nonresident fishing pressure increased across 90% of river sections (~4500 km), and in some of the most popular rivers (i.e., Blackfoot, Bitterroot, and Madison rivers), fishing pressure increased up to 1600% (reaching 13,000 fisher-days km⁻¹ year⁻¹ in some sections), generating substantial spending across the region. Resident fishing pressure also increased in many sections (70%) but experienced pronounced declines across 30% (~1500 km) of river sections (Fig. 1B). This spatiotemporal variation in fishing pressure within and among rivers is the result of complex interactions between many socioeconomic, ecological, and environmental factors affecting fisher behavior.

Effects of changing environmental conditions on fishing pressure

Extreme climate events, particularly drought and its effects on streamflow, strongly influenced the spatiotemporal dynamics of resident and nonresident fishing pressure among rivers (Fig. 2 and fig. S1). Drought had a strong negative effect on fishing pressure for some river sections (herein referred to as drought-sensitive), most notably in the Big Hole River where fishing pressure declined by 127 (24%) and 252 (48%) fisher-days km⁻¹ year⁻¹ under moderate and severe drought conditions, respectively (Fig. 2, D and E). However, for other river sections, fishing pressure increased in drought years (herein referred to as drought-resistant), especially by resident fishers (Fig. 2D).

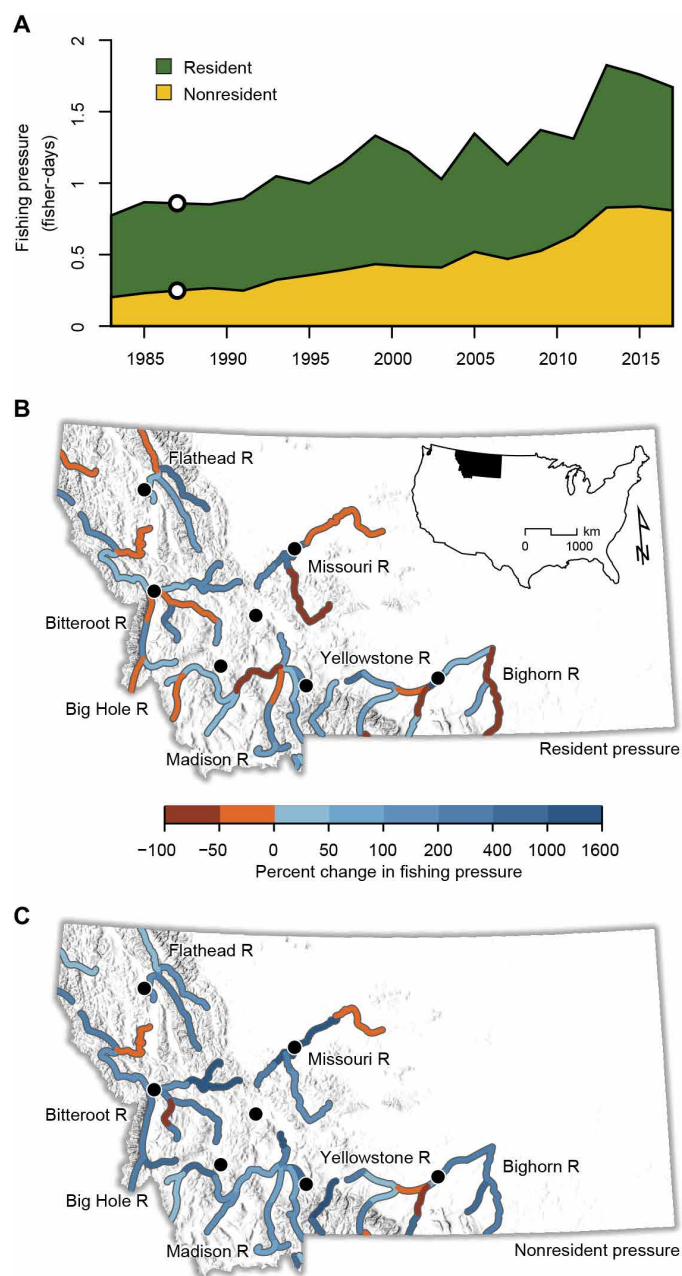


Fig. 1. Changing fishing pressure in freshwater trout fisheries across the northern Rocky Mountains. (A) Changes in total fishing pressure across popular trout rivers in Montana, USA between 1983 and 2017. No survey was conducted in 1987, indicated by open points. Estimates of change in resident (B) and nonresident (C) fishing pressure across river sections. Percent change is measured as the difference between the 1983–1989 surveys and 2013–2017 surveys. Black dots indicate regionally important cities with major airports. Hill shade has been added for geographic context. Note the nonlinear color scale.

Overall, there were more negative effects and greater variation in drought responses among sections for nonresident anglers than residents. The largest positive drought effects occurred in portions of the upper Yellowstone River and in tailwater sections of the Madison, Missouri, and Bighorn rivers (Fig. 2, D and E), where dams influence downstream water temperatures and streamflows. A substantial amount

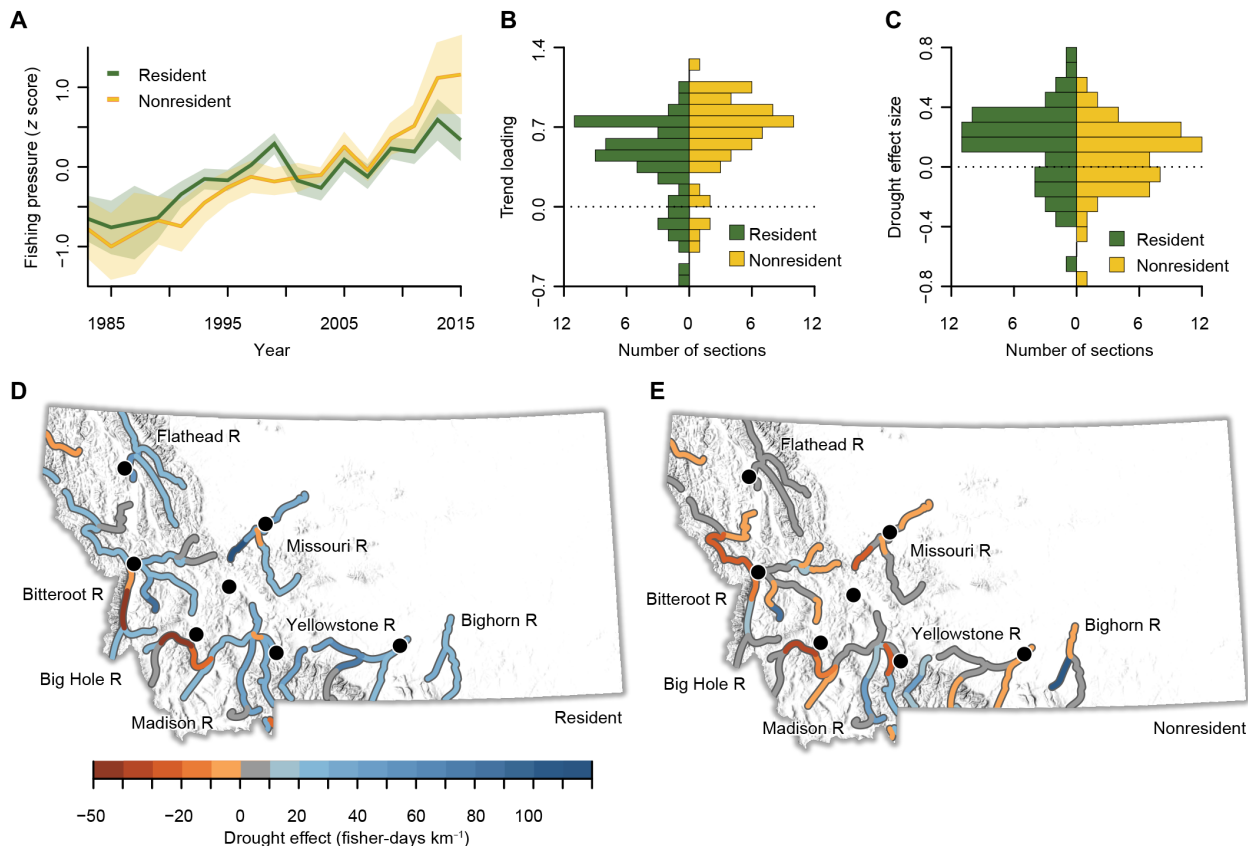


Fig. 2. The effects of drought on fishing pressure across popular trout rivers. (A) Common trends in resident (green) and nonresident (yellow) fishing pressure among river sections through time. Polygons represent 95% confidence intervals. Loadings of individual river sections on common trends. (B) Negative loadings indicate opposite trend. Effects of spring/summer PDSI (C) on resident and nonresident fishing pressure. Spatially explicit drought effects on resident (D) and nonresident (E) fishing pressure across rivers.

of variation in both resident and nonresident fishing pressure was explained by shared trends among river sections (Fig. 2A). These trends probably represent an aggregate of social (e.g., popularity of trout fisheries), economic (e.g., increase in disposable income), and other environmental factors (e.g., effective resource management) that are not explained by drought conditions through time.

Stabilizing portfolio effects

We calculated the stabilizing effect of shifting fishing pressure in space and time (i.e., portfolio effects) by comparing the average interannual variability [coefficient of variation (CV)] in fishing pressure across individual river sections (~60 km on average), rivers (multiple river sections; ~230 km), drainages (multiple rivers within a major river basin; ~770 km), and the region (full study area; ~5400 km; fig. S2). Interannual variation in fishing pressure and spending was greatest in individual river sections (Fig. 3A and fig. S3), but the dynamics among sections were asynchronous through time (synchrony = 0.49; fig. S3). Averaging across these dynamics at increasing spatial scales (i.e., sections, rivers, drainages, and region) dampened the interannual variability in fishing pressure and spending (Fig. 3A and fig. S3). Across the region, fishing pressure was 2.6 times more stable than the average of individual river sections and 3.2 times more stable for fisher spending (Fig. 3B). Furthermore, interannual variability and the strength of portfolio effects differed between nonresident

fishers (3.9) and resident fishers (2.7; Fig. 3B). Overall, these strong portfolio effects increased the reliability of fishing opportunities and fisher spending across the regional fishery. Aggregating fishing pressure at each successive spatial scale decreased interannual variability in fishing pressure and spending by about 25%, demonstrating the importance of portfolio effects occurring across a range of spatial scales.

Transitioning from cold- to cool-water habitats

Cold-water habitats (defined by trout dominance; see Methods) were disproportionately important for fisher use and economic value across the region compared to cool-water sections (defined by fewer trout and the presence of cool-water species; Fig. 4). In recent years, overall fishing pressure was four times higher in cold-water sections than in adjacent cool-water sections and was 10 times higher for nonresident fishers (Fig. 4A). Differences in fishing pressure between cold- and cool-water habitats amounted to substantial differences in fisher spending, with cold-water sections generating US\$500,000 km⁻¹ year⁻¹ and cool-water sections generating US\$60,000 km⁻¹ year⁻¹ (Fig. 4B), primarily due to the preference for cold-water by nonresident fishers.

In cool-water river sections, August water temperatures exceeded 18°C along 90% of their extent (Fig. 4C), a threshold that is consistent with previous research on thermal extremes for trout (32). Using

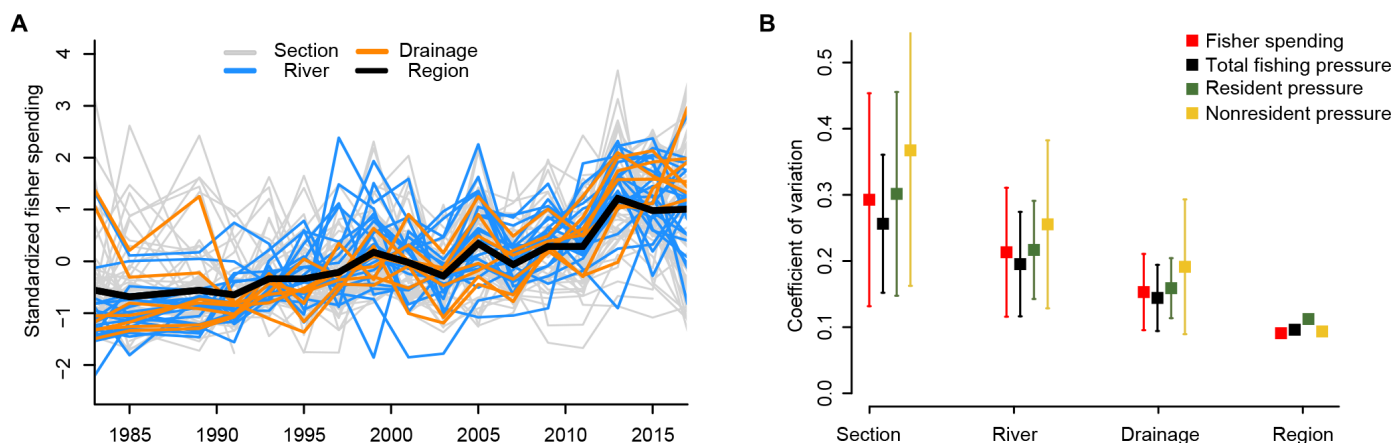


Fig. 3. Portfolio effects stabilize fishing pressure and fisher spending across spatial scales. (A) Estimated fisher spending through time among sections (gray), rivers (blue), drainages (orange), and the region (black). (B) Interannual variability (as measured by the CV; ± 1 SD) in fisher spending (red), total fishing pressure (black), resident fishing pressure (green), and nonresident fishing pressure (yellow) at four spatial scales. See Methods for description of spatial scales.

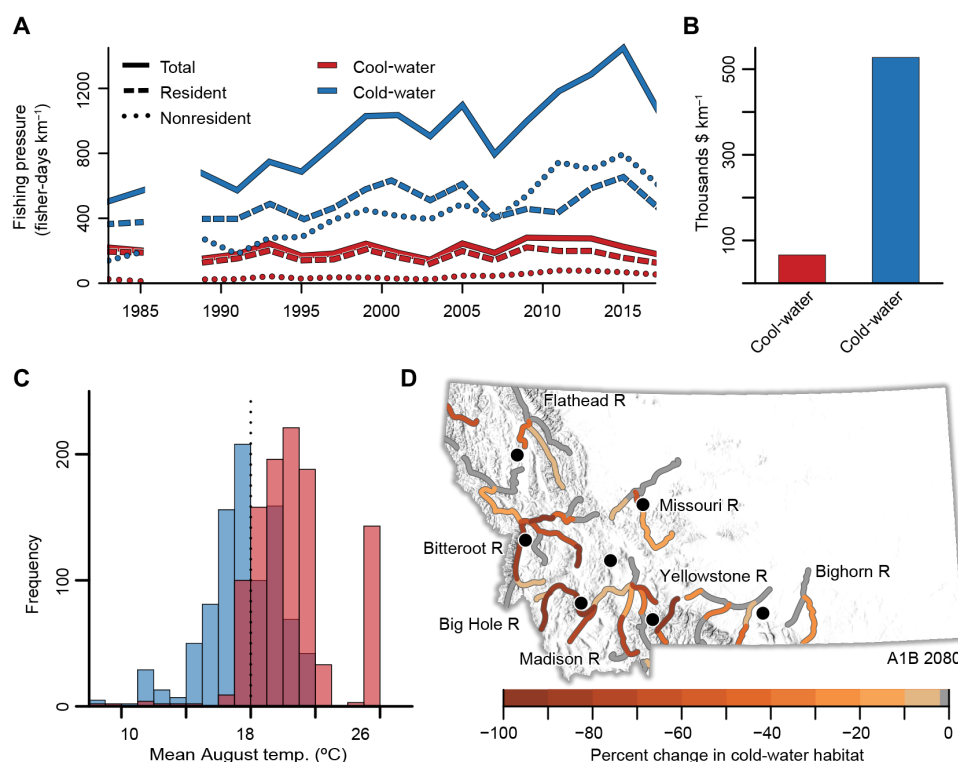


Fig. 4. Cold-water habitats are critical for fishers and economic value. Resident and nonresident fishing pressure over time (A) and economic value (B) of cold- and cool-water habitats (see fig. S7 for map of cold- and cool-water habitats). (C) Water temperature distributions in cold-water (blue) and cool-water (red) habitats. (D) Predicted losses in cold-water habitat by 2080 under A1B emissions scenarios. Dollar values are in 2018 US\$.

this 18°C threshold to delineate cold- and cool-water habitat, we projected substantial losses in cold-water for most river sections across the region (Fig. 4D). Overall, 17 and 35% of the current cold-water habitat are projected to be warmer than 18°C by 2040 and 2080, respectively (Fig. 4D and fig. S4). However, losses in cold-water habitat were spatially heterogeneous, where some river sections exhibited little change and other sections exhibited losses in excess of 80% by 2080 (e.g., Bitterroot, Big Hole, and Yellowstone rivers; Fig. 4D). Given current fishing pressure distributions and preferences for cold-water

fisheries (Fig. 4A), losses in cold-water habitat availability could reduce fishing pressure by 100 to 800 fisher-days km^{-1} (~20 to 80% reduction in current fishing pressure) in many rivers by 2080 (fig. S5).

Economic impacts of future climate change

The effects of cold-water habitat loss and increased frequency and severity of drought on fishing pressure could result in substantial economic impacts across the region (Fig. 5). Spatial shifts in fishing pressure during past extreme droughts decreased spending in some

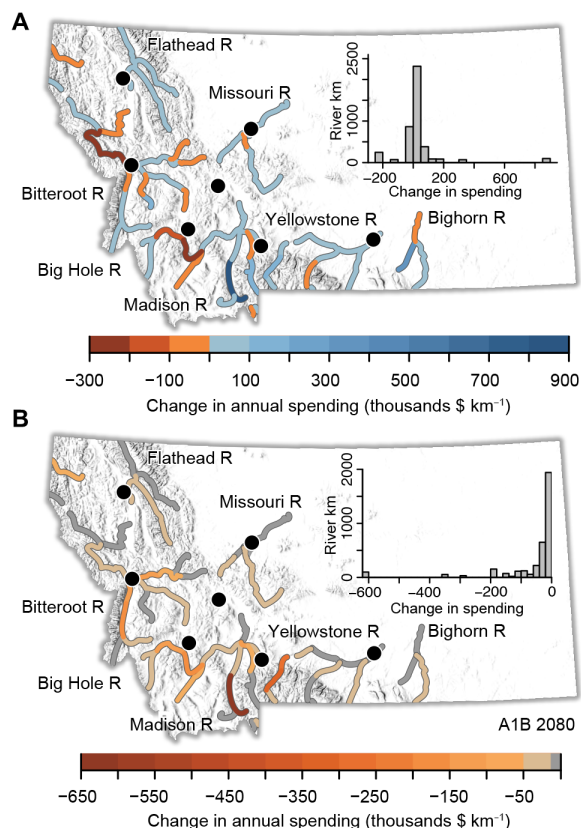


Fig. 5. Economic impacts of extreme drought and future range shifts on cold-water fisheries. (A) Potential shifts in fisher spending across rivers under extreme drought. (B) Changes in annual spending by fishers in response to cold-water habitat losses by 2080 under A1B emissions scenarios. Histograms summarize the distributions presented in each map. Dollar values are in 2018 US\$.

river sections (e.g., US\$150,000 km⁻¹ year⁻¹ in the Big Hole River) and increased spending in others (e.g., US\$600,000 km⁻¹ year⁻¹ in the Madison River; Fig. 5A). In contrast to these variable economic impacts of drought, loss of cold-water habitat is projected to cause widespread economic impacts across this region, with spending projected to decline in 64 and 76% of river sections by 2040 and 2080, respectively (Fig. 5B and fig. S6). Economic impacts were concentrated in southwestern rivers, with sections of the Yellowstone, Madison, Big Hole, and Bitterroot rivers having the largest potential changes in spending as large changes in cold-water habitat intersect with popular fishing areas for nonresident fishers. Decreases in spending of US\$50,000 to US\$100,000 km⁻¹ year⁻¹ were projected across many river sections, with some sections as high as US\$600,000 km⁻¹ year⁻¹. The cumulative impacts of these changes in spending across these rivers could put a total of US\$103 million year⁻¹ (16% of 2017 spending in these rivers) and US\$192 million year⁻¹ (30% of 2017 spending) at risk by 2040 and 2080, respectively.

DISCUSSION

Heterogeneity is a central feature of ecosystem resilience (1, 3, 33), but how this translates into socioeconomic resilience depends on people's ability to track shifting resources in space and time. By integrating long-term fishing surveys and bioclimatic data, we captured

emergent fisher behavior in response to past climate extremes, demonstrating that fishers adaptively moved across the landscape to exploit shifting fishing opportunities, resulting in negligible or even positive changes in regional fishing pressure and expenditures. Heterogeneity in drought responses across riverscapes provided opportunities for fishers to find cold-water fishing refuges in drought-resistant rivers, ultimately stabilizing social and economic components of the regional fishery. However, future climate warming may reduce the diversity of habitats that enable this adaptive behavior. Thus, conserving a diversity of habitats and biological communities across landscapes would promote adaptation and socioeconomic resilience in freshwater fisheries.

Our results indicate that the future loss of cold-water habitats could have substantial impacts on the local and regional economies supported by freshwater fisheries. Projected losses in cold-water habitat under future climate warming may put 30% of current spending at risk by 2080 (US\$192 million year⁻¹), representing 21% of the total annual fishing economy in the region (21). These findings are similar to climate projections from other studies in commercial and recreational fisheries (13, 14, 16, 18). Droughts and associated extreme events (e.g., wildfires and heat waves) will likely exacerbate these impacts for some local economies as fishers avoid poor fishing conditions and management closures. Although there is substantial uncertainty in future climate, adaptation by fishers to changing species distributions, emergence of novel fishing opportunities, and extreme drought conditions, as shown here, may help mitigate future socioeconomic losses in freshwater fisheries.

Despite evidence of socioeconomic resilience to recent climatic variation and extremes, future climate change may erode stabilizing portfolio effects that sustain freshwater fisheries and the livelihoods and well-being they support. Droughts are predicted to increase in frequency, severity, duration, and extent in the future (9, 34), leading to more widespread impacts on freshwater fisheries, including reductions in streamflow, increases in water temperature, altered water quality, and habitat fragmentation (35). The combined impacts of severe drought and losses in cold-water habitats are likely to negatively affect trout populations (e.g., size structure, abundance, and production) and thus may reduce fishing opportunities and the potential for fishers to exploit alternative habitats during poor environmental conditions. Maintaining a diversity of fishing opportunities across the landscape would help to stabilize the ecosystem services that freshwater fisheries provide.

Enhancing socioeconomic resilience in freshwater fisheries under climate change will require a broad suite of proactive and innovative management strategies that conserve habitats and fish populations while simultaneously allowing people to adaptively exploit shifting resources. This will require coordinated efforts at multiple spatial and temporal scales to protect and restore habitat and biological complexity and the processes that generate and maintain it across landscapes (1). In riverine ecosystems, this may include reconnecting rivers with floodplains, restoring geomorphic complexity and connectivity, and sustaining streamflows and cold-water inputs that support productive trout fisheries (36, 37). With increasing demands for diminishing water supplies (38), coordinated and multifaceted water management plans and policies that consider trade-offs among multiple ecological, social, and economic goals would help to improve system resiliency. In some cases, incentivizing water users to maintain in-stream flows may provide cold-water to sustain socioeconomically important trout fisheries, especially during periods of drought.

Equally important, effective climate adaptation may also require new ways of managing people. Fishing restrictions, such as closures or permitting, are often used to help protect vulnerable fish populations during periods of extreme drought and to regulate increasing fishing pressure. However, traditional paradigms that focus on restricting fishing effort to protect biological resources may have unintended consequences for social portfolio effects as they limit people's ability to opportunistically adapt to climatic extremes and shifting resources. Moreover, movement of anglers to fishing refuges during periods of drought will challenge managers to mitigate the potential ecological impacts of increased fishing pressure on underlying populations. In situations where climate change effects become so severe that mitigating impacts is untenable, managers may need to help people and communities adapt to new ecological and socioeconomic states (39, 40), such as transitioning from cold-water to cool-water fisheries. Climate change will thus pose complex and challenging dilemmas for freshwater fisheries management in the future.

Worldwide, trout fishing has grown markedly in popularity, and fishers travel to all parts of the globe to fish highly prized cold-water fisheries, including Montana's world-renown trout rivers (20). We found that nonresident fishing pressure was more variable across space and time than resident fishers, indicating that nonresident fishers were more flexible to adapt to climate-induced changes in fishing conditions and management closures. This behavioral flexibility contributed to more robust portfolio effects that stabilized regional spending. Conversely, we found reduced variation in fishing pressure by resident fishers, suggesting that they may have been less willing to travel to find better conditions during periods of drought and thus may be more sensitive to management closures and potential crowding effects. As fishing pressure continues to increase and cold-water habitats become more limited, the potential for fisher conflicts is likely to increase, thereby reducing the quality fishing experiences for both nonresident and resident fishers and the economic benefits they provide to local and regional economies.

Fisheries are coupled social-ecological systems that are affected by not only physical and biological changes in ecosystems but also human responses to changes and associated feedbacks on ecosystems (41). As species and fishing opportunities shift under climate change, fishers will either need to travel farther in pursuit of specific species (13, 15) or fish in different habitats, such as protected areas or headwater streams that serve as critical thermal refugia for trout during the warm summer months (42), which may increase costs to fishers. Fishers seeking cold-water fishing refuges during drought may intensify fishing pressure in specific rivers, potentially increasing crowding among anglers and overfishing on fish populations already facing climate-induced stress, a pattern that will be exacerbated as demand for limited cold-water fisheries increases. Furthermore, with extended duration of warm summer temperatures and low streamflows (24, 43), fishers may shift seasonally by fishing in the spring and fall to avoid stressful conditions and associated management closures during the summer months. Last, fishers may ultimately need to adapt to fish for new species, yet shifts to cool-water fisheries may not compensate for lost revenue as they are currently less popular than cold-water fisheries, especially among nonresident fishers. Potential decreases in fishing pressure may reduce funding available for management and mitigation through losses in license fees and excise taxes. Better understanding the social dynamics of fishers, such as where, when, and what species fishers target, especially during extreme climatic

events, will be critical for developing effective climate mitigation and management strategies (13, 44, 45).

Accelerating climate change and increasing extreme weather events pose potentially serious socioeconomic consequences for fisheries (46). These impending impacts motivate a need to enhance ecological, social, and economic resilience, as climatic changes become more severe and unpredictable (47). More work is needed to understand the adaptive potential of different components of fisheries (e.g., biological communities, fishers, institutions, and economies) in the face of uncertain but inevitable environmental and social change. Maintaining a diverse portfolio of adaptive fishing opportunities across broad spatial scales provides an important resilience mechanism for mitigating the potentially severe socioeconomic impacts of climate change on fisheries and the well-being and livelihoods they support.

METHODS

Fisher survey and environmental data

We used fishing pressure data from individual river sections across the region to quantify shifts in fishing pressure in response to changing environmental conditions and future shifts in thermally suitable trout habitat. Montana Fish, Wildlife & Parks (MFWP) has been conducting a mail-based survey of all licensed fishers every other year since 1983 (no survey was conducted in 1987). All anglers using waters in the state of Montana are required to have a fishing license. Licenses for resident and nonresident anglers differ in cost but grant anglers the same access and privileges. Although we do not have information on licensing compliance among groups, this number of unlicensed anglers (or angler-days) is likely to be small and is probably not biasing the results and conclusions presented here. Fishers responded with residency status (resident or nonresident) and days fished on specific river sections (delineated on maps included in the survey). Fishing pressure estimates (i.e., fisher-days) were computed by MFWP for each water body or river section, including variance estimates to account for the survey-related errors (48). Between 67,000 and 97,000 surveys were used in most years, and response rates ranged from 40 to 60%. A small number of river reporting sections have changed over time (i.e., larger sections were divided); therefore, we combined annual fishing estimates in these sections to integrate over these changes in survey methodology. While we used annual fishing pressure, it is important to note that the majority of fishing pressure (69% in 2015) occurred during the summer period (May to September).

Trout fisheries in this region are predominately catch-and-release sport fisheries. Catch-and-release is regulated for some species in specific waterbodies (e.g., bull trout *Salvelinus confluentus* and westslope cutthroat trout *Oncorhynchus clarkii lewisi*), but commonly practiced by most fishers. There are no commercial harvest fisheries for trout in the region, but a small proportion of fishers harvest trout for food.

To characterize historical climate conditions, we used annual and seasonal estimates of air temperature, streamflow, and Palmer Drought Severity Index (PDSI) calculated for each river reach. Daily air temperature (49) and the 10-day PDSI data (www.climatologylab.org/gridmet.html) were downloaded for the years ranging from 1980 to 2017 for our study area. Individual yearly Geotifs were generated in R (50) to represent mean maximum daily August temperature, 7-day maximum temperature for summer months (July, August, and September), annual PDSI, and spring/summer PDSI (April to

September). For each water code reach, yearly mean temperatures (August and 7-day max) and mean PDSIs (annual and spring/summer) were calculated using zonal statistics in ArcGIS 10.6.1.

Monthly natural streamflow data from 1980 to 2015 (51) were summarized to calculate mean August and mean annual streamflow estimates. For rivers that originate in Canada (i.e., Flathead and Kootenai rivers), streamflow predictions were not available; therefore, we used U.S. Geological Survey discharge data accessed from <https://waterdata.usgs.gov/nwis/rt> (51).

Analyzing drivers of fishing pressure

We used DFA to evaluate common patterns in fishing pressure and its sensitivity to changes in environmental conditions. DFA is a dimension reduction technique, similar to principal components analysis, designed specifically for time series analysis. DFA characterizes common trends among N time series with many fewer M common trends.

More specifically, following (29), we can write the DFA model as

$$x_t = Z u_t + D d_t + v_t \quad (1)$$

$$u_t = u_{t-1} + w_t \quad (2)$$

The $N \times 1$ vector of data observed at time t (x_t) is modeled as a linear combination of the M latent trends (u_t), a $P \times 1$ vector of explanatory variables (d_t), and an $N \times 1$ vector of observation errors (v_t), which are distributed as a multivariate normal with mean $\mathbf{0}$ and $N \times N$ variance-covariance matrix $\mathbf{R}$. The $N \times M$ vector $\mathbf{Z}$ and $N \times P$ matrix $\mathbf{D}$ contain the stream-specific loadings on the trend and explanatory effects of environmental covariates, respectively. We incorporated error estimates from the survey methodology by adding an additional observation process

$$y_t \sim \text{normal}(x_t, s_t) \quad (3)$$

where the vector of observations of fishing pressure (y_t) is distributed as normal with mean equal to the latent “true” estimate of fishing pressure (x_t) and survey error variance (s_t).

Here, the common trend(s) is not simply a straight line but rather a random walk through time such that the value of x at time t is simply equal to its value at time $t - 1$ plus some random error w_t , which is distributed normally with mean $\mathbf{0}$ and variance-covariance matrix $\mathbf{Q}$. These common trend(s) can be thought of as an aggregate of unknown environmental, social, and economic drivers not captured by the explanatory environmental variables included in the model. To make the model identifiable, we set $\mathbf{Q}$ to a diagonal matrix with value 1 (29). All data were z-scored to account for differences in the mean of fishing pressure among the river sections.

We fit separate models for resident and nonresident fishing pressure with two types of observation error structures (i) where all sections share a single observation variance (diagonal and equal) and no covariance (ii) where each section has an independent observation variance with no covariance (diagonal and unequal). Candidate models (i.e., models with different combinations of trends, error structures, and covariate terms) can be viewed as different hypotheses describing how fishing pressure dynamics are structured and were compared using corrected Akaike information criteria (52). We assessed the significance of environmental covariates (i.e., air temperature, streamflow, and drought) in these models by comparing

effect size estimates and 95% confidence intervals to zero across river sections. For statistical analyses presented in figures and text, we retransformed these effect sizes to represent changes in fisher-days per kilometer per year to understand the fisher and economic effects.

Calculating portfolio effects across spatial scales

We calculated the magnitude of portfolio effects in fishing pressure (or spending) by dividing the average CV in fishing pressure (or spending) over time in individual river sections to the CV of aggregate fishing pressure across the region (4). We assessed the scale dependence of portfolio effects by calculating the CV at different spatial scales (individual sections, rivers, and drainages). To remove the potential effects of different rates of increase in fishing pressure among sections and to isolate how the interannual and other short-term dynamics among sections may stabilize fishing pressure and spending, we used a loess smoother with a span of 0.7 to detrend all time series before calculating the CV. Estimated portfolio effects were not sensitive to the choice of span parameters in the loess smoother. We also calculated synchrony among individual river sections using the “synchrony” package in R. The synchrony metric ranges from 0 (completely asynchronous) to 1 (perfectly synchronous). Asynchrony is calculated as $(1 - \text{synchrony})$.

Characterizing cool- and cold-water habitats

To assess how changes in fish communities may affect fishing pressure, we compared fishing pressure by resident and nonresident fishers in sections dominated by cold-water species (e.g., brown trout *Salmo trutta*, rainbow trout *Oncorhynchus mykiss*, and cutthroat trout *Oncorhynchus clarkii*) to sections that are transitioning cool-water species (e.g., black bass *Micropterus* spp. and walleye *S. vitreus*). Cool-water sections were identified using species composition data from electrofishing surveys conducted by MFWP and expert knowledge from state biologists. We delineated 14 cool-water sections across the Yellowstone, Bitterroot, Smith, Missouri, Bighorn, Jefferson, Clark Fork, and Madison rivers. Twelve cold-water sections adjacent to the cool-water sections were chosen for comparison to account for distance to population centers and river popularity (fig. S7). Differences in fishing pressure among these habitat types are qualitatively unchanged if cool-water sections are compared to all cold-water sections across the region.

To characterize future changes in cold-water habitat, we compared baseline (1993 to 2011) and future mean August water temperatures under the A1B scenario (31). We used existing temperature predictions that were developed under the A1B scenario, which is comparable to the RCP 6.0 scenario. Baseline mean August water temperatures (mean, 1993 to 2011) were significantly warmer in cool-water sections than in cold-water sections ($t = -27.558$, $P < 2.2 \times 10^{-16}$) and were consistently in excess of 18°C (Fig. 4C), which is similar to previous research on tolerance thresholds for cold-water trout species in the region (32). We used this 18°C threshold to project future distributions of cold-water habitat by quantifying where August water temperatures were currently less than 18°C but were predicted to be greater than 18°C in 2040 and 2080. Water temperature predictions were available at a finer spatial resolution than fishing pressure data; therefore, we calculated a percent loss of cold-water habitat for each fishing pressure reporting section.

In fishing sections that were currently less than 18°C but were projected to be warmer than 18°C in 2040 or 2080, we reduced fishing pressure in proportion to the percentage of habitat that transitioned

from cold-water to cool-water. To estimate changes in fishing pressure by resident and nonresident fishers due to shifts in cold- and cool-water habitat, we compared the average fishing pressure per kilometer per year in cool-water and cold-water sections over the past 3 years. Specifically, fishing pressure in cool-water sections was 10 and 35% of pressure in comparable cold-water sections for non-residents and residents, respectively (Fig. 4A). To project changes in fishing pressure, we reduced fishing pressure in proportion to these current preferences for cold- and cool-water habitats by resident and nonresident fishers.

Estimating the economic impacts of drought and shifts in cold-water habitat

We estimated the potential economic impacts of future drought and shifts from cold-water to cool-water habitat by calculating changes in spending by resident and nonresident fishers. We do not have data to determine differences in per diem spending by anglers targeting cold- versus cool-water fisheries. Therefore, we assumed that spending was the same across these target fisheries and all projected economic impacts are the result of only changes in angler pressure for resident and nonresident groups. To estimate the socioeconomic impacts of drought, we transformed effect sizes of PDSI to fisher-days per PDSI from DFA models for resident and nonresident fishers (Fig. 2, D and E). We combined these coefficients with current estimates of spending by fisher-day and fisher demographics (resident or nonresident) from MFWP (21) to calculate the cumulative effect of moderate, severe, or extreme drought on spending in each river section. To calculate the changes in spending in response to changes in cold-water habitat, we combined projected changes in fishing pressure as a result of cold-water habitat transitioning to cool-water habitat (see above) with spending by resident and nonresident fishers. These calculations are not intended to be specific projections and do not account for future valuation (i.e., they are not a net present value calculation), but rather provide an estimate of the scope of potential economic impacts.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at <https://science.org/doi/10.1126/sciadv.abn1396>

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Socioeconomic resilience to climatic extremes in a freshwater fishery

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