Reducing uncertainty in climate change responses of inland fishes: A decision-path approach

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Abstract
Climate change will continue to be an important consideration for conservation practitioners. However, uncertainty in identifying appropriate management strategies, particularly for understudied species and regions, constrains the implementation of science-based solutions and adaptation strategies. Here, we share a decision-path approach to reduce uncertainty in climate change responses of inland fishes to inform conservation and adaptation planning. With the Fish and Climate Change database (FiCli), a comprehensive, online, public database of peer-reviewed literature on documented and projected climate impacts to inland fishes and aquatic sciences, Burlington, Ontario, Canada, users can identify relevant studies and associated management recommendations via geographic regions, response types (i.e., fish assemblage dynamics, demographic, distributional, evolutionary, phenological), fish taxa, and traits (e.g., thermal guilds, feeding type, parental care, habitat type) and use a suite of summary tools to make more informed decisions. For both data-rich and data-poor scenarios, we demonstrate that this approach can reduce uncertainty in understanding climate change responses.

†Deceased.
Dedication: To our dear friend, Tom, an avid supporter and contributor to FiCli from the very beginning. We celebrate the good times we had together, grieve the loss of those not to be, and honor you with this manuscript and future FiCli efforts.

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Using thermal sensitivity as an example, we also establish the utility of FiCli database to address other user-defined, management-relevant questions via supplementary analyses. This decision-path approach can be applied to rapid assessments, management decisions, and policy development and may serve as a model for other conservation decision-making processes.

**KEYWORDS**
certainty metrics, data-poor, decision support, Fish and Climate Change database “FiCli”, freshwater fishes, natural resource management, synthesis tool

### 1 | INTRODUCTION

Uncertainty can hinder climate change adaptation and mitigation planning across spatial scales. Limited biology and life history knowledge for many species, even at the local level, creates uncertainty in predictions of ecosystem responses to climate change (e.g., Sievert et al., 2016). But, if managers can understand climate change responses, adaptation strategies are available to help protect, maintain, and restore fisheries resources (Paukert et al., 2016, 2021; Tingley et al., 2019). Fisheries managers can, for example, create or protect riparian habitat, remove barriers to fish movements, and or regulate harvest (Carter et al., 2019; Hansen et al., 2015; Paukert et al., 2016, 2021). When confronting climate change, frequently missing elements for decision making are: (1) what actions to implement, and (2) where to implement actions given the underlying uncertainty in species response.

Inland fishes (found in fresh and other land-locked waters) are critically important for global food security, livelihoods, and well-being, such as through recreational and subsistence fisheries (Lynch, Cooke, et al., 2016). Understanding how climate change may affect inland fishes and fisheries is critical to develop management strategies to sustain these important resources. While substantial evidence supports that climate change has (or will) shift species ranges and phenologies, change phenotypes, facilitate biological invasions, and create novel communities (Carter et al., 2019; Krabbenhoft et al., 2020; Lynch, Myers, et al., 2016), the direction and magnitude of some biological responses may differ across geographic regions and species. Even for the most well-studied fishes, there are inconsistent patterns in the literature of how fishes respond to climate change (Krabbenhoft et al., 2020). For example, decreased salmonid abundance from climate change was observed in over 89% of documented responses, but only 35% of modeled responses projected decreases (Myers et al., 2017). In addition, literature on climate change effects on salmonids disproportionately originates from North America and western Europe and, in general, few studies exist outside these regions (Kovach et al., 2016). These discrepancies further suggest that it is difficult to disentangle the effect of climate change from other stressors (Staudt et al., 2013) and across regions, which create challenges for fisheries managers who must predict which actions will produce a desired result.

Managers and other scientists are challenged to develop or implement management actions in response to climate change when the biological outcomes are uncertain and may differ by functional group, taxon, ecosystem type, or geographic region. However, global resources such as the Fish and Climate Change database (“FiCli,” pronounced fick-lee; Krabbenhoft et al., 2020) and FishBase (Froese & Pauly, 2021) can provide catalogued empirical data that can be used to reduce some uncertainty in the biological responses of fishes to climate change. These resources are particularly relevant for understudied species or regions, where applying actions based on responses of related species or species with similar niches within the same region may be the only option. Our objectives here are to: (1) showcase how climate change responses of inland fishes can be summarized and synthesized across geographic regions, taxa, and traits (e.g., thermal guilds, feeding type, parental care, habitat type), (2) demonstrate how a suite of summary tools and supporting analyses can help reduce uncertainty in climate change responses for data-rich and data-poor scenarios (e.g., species, traits, or geographic regions), and (3) highlight areas for future research to address climate change effects on inland fishes.

Our goal is to provide users, particularly fisheries managers, with an approach using a suite of summary tools associated with filtered outputs to generate informed predictions for likely climate effects (e.g., surrogate species approach; Wiens et al., 2008). We present this as a decision path as opposed to a decision tree because each filtering and summarization stage provides a means to reduce uncertainty around understanding of climate relationships to support decision making rather than provide a decision itself. Such a model could be
adapted to support other natural resource management decision needs and findings may form the basis for more structured decision-making approaches (Conroy & Peterson, 2013).

2 | METHODS

2.1 | FiCli database

The FiCli database (https://ficli.shinyapps.io/database/) is a comprehensive and growing global database that currently contains information on documented and projected impacts of climate change on inland fishes extracted from peer reviewed literature published in English between 1985 and 2020 (Krabbenhoft et al., 2020; Myers et al., 2017). Studies included in this database observed, documented, or projected fish responses to climate change (even if there was no relationship or statistically significant response). Related studies not included in this database were those that only examined climate variability or only suggested a potential impact or effect on fish (i.e., did not quantitatively project, observe, or document an impact on fish). The database can be filtered by a combination of taxonomic, biological, physical, ecological trait, and geographic parameters including climate change response type (Table S1). These user-defined queries allow for increasing specificity in the FiCli output to provide the most relevant information to address management-relevant questions.

2.2 | Decision path

The FiCli decision path (Online Graphical Abstract) synthesizes and summarizes FiCli output from customized queries based on the number of responses exhibiting a given climate change effect (i.e., positive, negative, or no effect) on the studied unit (i.e., individual fish, populations, assemblages, or species). Each response in the FiCli dataset was derived from the direction of change described in each publication (e.g., increased or decreased abundance, growth, recruitment, distribution). For example, if the abundance or growth rate of a species decreased in response to an increase in temperature or change in stream flow conditions, the response on the population was coded as negative, but if the study species showed a positive response to the physical climate change variable, then the response was coded as a positive effect on the fish population. The effect was coded with reference to the study species regardless of broader ecosystem effects (e.g., an increase in population size resulting from climate change for an invasive species is still coded as a positive for that particular species).

Summary and synthesis of the climate change responses can help improve understanding of the certainty (or uncertainty) of impacts on species or groups of species filtered by parameters as selected by users. For example, as FiCli contains both observed and projected responses of fishes to climate change, users can define whether they are solely interested in previously documented impacts of climate change on inland fish, projections of future responses of fish to climate change, or both. A user may want to better understand the uncertainty related to changes in the distribution of a coolwater species in a given region, or have increased confidence that its phenology is expected to shift with increased temperatures in a particular country or region. For a given search, a trade-off exists between the specificity of filters (Table S1) used and the number of studies obtained.

2.3 | Confidence metrics

The filtered output of a FiCli decision search includes a series of confidence metric algorithms around the fish response to climate change. These confidence metrics were adapted from the Intergovernmental Panel on Climate Change (IPCC) confidence scale guidelines for qualitative findings (Mastrandrea et al., 2011) and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) model for qualitative communication of confidence (Brondizio et al., 2019). Similar to their application by IPCC, the goal of these confidence metrics is to provide users with the ability to reduce uncertainty in climate change responses for a specified subset of the FiCli database entries. IPBES conducts large-scale assessments related to biodiversity change and ecosystem services impacts that incorporate extensive literature and other lines of evidence, which provides a relevant model for the FiCli confidence metrics tool.

The two elements used to derive confidence metrics are evidence and agreement (Brondizio et al., 2019; Mastrandrea et al., 2011). FiCli evidence is calculated as the proportion of fish responses to climate change given a user-defined evidence threshold, which represents the number of responses needed to be considered robust. The three evidence thresholds are limited (i.e., ≤20% of responses showing a given result), medium (21%–49%), and robust (≥50% where any number of responses at or exceeding the evidence threshold are considered 100%). Agreement is defined as the measure of consensus among scientific studies on a given topic, namely low (≤33%), medium (34%–65% similar evidence), and high (i.e., ≥66% of responses providing similar evidence). The
degree of agreement and evidence can be used to determine the confidence in the direction of the response (i.e., positive, negative, or no response) to climate change of queried fish populations. Well-established confidence is characterized by robust evidence and medium or high agreement, established but incomplete confidence is characterized by low evidence but medium or high agreement, unresolved is characterized by robust evidence but low agreement, and inconclusive is characterized by low evidence and low agreement. Although these criteria are subjective, they provide information regarding the level of evidence and agreement among the studies in Fi Cli. Taken together, the confidence metrics provide a qualitative metric to managers and other users of literature-based evidence and agreement for a given fish response to climate change, helping reduce some of the uncertainty in selecting different management strategies that will address certain positive or negative responses.

2.4 Supporting analyses

The first stages of the decision path are automated based on user-defined queries and summarized output. But, users can further interpret the synthesized information to better inform decision processes for “data-rich” and “data-poor” scenarios. For illustrative purposes, we hereafter define “data-rich” species as those with five or more responses reported from at least two different studies in the Fi Cli database. Species that did not meet these criteria are identified as “data-poor.” By these criteria, 15% of the 392 species within Fi Cli are labeled as data-rich and 85% are data-poor. While these criteria may not be considered robust evidence in any traditional trend analysis, Fi Cli is the most comprehensive global database of published studies specifically addressing climate change impacts on fishes, and it is representative of the current state of peer-reviewed literature written in English on the subject. The utility of Fi Cli will only improve as more studies and species are added to the database.

Here, we provide two examples of supporting analyses that examine thermal sensitivity to demonstrate the utility of the Fi Cli decision path in data-rich and data-poor contexts:

2.5 Data-rich case study: Thermal sensitivity of well-studied species

As meta-analysis is an increasingly useful tool for ecological studies (Koricheva et al., 2013), the Fi Cli database can serve as a foundational resource for synthesizing evidence from across research studies. In an exploratory analysis, the studies in Fi Cli can be used to determine the “thermal sensitivity” of fish species to climate change. For example, Brown Trout (Salmo trutta), Northern Pike (Esox lucius), and Common Carp (Cyprinus carpio) are the most represented coldwater, coolwater, and warmwater species, respectively, in the Fi Cli database (Table S2 and supplemental methods for thermal guild classification process).

Each relevant study in Fi Cli was reviewed and, when available, the maximum temperature increase reported was extracted. For example, if a study examined projected changes in Brown Trout distributions with increasing air temperatures during the 2020s, 2050s, and 2080s, the maximum temperature increase for the 2080s climate scenario was recorded for that study. For most studies, the maximum temperature increases were based on air rather than water temperatures (e.g., Stefan & Preud’homme, 1993), but both were recorded because the focus was the relative increases in temperature (e.g., increase of 3°C by the 2080s) rather than absolute temperatures. Maximum, as opposed to minimum or intermediate, temperature changes were recorded because species responses to warming may be more variable at those latter temperatures. To simplify this exploratory analysis, maximum temperature changes were rounded to the nearest °C (if change in temperature ≤0.5°C, temperature increase was listed as 0°C).

Thermal sensitivity was calculated for data-rich species, including Brown Trout, Northern Pike, and Common Carp, by first calculating the proportion of negative responses for each maximum temperature increase as the number of negative responses divided by the total number of positive, negative, and no effect responses. No-effect responses were included because they suggest that climate change is not an immediate concern for management and conservation. For these analyses, the number of responses included all of the response types (i.e., assemblage dynamics, demographic, distributional, evolutionary, phenological; Lynch, Myers, et al., 2016; Myers et al., 2017). For species whose proportion of negative responses was consistently above (negative response to increasing temperature) or below (positive response to increasing temperature) a 50% threshold, thermal sensitivity was set to the first temperature increase reported in the dataset. The remaining species were filtered to those that had at least two responses for three or more temperature increases. The proportion of negative responses was plotted against temperature increase and “thermal sensitivity” was defined as the increase in temperature at which 50% of the responses were either negative or positive and remained ≥50% positive or negative as temperatures warmed. Additionally, a qualitative data confidence
ranking of “high” or “low” was assigned to each thermal sensitivity value.

2.6 Data-poor case study: Thermal sensitivity of under-studied species

Because thermal guild is a key factor in the FiCli database, we can also explore thermal sensitivity further for data-poor situations. We paired information available in FiCli with phylogenetic and species trait information to infer the thermal sensitivity of data-poor species. Species that are closely related often share similar ecological traits and niches, and thus tolerate similar environmental conditions (Qian et al., 2020; Qian & Ricklefs, 2004; Wiens & Donoghue, 2004). Therefore, phylogenies for fish species may serve as maps to estimate data-poor species responses to climate change. Salmonidae is one of the well-studied families in FiCli, and their phylogenetic relationships have been largely resolved (Crespi & Fulton, 2004). The thermal sensitivities of the data-rich salmonids were added to their phylogenetic tree to demonstrate how relatedness may be used to estimate the thermal sensitivity of data-poor salmonids.

3 RESULTS

3.1 Summarized inland fish responses to climate change

FiCli currently contains 1472 responses (35% documented, 65% projected) from studies published between 1985 and 2020 across 58 families and 392 species (Figure 1). Fish responses in FiCli are linked to temperature (91%), precipitation (25%), streamflow (17%), and ice cover (3%) as climate change variables; many responses have more than one associated climate change variable (so the proportions do not sum to 100%). Distributional and demographic responses dominate with 64% and 31% of the database entries, respectively. Responses are from lotic environments (82%) and lentic environments (24%); some studies included both system types. FiCli includes studies from every continent with inland fish habitat (i.e., every continent except Antarctica). However, the responses are heavily skewed to Europe and North America with 46% and 43% of the database entries, respectively.

3.2 Confidence metrics

Fish responses to climate change are classified as negative (40%), positive (34%), mixed (10%), no effect (10%), or unknown (6%). Confidence metrics varied for response categories by thermal guild, habitat, continent, and the five most well-represented fish families when using an evidence threshold of 100 responses with projected studies half weighted compared to documented studies (Table 1). Demographic and distributional responses comprised the majority of well-established evidence (i.e., robust evidence, medium, or high agreement) across thermal guilds, habitat, most continents, and most of the top five fish families. Evolutionary, phenological, and assemblage dynamics responses had established but incomplete evidence (i.e., low evidence, medium/high agreement) across most thermal guilds and habitats, but inconclusive evidence (i.e., low evidence, low agreement) for many continents and major fish families. As one particular example, examining all coldwater responses, we have well-established confidence in negative demographic, distributional, and assemblage dynamics responses, inconclusive evidence for phenological responses, and unresolved evidence (i.e., low evidence, medium/high agreement) for evolutionary responses (Figure 2).

Confidence metrics for data-rich species can provide a decision-support tool to summarize and synthesize evidence from the literature across response types. For example, Brown Trout are well-studied in lotic systems in Europe (34 reported responses in FiCli). Based on an evidence threshold of 10 responses where projected responses were half-weighted compared to documented studies (Figure 3), we have well-established confidence in negative demographic responses (i.e., robust evidence as indicated by reaching the outer, dark gray ring and high agreement for a negative response as shown in dark red), established but incomplete confidence in negative evolutionary responses (i.e., limited evidence as indicated by placement in the inner, white circle and high agreement for a negative response as shown in dark red), and unresolved evidence for distributional responses (i.e., robust evidence as indicated by reaching the outer, dark gray ring but for both positive and negative responses as shown in dark blue and red) in Brown Trout in lotic systems of Europe.

For data-poor situations, we found thermal guilds to be an important predictor of fish response to climate change (Appendix 1 in Supporting information S1) but the responses are nuanced. As a fundamental baseline for data-poor species, the classification of these response categories by thermal guild can provide a useful reference (Figure 2). Using an evidence threshold of 100 responses with projected studies half weighted compared to documented studies, for coldwater responses (33% of the database), we found well-established confidence in negative demographic, distributional, and assemblage dynamics responses, inconclusive evolutionary evidence, and
unresolved phenological evidence. For coolwater responses (23%), we found well-established confidence in negative demographic and distributional responses, established but incomplete confidence in negative assemblage dynamics and phenological responses, and inconclusive evolutionary evidence. For warmwater responses (42%), we found well-established confidence in positive demographic and distributional responses, well-established confidence in negative phenological and assemblage dynamic responses, and established but incomplete confidence in negative evolutionary responses. Note that these responses do not sum to 100% as some studies include multiple thermal guilds and some assemblage studies have unknown thermal guilds.

3.3 | Data-rich case study: Thermal sensitivity of well-studied species

The responses of Brown Trout, Northern Pike, and Common Carp varied as temperatures warmed (Figure 4). Of the 32 responses included for Brown Trout, more than 50% were negative once temperatures increased by 1.4°C. The opposite was true for warmwater Common Carp which responded positively to all increases in temperature. Coolwater Northern Pike showed a curvilinear response where a temperature increase of 2°C had a negative effect, but at temperature increases of 4 and 5°C the proportion of negative responses decreased to the 50% threshold. Based on
these results, the thermal sensitivity of Brown Trout was set to 1.4°C and Common Carp was set to 1°C (i.e., the first temperature increases with at least two responses). The thermal sensitivity of Northern Pike was set to 2°C based on the 50% criterion.

Of the 59 data-rich species in FiCli, thermal sensitivities of 30 species were estimated (Table S2). Species that showed unidirectional responses to warming (such as the Brown Trout and Common Carp above) were assigned “high” data confidence while species such as Northern Pike that had complex responses to warming were assigned “low” confidence rankings. Although the coolwater species may accurately reflect a curvilinear response to temperature with regard to metabolism (i.e., bioenergetics), these findings may also be a product of the number of studies per species in FiCli and, thus, were assigned “low” confidence. It was not possible to estimate the thermal sensitivity of some data-rich species because their responses showed no obvious pattern as temperatures increased (Table S2).

| TABLE 1 | Summary of confidence metrics from the Fish and Climate Change database (FiCli) responses by thermal guild, habitat, continent, and family (only the five most well-represented fish families listed) using an evidence threshold of 100 responses with projected studies half weighted compared to documented studies |
|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| **Demographic** | **Distributional** | **Evolutionary** | **Phenological** | **Assemblage dynamics** |
| Well-established (i.e., medium/robust evidence, medium/high agreement) | Coldwater (−) | Coolwater (−) | Warmwater (+) | Warmwater (−) |
| | Warmwater (+) | Lentic (+) | Lotic (+) | Lotic (−) |
| | Asia (−) | Europe (−) | North America (−) | Asia (−) |
| | Oceania (+) | Cyprinidae (+) | Centrarchidae (+) | Centrarchidae (+) |
| | Salmonidae (−) | Ictaluridae (−) | Percidae (−) | Salmonidae (−) |
| Established but incomplete (i.e., low evidence, medium/high agreement) | Coldwater (−) | Warmwater (−) | Coolwater (−) | Coolwater (−) |
| | Lentic (−) | Lotic (−) | North America (−) |
| | Africa (−) | South America (−) | Africa (−) | Europe (−) |
| | South America (NR) | Europe (−) | North America (−) | South America (−) |
| | Ictaluridae (+) | Ictaluridae (−) | Percidae (−) | Ictaluridae (−) |
| | Percidae | Salmonidae | Coldwater | Salmonidae |
| Inconclusive (i.e., low evidence, low agreement) | Africa | Coolwater | Asia | Africa |
| | Asia | Africa | Oceania | Asia |
| | South America | Centrarchidae | Cyprinidae | Centrarchidae |
| | Oceania | Percidae | Percidae | Cyprinidae |
| | Centrarchidae | Ictaluridae | Percidae | Ictaluridae |
| | Cyprinidae | Percidae | Salmonidae | Salmonidae |

Note: (−) Indicates a consensus negative response, (+) consensus positive response, and (NR) consensus no response for the listed categories.
The thermal sensitivities derived here provide a quantitative means to rank the sensitivity of species to warming and can be incorporated into management and adaptation decision-support tools. At its core, the sensitivity of a species to warming is driven by metabolic demands (Brown et al., 2004) and studies linking...
physiology to climate change vulnerability are prevalent in the literature (Farrell, 2009; Kelly et al., 2014; Whitney et al., 2016). FiCli provides an alternative approach to determine the sensitivity of species based on the different study areas, habitats, and response types (i.e., distributional, phenological, demographic, assemblage, and/or evolutionary changes) that have been researched and published. The sensitivities can be used to set guidelines that trigger management or adaptation actions. For example, if waters warm by 1°C in Brown Trout and Common Carp habitats, managers may choose to increase monitoring and assessment of the populations. However, if temperatures increase by more than 1°C, more aggressive management and adaptation planning may be initiated. For Brown Trout, these actions may be aimed toward conservation (e.g., reductions in harvest or restoration of habitat). However, for Common Carp, who respond positively to warming, actions may be focused on controls where the species is invasive (Myers et al., 2017; e.g., increase in fishing season length or harvest limits; Krabbenhoft et al., 2020). However, it is important

| Species                | Common name       | Temperature (°C) increase at which 50% of responses were negative |
|-----------------------|-------------------|---------------------------------------------------------------|
| Oncorhynchus mykiss   | Rainbow Trout     | 3.4                                                           |
| Oncorhynchus clarkii  | Cutthroat Trout   | 2                                                             |
| Oncorhynchus masou    | Masou Salmon      |                                                               |
| Oncorhynchus tshawytscha | Chinook Salmon | 2.1                                                           |
| Oncorhynchus kisutch  | Coho Salmon       |                                                               |
| Oncorhynchus gorbuscha | Pink Salmon      |                                                               |
| Oncorhynchus keta     | Chum Salmon       |                                                               |
| Oncorhynchus nerka    | Sockeye Salmon    |                                                               |
| Salvelinus alpinus    | Arctic Char       | 1                                                             |
| Salvelinus malma      | Dolly Varden      |                                                               |
| Salvelinus confluentus| Bull Trout        | 2                                                             |
| Salvelinus leucomaenis| Whitespotted Char |                                                               |
| Salvelinus fontinalis | Brook Trout       | 1                                                             |
| Salvelinus namaycush  | Lake Trout        |                                                               |
| Salmo salar           | Atlantic Salmon   | 4                                                             |
| Salmo ohridanus       | Belvica           |                                                               |
| Salmo trutta          | Brown Trout       | 1.4                                                           |
| Hucho perryi          | Sakhalin taimen   |                                                               |
| Coregonus lavaretus   | Common Whitefish  |                                                               |
| Hucho hucho           | Danube Salmon     |                                                               |
| Brachymystax lenok    | Sharp-snouted Lenok |                                                         |

FIGURE 4 Proportion of negative responses (e.g., decreased growth, range contractions) of coldwater Brown Trout (Salmo trutta), coolwater Northern Pike (Esox lucius), and warmwater Common Carp (Cyprinus carpio) to increases in temperature based on the studies in the Fish and Climate Change database. Dashed line indicates where 50% of the responses were negative (\( n \) = number of species-specific responses). The maximum temperature changes were rounded to the nearest °C (if change in temperature ≤0.5°C, temperature increase listed as 0°C). Arrows indicate thermal sensitivity values for each species.

FIGURE 5 Phylogeny of Salmonidae (Crespi & Fulton, 2004) and thermal sensitivities of data-rich salmonid species in the Fish and Climate Change database.
to note that thresholds may be crossed (biologically or physically) by the time these temperature changes are detected.

3.4 Data-poor case study: Thermal sensitivity of under-studied species

Overlaying the thermal sensitivities of data-rich salmonids on their phylogenetic tree indicated that the thermal sensitivities of species within Salmonidae ranged from 1°C to 4°C with Oncorhynchus species ranging from 2 to 3.4°C, Salvelinus species ranging from 1 to 2°C and Salmo species ranging from 1.4 to 4°C (Figure 5). Although thermal sensitivities were not available for ~50% of the salmonids, six of the eight most closely related species pairs had one estimate of thermal sensitivity. In the absence of other information, the sensitivities of the known species may serve as surrogates for the closely related data-poor species. When scaled up to genus, Salvelinus appears to be more sensitive to temperature increases than Oncorhynchus and Salmo. These results are consistent with species distribution studies. For example, Bull Trout (Salvelinus confluentus) and Brook Trout (S. fontinalis) distributions were sensitive to climate whereas Cutthroat Trout (Oncorhynchus clarkii) were more sensitive to the presence of non-native species and less sensitive to climate (Wenger et al., 2010). Therefore, these results suggest that if one sought to rank the climate vulnerability and prioritize management and adaptation actions among salmonids, Salvelinus species may warrant precedence over the others.

4 DISCUSSION

The FiCli database provides a comprehensive resource of available peer-reviewed literature focused on how climate change has impacted and will continue to impact inland fishes worldwide (Krabbenhoft et al., 2020). These studies have been compiled through an extensive, systematic, primary literature review to identify English-language, peer-reviewed journal publications with projected and documented examples of climate change impacts on inland fishes globally. With the addition of summary tools, including confidence metrics, managers and other users can customize a decision path in FiCli. They can build value-added analyses in data-rich situations and use established relationships for data-rich situations to infer climate vulnerability for those that are data-poor (Online Graphical Abstract). FiCli results may reduce some of the uncertainty about species responses to climate change to inform management strategies and adaptation approaches.

In particular, coupling FiCli information with local fish data and tools can assist with management and adaptation planning by improving understanding of climate impacts for a unit of interest (e.g., filtered by taxa, geographic region, or traits). For data-rich analyses, the FiCli database can provide a synthesis of documented and projected climate change effects and can be used to yield new ecological and management insights; for data-poor examinations, surrogate approaches (e.g., Wiens et al., 2008) can help provide inference into current or anticipated climate change responses and identify research needs.

For instance, climate change is generally held to negatively impact coldwater fishes and positively impact warmwater species, with cooler species having a mix of positive and negative responses (Comte et al., 2013; Sharma et al., 2007). However, the actual impact and resilience of species depends on their adaptive capacity, and the ecosystems they inhabit (Foden et al., 2013). Case in point, the negative, positive, and no effect responses among thermal guilds in the FiCli database illustrate that although coldwater species were more negatively impacted than cool- and warmwater species, the responses of thermal guilds to climate change are complex (Figure 2). This nuanced result suggests that the typical trope of climate change “winners” and “losers” (Somero, 2010) is incomplete and is a reminder that climate change adaptation and management for fishes is not a “one-size-fits-all” approach, even within thermal guilds. For example, while seasonal temperature is not currently standardized in FiCli, the database does contain more detailed climate driver information that could be used to examine seasonal use of habitats further (sensu Armstrong et al., 2021).

4.1 Limitations

Our decision-path approach may elucidate broad-scale trends in climate change impacts to inland fishes, but limitations and biases still exist. Understanding potential bias or error associated with climate change effects derived from literature compilation is critical for interpreting results and informing decisions. We acknowledge that there are limitations with operationalizing these evidence and agreement metrics due to the aggregate nature of this database. For example, comparing projected and documented studies, studies of different spatial extents, or studies reliant upon the same datasets can introduce biases into summarized metrics.

Our decision-path approach, including the confidence metrics and summary tools, does not supplant formal meta-analysis and thus interpretations should be made in the context of several limitations. First, we categorize climate change effects as positive, negative, or no effect,
which apply clearly to population demographics or distribution, but are less straightforward when considering phenological alterations. In cases when responses are ambiguous or research evidence (i.e., number of responses) or agreement is low, additional research is warranted. Moreover, the literature in FiCli is not evenly distributed among fish taxa and geographic locations (i.e., few studies exist outside of Europe and North America), and examination of the evidence metrics can be used to identify specific knowledge gaps and research needs to guide management decisions (Myers et al., 2017). Similarly, patterns in FiCli may be affected by environmental tolerance and cumulative human activities in addition to climate change. Ubiquitously distributed species may be more tolerant to disturbance or plastic in their response relative to spatially restricted species or populations (e.g., Karatayev et al., 2009). Spatial and temporal scale of research may strongly influence conclusions, which may be erroneous if applied to alternate scales (Durance et al., 2006; Meentemeyer, 1989). Lastly, findings documenting past and current climate change impacts to fishes have stronger inference than projections of future impacts. Considering such potential forms of bias or error may explain low agreement among studies and enhance interpretation to guide management.

Second, our effort to provide a decision path based on a rigorous, robust, and standardized database of studies precluded inclusion of published research on several tangential topic areas, including those with focus on: climate variability, laboratory experiments, habitat- or physical process-based studies (e.g., no organismal response), and research with space-for-time substitutive experimental designs. However, we acknowledge the value of such work to inform decisions related to climate effects on fish. For example, quantifying the scope of historical and current climate variation provides critical information that can be used to link key freshwater physical processes (e.g., stream flow and water temperature) with organismal life histories and ecology, produce realistic climate scenarios, and thus better predict how future climate change may impact populations (Falke et al., 2019; Kovach et al., 2016). Experimental work has also expanded our understanding of how climate change is likely to impact inland fishes, particularly studies that link adaptive capacity to climate drivers (e.g., water temperature variability; Sparks et al., 2017), which are challenging to conduct in field settings. In areas where climate-fish relationships are well understood (e.g., salmonids in the Pacific Northwest, USA), studies that evaluate current and future climate impacts on habitats (e.g., fluvial geomorphology; Sloate et al., 2018; hydrologic regimes; Sergeant et al., 2020) may provide important insight for management of inland fishes without a specific focus on an organismal response.

Before generating confidence metrics plots using the FiCli database, all users must click through a data limitations statement which expresses caution in interpreting the summarized results based on the issues mentioned above. FiCli outputs are all fully customizable; filtering options within a FiCli decision search allows users to address any bias concerns specific to individual queries. Users can, for example, identify their own thresholds for these classifications, weight projected and documented responses differently, and filter out studies geographically at their discretion. We recognize that managers must still make decisions and, even acknowledging its limitations, the FiCli decision path can support these processes by collating the most up-to-date peer-reviewed literature on documented and projected impacts of climate change on inland fishes.

### 4.2 Climate action

The FiCli decision path can contribute to climate action within assessment, management, and policy realms, and at multiple scales (e.g., State Wildlife Action Plans, Species Status Assessments, the National Climate Assessment in the United States, global IPCC, IPBES, and International Union for Conservation of Nature assessments). All of these processes strive to use the best-available science which, in many cases, is quite limited. In support of these activities, FiCli can be used to synthesize the currently available information and provide confidence metrics to gauge uncertainty. For example, one could evaluate factors relevant to vulnerability assessments drawing on three axes (i.e., sensitivity, exposure, and adaptive capacity; Foden et al., 2013) for specific taxa, or insight could be gained that might be applied in surrogacy (e.g., Figure 5; Table S1), based on information contained in FiCli. While deterministic and mechanistic linked climate-freshwater process models (Isaak et al., 2017; Janse et al., 2015; Wenger et al., 2010) are beyond the scope of FiCli, the database is a starting point to characterize and evaluate vulnerability which can be paired with such modeling to provide key context for the magnitude of climate impacts on inland fishes.

Informed fisheries management decisions related to climate change are complicated by uncertainty surrounding the impact of climate relative to other anthropogenic stressors (Gutowsky et al., 2019; Lynch, Myers, et al., 2016). However, the decision path we describe can provide insight and evidence toward untangling these complex relationships and inform adaptive management for inland fishes and other natural resources. The Resist-Accept-Direct (RAD) framework is one such adaptive approach to address ecosystem change by identifying whether such change should be resisted by maintaining
current ecosystem composition, accepted when such maintenance is infeasible, or directed toward a desired future outcome (Lynch et al., 2021; Schuurman et al., 2022; Thompson et al., 2021). Knowledge required to support RAD freshwater fisheries management (Rahel, 2022) can be gleaned from the FiCli database, and identified through the decision path developed here. Key areas identified by Thompson et al. (2021) to support effective management include: focused ecosystem assessment and monitoring, a better mechanistic understanding of environmental drivers, and development of flexible and responsive management strategies. Our decision-path approach could be used to identify specific management strategies that incorporate these key areas and provide direction and support for decisions to resist, accept, or direct ecosystem change in the context of freshwater fisheries and other natural resources.

Lastly, FiCli serves as a clearinghouse for documented and projected climate impacts to inland fishes. FiCli may also serve as a summary tool and resource to support policy in alignment with a recent statement made by 110 global aquatic scientific societies expressing support policy in alignment with a recent statement. FiCli can help feature inland fishes in such initiatives and elevate inland fishes within local, regional, and global planning for assessment activities and management, such as local wildlife action plans, national climate assessments, and global biodiversity assessments. Likewise, our decision-path approach may serve as a model for integrating evidence syntheses into other natural resource decision-making processes.

AUTHOR CONTRIBUTIONS
Conceptualization: Abigail J. Lynch, Bonnie J. E. Myers, Cindy Chu, Ralph W. Tingley, Jeffrey A. Falke, Thomas J. Kwak, Craig P. Paukert, Trevor J. Krabbenhoft; Software: Jesse P. Wong; Analysis: Abigail J. Lynch, Bonnie J. E. Myers, Cindy Chu, Ralph W. Tingley; Data Curation: Abigail J. Lynch, Bonnie J. E. Myers, Jesse P. Wong, Trevor J. Krabbenhoft; Writing, Editing, Review: Abigail J. Lynch, Bonnie J. E. Myers, Jesse P. Wong, Trevor J. Krabbenhoft; Project administration: Abigail J. Lynch, Trevor J. Krabbenhoft.

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CONFLICT OF INTEREST
None to declare.

DATA AVAILABILITY STATEMENT
The data used in this study are publicly available at https://ficli.shinyapps.io/database/. The data and code to create the user interface are also publicly available at https://doi.org/10.5066/P9F6HA3M. Code was implemented in R (version 3.6.1; https://r-project.org) using the package shiny (version 1.3.2). There are no restrictions to the access or use.

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REFERENCES

Armstrong, J. B., Fullerton, A. H., Jordan, C. E., Ebersole, J. L., Bellmore, J. R., Arismendi, I., Penaluna, B. E., & Reeves, G. H. (2021). The importance of warm habitat to the growth regime of cold-water fishes. Nature Climate Change, 11(4), 354–361. https://doi.org/10.1038/s41558-021-00994-y

Bonar, S. A. (2021). Development of the “statement of world aquatic scientific societies on the need to take urgent action against human-caused climate change, based on scientific evidence.” Fisheries, 46(9), 411–412. https://doi.org/10.1002/fsh.10641

Brondizio, E. S., Diaz, S., Settele, J., Ngo, H., Guèze, M., Aumeeruddy-Thomas, Y., Bai, X, Geschke, A, Molnár, Z, Niamir, A, Pascual, U, Simcock, A, Jaureguierry, P, Hien, N, Brancalion, P, Chan, KMA, Dubertret, F, Hendry, A, Liu, J, ... Zayas, C. 2019. Assessing a planet in transformation: Rationale and approach of the IPBES Global Assessment on Biodiversity and Ecosystem Services. In IPBES Global Assessment on Biodiversity and Ecosystem Services. https://ipbes.net/global-assessment%0Ahttps://ipbes.net/global-assessment-report-biodiversity-ecosystem-services

Brown, J. H., Gillooly, J. F., Allen, A. P., Savage, V. M., & West, G. B. (2004). Toward a metabolic theory of ecology. Ecology, 85(7), 1771–1789.

Carter, S. L., Lynch, A. J., Myers, B. J. E., Rubenstein, M. A., & Thompson, L. M. (2019). Hypotheses from recent assessments of climate impacts to biodiversity and ecosystems in the United States. In W. L. Filho, J. Barbir, & R. Preziosi (Eds.), Handbook of climate change and biodiversity (pp. 355–375). Springer International Publishing. https://doi.org/10.1007/978-3-319-98681-4

Comte, L., Buisson, L., Daufresne, M., & Grenouillet, G. (2013). Climate-induced changes in the distribution of freshwater fish: Observed and predicted trends. Freshwater Biology, 58(4), 625–639. https://doi.org/10.1111/fwb.12081

Conroy, M. J., & Peterson, J. T. (2013). Decision making in natural resource management: A structured, adaptive approach. John Wiley & Sons, Ltd. https://doi.org/10.1002/9781118506196

Crespi, B. J., & Fulton, M. J. (2004). Molecular systematics of Salmonidae: Combined nuclear data yields a robust phylogeny. Molecular Phylogenetics and Evolution, 31(2), 658–679. https://doi.org/10.1016/j.ympev.2003.08.012

Durance, I., Lepichon, C., & Ormerod, S. J. (2006). Recognizing the importance of scale in the ecology and management of riverine fish. River Research and Applications, 22, 1143–1152.

Falke, J. A., Huntsman, B. M., & Schoen, E. R. (2019). Climatic variation drives growth potential of juvenile Chinook Salmon along a subarctic boreal Riverscape. In R. M. Hughes, D. M. Infante, L. Wang, K. Chen, & B. d. P. Terra (Eds.), Advances in understanding landscape influences on freshwater habitats and biological assemblages. American Fisheries Society Press. https://doi.org/10.4786/9781934874561.ch4

Farrell, A. P. (2009). Environment, antecedents and climate change: Lessons from the study of temperature physiology and river migration of salmonids. The Journal of Experimental Biology, 212(23), 3771–3780. https://doi.org/10.1242/jeb.023671

Foden, W. B., Butchart, S. H. M., Stuart, S. N., Vié, J. C., Akçakaya, H. R., Angulo, A., DeVantier, L. M., Gutsche, A., Turak, E., Cao, L., Donner, S. D., Katariya, V., Bernard, R., Holland, R. A., Hughes, A. F., O’Hanlon, S. E., Garnett, S. T., Šekercioğlu, Ç. H., & Mace, G. M. (2013). Identifying the world’s most climate change vulnerable species: A systematic trait-based assessment of all birds, amphibians and corals. PLoS One, 8(6), e65427. https://doi.org/10.1371/journal.pone.0065427

Froese, R., & Pauly, D. (Eds.). (2021). FishBase. World Wide Web Electronic Publication. https://www.fishbase.se/

Gutowsky, L. F. G., Giacomini, H. C., de Kerckhove, D. T., Mackereth, R., McCormick, D., & Chu, C. (2019). Quantifying multiple pressure interactions affecting populations of a recreationally and commercially important freshwater fish. Global Change Biology, 25(3), 1049–1062. https://doi.org/10.1111/gcb.14556

Hansen, G. J. A., Gaeta, J. W., Hansen, J. F., & Carpenter, S. R. (2015). Learning to manage and managing to learn: Sustaining freshwater recreational fisheries in a changing environment. Fisheries, 40(2), 56–64. https://doi.org/10.1080/03632415.2014.996804

Isaak, D. J., Wenger, S. J., Peterson, E. E., Ver Hoef, J. M., Nagel, D. E., Luce, C. H., Hostetler, S. W., Dunham, J. B., Roper, B. B., Wolfrap, S. P., Chandler, G. L., Horan, D. L., & Parkes-Payne, S. (2017). The NorWest summer stream temperature model and scenarios for the Western U.S.: A crowd-sourced database and new geospatial tools foster a user community and predict broad climate warming of rivers and streams. Water Resources Research, 53(11), 9181–9205. https://doi.org/10.1002/2017WR020969

Janse, J. H., Kuiper, J. J., Weijters, M. J., Westerbeek, E. P., Jeuken, M. H. J., Bakkenes, M., Alkemade, R., Mooij, W. M., & Verhoeven, J. T. A. (2015). GLOBIO-aquatic, a global model of human impact on the biodiversity of inland aquatic ecosystems. Environmental Science & Policy, 48, 99–114. https://doi.org/10.1016/j.envsci.2014.12.007

Karatayev, A. Y., Burlakova, L. E., Padilla, D. K., Mastitsky, S. E., & Olenin, S. (2009). Invaders are not a random selection of species. Biological Invasions, 11(9), 2009–2019. https://doi.org/10.1007/s10530-009-9498-0

Kelly, N. I., Burness, G., McDermid, J. L., & Wilson, C. C. (2014). Ice age fish in a warming world: Minimal variation in thermal acclimation capacity among lake trout (Salvelinus namaycush) populations. Conservation Physiology, 2(1), 1–14. https://doi.org/10.1093/comphys/cou025

Koricheva, J., Gurevitch, J., & Mengersen, K. (2013). Handbook of meta-analysis in ecology and evolution. Princeton University Press. https://doi.org/10.1515/9781400846184

Kovach, R. P., Muhlfeld, C. C., Al-Chokhachy, R., Dunham, J. B., Letcher, B. H., & Kershner, J. L. (2016). Impacts of climatic variation on trout: A global synthesis and path forward. Reviews in Fish Biology and Fisheries, 26, 135–151. https://doi.org/10.1007/s11160-015-9414-x

Krabbenhoft, T. J., Myers, B. J. E., Wong, J. P., Chu, C., Tingley, R. W., Falke, J. A., Kwak, T. J., Paukert, C. P., & Lynch, A. J. (2020). FiCl, the Fish and Climate Change database, informs climate adaptation and management for freshwater fishes. Scientific Data, 7(1), 1–6. https://doi.org/10.1038/s41597-020-0465-z

Lynch, A. J., Cooke, S. J., Deines, A. M., Bower, S. D., Bunnell, D. B., Cowx, I. G., Nguyen, V. M., Nohner, J.,...
Phouthavong, K., Riley, B., Rogers, M. W., Taylor, W. W., Woelmer, W., Youn, S.-J., & Beard, T. D. (2016). The social, economic, and environmental importance of inland fish and fisheries. *Environmental Reviews*, 24(2), 1–7. https://doi.org/10.1139/er-2015-0064

Lynch, A. J., Myers, B. J. E., Chu, C., Eby, L. A., Falke, J. A., Kovach, R. P., Krabbenhoft, T. J., Kwak, T. J., Lyons, J., Paukert, C. P., & Whitney, J. E. (2016). Climate change effects on North American inland fish populations and assemblages. *Fisheries*, 41(7), 346–361. https://doi.org/10.1080/03632415.2016.1186016

Lynch, A. J., Thompson, L. M., Beever, E. A., Cole, D. N., Engman, A. C., Hawkins Hoffman, C., Jackson, S. T., Krabbenhoft, T. J., Lawrence, D. J., Limpinesel, D., Magill, R. T., Melvin, T. A., Morton, J. M., Newman, R. A., Peterson, J. O., Porath, M. T., Rahel, F. J., Schuurman, G. W., Sethi, S. A., & Wilkening, J. L. (2021). Managing for RADical ecosystem change: Applying the Resist-Accept-Direct (RAD) framework. *Frontiers in Ecology and the Environment*, 19(8), 461–469. https://doi.org/10.1002/fee.2377

Mastrandrea, M. D., Mach, K. J., Plattner, G. K., Edenhofer, O., Stocker, T. F., Field, C. B., Ebi, K. L., & Matschoss, P. R. (2011). The IPCC AR5 guidance note on consistent treatment of uncertainties: A common approach across the working groups. *Climatic Change*, 108(4), 675–691. https://doi.org/10.1007/s10584-011-0718-6

Meentemeyer, V. (1989). Geographical perspectives of space, time, and scale. *Scale: Landscape Ecology*, 3(3–4), 163–173. https://doi.org/10.1007/BF00131535

Myers, B. J. E., Lynch, A. J., Bunnell, D. B., Chu, C., Falke, J. A., Kovach, R. P., Krabbenhoft, T. J., Kwak, T. J., & Paukert, C. P. (2017). Global synthesis of the documented and projected effects of climate change on inland fishes. *Reviews in Fish Biology and Fisheries*, 27(2), 339–361. https://doi.org/10.1007/s11160-017-9476-z

Paukert, C. P., Glazer, B. A., Hansen, G. J. A., Irwin, B. J., Jacobson, P. C., Kershner, J. L., Shutler, B. J., Whitney, J. E., & Lynch, A. J. (2016). Adapting inland fisheries management to a changing climate. *Fisheries*, 41(7), 374–384. https://doi.org/10.1080/03632415.2016.1185009

Paukert, C. P., Olden, J. D., Lynch, A. J., Breshears, D. D., Christopher Chambers, R., Chu, C., Daly, M., Dibble, K. L., Falke, J., Issak, D., Jacobson, P., Jensen, O. P., & Munroe, D. (2021). Climate change effects on North American fish and fisheries to inform adaptation strategies. *Fisheries*, 46(9), 449–464. https://doi.org/10.1002/fsh.10668

Qian, H., Cao, Y., Li, D., Chu, C., Sandel, B., & Wang, X. (2020). Geographic patterns and environmental correlates of phylogenetic relatedness and diversity for freshwater fish assemblages in North America. *Ecography*, 43, 1–11. https://doi.org/10.1111/ecog.05280

Qian, H., & Ricklefs, R. E. (2004). Geographical distribution and ecological conservatism of disjunct genera of vascular plants in eastern Asia and eastern North America. *Journal of Ecology*, 92(2), 253–265. https://doi.org/10.1111/j.0022-0477.2004.00868.x

Rahel, F. J. (2022). Managing freshwater fish in a changing climate: Resist, accept, or direct? *Fisheries*. Advance online publication. https://doi.org/10.1002/fsb.10726

Schuurman, G. W., Cole, D. N., Cravens, A. E., Covington, S., Craushay, S. D., Hoffman, C. H., Lawrence, D. J., Magnness, D. R., Morton, J. M., Nelson, E. A., & O’Malley, R. (2022). Navigating ecological transformation: Resist–accept–direct as a path to a new resource management paradigm. *Bioscience*, 72(1), 16–29. https://doi.org/10.1093/biosci/biaa067

Sergeant, C. J., Falke, J. A., Bellmore, R. A., Bellmore, J. R., & Crumley, R. L. (2020). A classification of streamflow patterns across the coastal Gulf of Alaska. *Water Resources Research*, 56(2), 1–17. https://doi.org/10.1029/2019WR026217

Sharma, S., Jackson, D. A., Minns, C. K., & Shuter, B. J. (2007). Will northern fish populations be in hot water because of climate change? *Global Change Biology*, 13(10), 2052–2064. https://doi.org/10.1111/j.1365-2486.2007.01426.x

Sievert, N. A., Paukert, C. P., Tsang, Y. P., & Infante, D. (2016). Development and assessment of indices to determine stream fish vulnerability to climate change and habitat alteration. *Ecological Indicators*, 67, 403–416. https://doi.org/10.1016/j.ecolind.2016.03.013

Sloat, M. R., Reeves, G. H., & Christiansen, K. R. (2018). Stream network geomorphology mediates predicted vulnerability of anadromous fish habitat to hydrologic change in Southeast Alaska. *Global Change Biology*, 23(2), 604–620. https://doi.org/10.1111/gcb.13466

Somero, G. N. (2010). The physiology of climate change: How potentials for acclimatization and genetic adaptation will determine “winners” and “losers”.” *The Journal of Experimental Biology*, 213(6), 912–920. https://doi.org/10.1242/jeb.037473

Sparks, M. M., Westley, P. A. H., Falke, J. A., & Quinn, T. P. (2017). Thermal adaptation and phenotypic plasticity in a warming world: Insights from common garden experiments on Alaskan sockeye salmon. *Global Change Biology*, 23(12), 5203–5217. https://doi.org/10.1111/gcb.13782

Staudt, A., Leidner, A. K., Howard, J., Brauman, K. A., Dukes, J. S., Hansen, L. J., Paukert, C., Sabo, J., & Solórzano, L. A. (2013). The added complications of climate change: Understanding and managing biodiversity and ecosystems. *Frontiers in Ecology and the Environment*, 11(9), 494–501. https://doi.org/10.1890/120275

Stefan, H. G., & Preud’homme, E. B. (1993). Stream temperature estimation from air temperature. *Journal of the American Water Resources Association*, 29(1), 27–45. https://doi.org/10.1111/j.1752-1688.1993.tb01502.x

Thompson, L. M., Lynch, A. J., Beever, E. A., Engman, A. C., Falke, J. A., Jackson, S. T., Krabbenhoft, T. J., Lawrence, D. J., Limpinesel, D., Magill, R. T., Melvin, T. A., Morton, J. M., Newman, R. A., Peterson, J. O., Porath, M. T., Rahel, F. J., Sethi, S. A., & Wilkening, J. L. (2021). Responding to ecosystem transformation: Resist, accept, or direct? *Fisheries*, 46(1), 8–21. https://doi.org/10.1002/fsb.10506

Tingley, R. W., Hansen, J. F., Isermann, D. A., Fulton, D. C., Musch, A., & Paukert, C. P. (2019). Characterizing angler preferences for largemouth bass, bluegill, and walleye fisheries in Wisconsin. *North American Journal of Fisheries Management*, 39(4), 676–692. https://doi.org/10.1002/nafm.10301

Wenger, S. J., Luce, C. H., Hamlet, A. F., Isaak, D. J., & Neville, H. M. (2010). Macroscale hydrologic modeling of ecologically relevant flow metrics. *Water Resources Research*, 46(9), 1–10. https://doi.org/10.1029/2009WR008839
Whitney, J. E., Al-Chokhachy, R., Bunnell, D. B., Caldwell, C. A., Cooke, S. J., Eliason, E. J., Rogers, M., Lynch, A. J., & Paukert, C. P. (2016). Physiological basis of climate change impacts on North American inland fishes. *Fisheries, 41*(7), 332–345. https://doi.org/10.1080/03632415.2016.1186656

Wiens, J. A., Hayward, G. D., Holthauser, R. S., & Wisdom, M. J. (2008). Using surrogate species and groups for conservation planning and management. *Bioscience, 58*(3), 241–252. https://doi.org/10.1641/B580310

Wiens, J. J., & Donoghue, M. J. (2004). Historical biogeography, ecology and species richness. *Trends in Ecology & Evolution, 19*(12), 639–644. https://doi.org/10.1016/j.tree.2004.09.011

**SUPPORTING INFORMATION**

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