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Threats to freshwater fisheries in the United States: perspectives and investments of state fisheries administrators and Agricultural Experiment Station directors

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Abstract

Freshwater fisheries provide human benefits (e.g., food, recreation) but are increasingly threatened by climate change, invasive species, and other stressors. Our purpose was to survey fisheries administrators from state fisheries agencies and Agricultural Experiment Stations (AESs) about their perceptions of, and resource investment toward threats to freshwater fisheries in the United States. Our rationale for studying these two types of fisheries administrators simultaneously was to inform state fisheries professionals about the fisheries relevance of AESs, elevate the profile of fisheries within AESs, and promote mutually beneficial state agency–AES partnerships. Survey respondents generally agreed that recreational, socioeconomic, and ecological services of fisheries were more important than nutritional and commercial benefits. The greatest perceived fisheries threats were water quality/quantity impairment, land-use change, and invasive species—but, interestingly, not climate change. State fisheries agencies invested more personnel and finances into issues rated as less important but more controllable (e.g., fish production, habitat management) than issues rated as more important but larger in scale and more difficult to control (e.g., water quality/quantity, invasive species). Our research underscores the importance of ensuring that state agencies can address long-term, socio-ecologically critical management issues (e.g., climate change) amid budgetary constraints. We call for state agencies to collaborate with new partners (e.g., AESs) to mitigate fisheries threats by expanding fisheries management to more fully encompass terrestrial and human systems; promoting receptiveness to novel

research/management ideas; actively predicting, monitoring, and planning for future stressors; and enhancing fisheries social-ecological resilience.

Introduction

Fish and fisheries have a long and rich history in the United States, from early Native American subsistence fisheries to today's large-scale recreational and commercial fisheries that support local, regional, and national economies (Hughes 2015). For instance, in 2011, recreational fishing in the United States was valued at US$115 billion dollars in economic output and supported over 800,000 jobs (ASA 2013). As sentinels of social-ecological resilience, fish populations can signal unsustainable human activities occurring in water and on land, often before changes manifest in other parts of ecosystems (Colburn et al. 2016). Furthermore, fish are a critical food source, drive trade patterns, and influence human settlement and employment while offering many other societal and environmental benefits (e.g., cultural services, human health and wellbeing, food web control; Lynch et al. 2016a).

Considering the ecological goods and services that fisheries provide, it is important to understand stressors that are currently transforming freshwater and coastal ecosystems and their fisheries (Sullivan et al. 2019). Individual aquatic stressors (e.g., land-use change, sedimentation, organic/inorganic pollution) and stressor interactions (e.g., climate change and invasive species) affect fish and aquatic biota directly via changes in growth, reproduction, and survival, and indirectly via aquatic and terrestrial habitat impairment (Nõges et al. 2016). Aquatic stressors can reduce fisheries production by impairing ecosystem structure and function, and decreasing biodiversity (Ormerod et al. 2010) with severe socioeconomic effects. For example, the estimated cost of climate change impacts on stream fisheries in the United States ranges from $101 million to $7.1 billion (in FY2015 dollars over the period 2009−2100; Jones et al. 2013). Locally, costs can be as high as $95 to $911 million per year,

as calculated for North Carolina fisheries (Ahn et al. 2000). Although the increased growth and survival of warmwater fishes in a warming climate may partially offset projected economic losses (Pendleton and Mendelsohn 1998), the total cost of climate change effects on coldwater fisheries (i.e., stream, river, lake, reservoir) will likely be severe (Jacobson et al. 2012; Eby et al. 2014). Moreover, the environmental and economic costs of invasive species (i.e., terrestrial and aquatic) in the United States are estimated at $120 billion per year, with estimated annual losses of $5.4 billion due to invasive fishes (Pimentel et al. 2005). In the Laurentian Great Lakes, the estimated cost of managing aquatic invasive species (e.g., Sea Lamprey *Petromyzon marinus*, Dreissenid mussels) is between $138 and $800 million annually (Rothlisberger et al. 2012), including effects on fisheries production.

Sustainable fisheries management requires collaboration among many institutions (e.g., state, federal, and tribal fisheries agencies; academic institutions; non-governmental organizations (NGOs)) and public stakeholders to create and maintain fisheries and human societies that are resilient to social-ecological perturbations (Paukert et al. 2016). Although U.S. federal agencies have some inland fisheries oversight (via the Endangered Species Act, Clean Water Act, etc.), state natural resource agencies are the primary entities charged with managing most fisheries and aquatic resources in the public trust, with their primary stakeholders including recreational anglers and commercial fishers. In most cases, state agencies play the central role in developing and implementing freshwater fisheries policies that merge the scientific and societal missions of many institutions and the public to optimize the diversity of social-ecological benefits that well-functioning fisheries provide.

Agricultural Experiment Stations (AESs) based at U.S. Land Grant universities also play an important role in freshwater fisheries management. AESs are scientific research centers whose primary mission is to develop knowledge to improve natural resource and agricultural supply chains and thereby enhance food production and societal wellbeing at

local, state, regional, and national levels. AES scientists often work closely with farmers, ranchers, and aquaculturists on topics such as soil productivity, pest management, livestock, and fish production. Specific initiatives whereby AESs support fisheries research and management include the United States Department of Agriculture (USDA) Agricultural Research Service programs (e.g., Aquaculture, Water Availability, and Watershed Management) and the Regional Aquaculture Centers of the USDA National Institute of Food and Agriculture [NIFA]). Together, state fisheries agencies and AESs are key contributors to fisheries research, management, and conservation. Efforts of both entities are typically focused within (rather than across) state boundaries, but mechanisms for multistate engagement exist to improve the productivity of fish stocks of common concern. For instance, state and federal fisheries agencies and academic partners often collaborate regionally (e.g., Midwest Glacial Lakes Partnership) and nationally (e.g., National Fish Habitat Partnership) to pursue shared resource interests. Indeed, authors of this study are members of an AES multistate research project (USDA NIFA Project No. MICL04161, Multistate No. NC1189), whose goal is to understand how to achieve sustainable fisheries resource policy and management in the United States amid ecological and social constraints, with particular emphasis on the threats posed by climate change and invasive species.

In an ideal world, the priorities of state agencies and AESs would be aligned. However, differences in goals and methodologies between state agencies and AESs may serve as barriers to effective partnerships. On one hand, state agencies and AESs can share knowledge and resources (e.g., personnel, equipment) and collaborate with conservation organizations (e.g., U.S. Fish and Wildlife Service, National Marine Fisheries Service, Natural Resources Conservation Service) to implement ecosystem-based solutions and reach broad stakeholder audiences. On the other hand, barriers to effective collaboration may include conflicts between agencies and AESs or their stakeholders, differences in the

allocation of resources for fisheries and water-resource management (often regulated by non-fisheries agencies, e.g., Departments of Environmental Quality, Pollution Control Agencies), disparities in defining or understanding existing problems, or impediments to cross-organizational communication. For instance, AES directors are generally not trained in the theory and practice of fisheries production and management, yet they are often responsible for hiring and promoting fisheries scientists at their respective universities. Conversely, state fisheries agency administrators are more likely to have training in fisheries science and management (but not agriculture and food production systems), overseeing personnel with expertise similar to their own while interacting with other disciplinary professionals to holistically manage landscapes and waterscapes. Although there are opportunities for, and barriers to, collaborative fisheries management programs between state agencies and their respective AESs, they have not been described in detail to date, particularly in relation to freshwater ecosystems and stressors such as climate change and invasive species.

Given the mission of our AES multistate research project to promote sustainable fisheries policy and management in the United States, the primary purpose of this study was to understand how state fisheries agency administrators perceive and allocate resources toward freshwater fisheries management amid current and future threats to fisheries productivity, particularly climate change and invasive species. Secondarily, due to our unique position as members of an AES project, we evaluated whether the perceptions and resource investments of state agency administrators were mirrored by AES directors. We surveyed both state agency administrators and AES directors to: (1) inform state fisheries professionals about the fisheries relevance of AESs, (2) elevate the profile of fisheries within AESs, and (3) promote mutually beneficial fisheries partnerships involving state agencies and AESs. It was important to study these entities simultaneously because both develop and apply evidence-based knowledge to address state-level natural resource issues, implying their compatibility

for collaborations that advance fisheries research and management. Moreover, state fisheries agencies and AESs both play an important role in achieving the tripartite research, teaching, and service mission of Land Grant universities, with which many of the authors are affiliated. Finally, many university fisheries programs are housed within colleges of agriculture with affiliated AESs. Thus, fisheries and related faculty, many of whom work with state fisheries agencies and AESs separately, are in an ideal position to help foster synergistic agency-AES collaborations.

We surveyed state fisheries agency lead administrators (e.g., directors, chiefs) and AES directors (N = 1 of each per state) about their perceptions of freshwater fisheries to identify and assess the factors that facilitate or hinder fisheries productivity and sustainability in the United States. We anticipated that survey results would illuminate state and national trends in fisheries management that are informative for sustaining productive freshwater fisheries amid current and future stressors. In particular, we hypothesized that state agency administrators would rate fisheries as being most important from recreational, economic, and ecological perspectives (rather than commercial or nutritional viewpoints) given the typical emphasis of most state agencies on angling and fish habitat and their mandated responsibility to protect aquatic resources in the public trust (Lamb and Coughlan 1993). We expected that the primary fish species of concern for state agency administrators would be those with wide-ranging recreational and socioeconomic importance (e.g., black bass *Micropterus* spp., trout *Salvelinus*, *Salmo*, and *Oncorhynchus* spp.; Tringali et al. 2015; Lobón-Cerviá and Sanz 2017). We also hypothesized that state agency administrators would perceive, and allocate resources toward, threats to freshwater fisheries in a regionally variable manner, reflecting distinct fisheries management priorities in areas of the United States with different climatic, ecological, and socioeconomic conditions. We predicted that administrator perceptions of current and optimal state agency resource allocation (i.e., personnel, funding) would largely

correspond with their rankings of perceived threats (i.e., larger resource allocation for important threats, smaller allocation for less important threats). Finally, we hypothesized that AES directors, living in the same states and facing the same challenges as state agency administrators, would perceive freshwater fisheries and invest resources toward fisheries threats in a manner similar to agency administrators. Our hope is that this study establishes a foundation for understanding fisheries priorities within a cohesive human-environmental framework that state fisheries agencies, AESs, and allied organizations can leverage to advance socio-ecologically sustainable fisheries in concert with other users of the nation's freshwater resources.

Methods

We emailed SurveyMonkey® questionnaires to state fisheries agency administrators and AES directors in the 50 U.S. states in the fall of 2016. The surveys used separate questionnaires but were fundamentally similar, asking state agency administrators and AES directors about state agency/AES characteristics and their perceptions of freshwater fisheries amid current and future stressors (Table 1, S1, S2). While we initially focused on climate change (e.g., increases in air/water temperatures and precipitation variability) and invasive species to fulfill specific goals of our multistate research project, we ultimately designed the questionnaires to enable comparison of the perceived importance of these stressors relative to others (e.g., land-use change, water quality impairment). An introductory letter accompanied both questionnaires and explained that participation was voluntary, confidential, and anonymous (i.e., participants' names were not required, and identification of their respective states was optional). In addition, all participants were notified that they could skip questions they preferred not to answer or withdraw from the survey at any time. We believe that anonymity was particularly important because state agency administrators and AES directors

may have felt reluctant to provide detailed responses if their names or respective states were identifiable. Survey reminder emails were sent every 20 days between November 2016 and February 2017. In total, 27 state fisheries chiefs (54%) and 11 AES directors (22%) responded to the surveys.

We structured the two surveys slightly differently to acknowledge the distinct missions and duties of state fisheries agencies and AESs relative to fisheries research and management. For instance, whereas some state fisheries agencies have jurisdiction over chemical and physical water quality/quantity in their respective states, AESs do not. Hence, it was insightful to survey state fisheries administrators about water quality/quantity jurisdiction (i.e., questions 3 and 4; Table S1), but these questions were not necessary in the AES survey. Similarly, we asked AES directors about AES-specific staffing and funding levels (Table S2), but these questions were not applicable to state fisheries agencies. Despite minor structural differences, both surveys yielded the most important information for comparing state fisheries agencies and AESs: agency-university interactions, aquatic stressors (e.g., climate change, land use change, invasive species), each state's most important fish species and most threatening aquatic organisms (to ecosystems, economies, and human health), fisheries staffing and budgets, and use of a hypothetical 25% budget increase. Compatible information on these topics was sufficient for comparing state fisheries agencies and AESs and achieving the purposes of our study.

The 21-question (state agency administrator) and 19-question (AES director) surveys were approved by the Michigan State University Institutional Review Board (IRB # x16-1436e, i052805; IRB # x16-1437e, i052806), which ensures that human subject research conducted by personnel from the university is ethical and protects individuals' rights. We developed the surveys in consultation with communications and survey specialists from universities affiliated with the researchers participating in the study to ensure that survey

questions were succinct, yet detailed enough to provide needed information for comprehensively characterizing the perspectives of state agency administrators and AES directors regarding threats to freshwater fisheries. Surveys began with questions about the relative importance of the various roles of fisheries (e.g., recreational, ecological, cultural) and the species that are most important to each state's fisheries (Table 1, S1, S2). We defined the "cultural" importance of fisheries as that stemming from the values, beliefs, attitudes, and traditions of human social groups and commonly expressed through art, literature, music, religion, etc. We also assessed perceptions of current and future fisheries stressors to gain insight into how these threats affect the administrator-defined and director-defined areas of research and management importance. Finally, we asked state agency administrators and AES directors about demographic, programmatic, and operational details of their workplaces (e.g., number of employees, employee responsibilities, budget allocation, interactions with external stakeholders) to understand the logistics of how state agencies and AESs address freshwater stressors. In this way, we attempted to acquire comprehensive information about each state agency and AES surveyed, ranging from their broad missions to the specific methods that they use to develop and implement strategies for advancing fisheries research and management in light of multiple freshwater stressors.

Many of the survey questions produced qualitative responses, including the importance of fisheries and fisheries threats (e.g., very important, important, somewhat important), the ways in which specific fish species are important (e.g., commercially, recreationally, ecologically), and the type of threats imposed by aquatic invasive species (e.g., ecological, economic, human health). We analyzed responses to these questions by calculating the percentage of state agency administrators and AES directors who selected each qualitative category. We followed the same procedure for questions including quantitative categories (e.g., 0–20, 21–50, or 51–100 fisheries employees). For questions

involving quantitative rankings (e.g., order of priority of aquatic ecosystem stressors such as climate change, invasive species, land-use change), we calculated median rankings. This approach facilitated evaluation and comparison of state agency administrator and AES director perspectives related to freshwater ecosystem management in the United States. Most state agency administrators (60%) voluntarily answered the optional question identifying the states that they represented, so we analyzed this subset of the survey data by U.S. region. In particular, we compared responses of state agency administrators in northern and southern U.S. states to determine if perceptions of climate change, invasive species, and other stressors differed in these regions of the country given underlying differences in climate and fish thermal guilds (i.e., generally coldwater/coolwater in the northern USA, warmwater in the southern USA). We grouped states by "region" as defined by the United States Census Bureau (2015) and used a Mann–Whitney *U* Test to compare median responses of state agency administrators in northern states (i.e., Indiana, Kansas, Michigan, Nebraska, North Dakota, South Dakota) and southern states (i.e., Arkansas, Delaware, Oklahoma, Tennessee, Texas, West Virginia). The northern and southern states each made up 37.5% of the pool of respondents who identified their states and were thus sufficiently representative for statistical analysis, in contrast to regions with fewer respondents (e.g., northeast, western USA). We did not conduct regional analyses for survey responses of AES directors due to a relatively small sample size and insufficient regional representation.

Results and Discussion

General importance of fisheries

The majority of state fisheries agency administrators indicated that freshwater fisheries were important or very important for the following reasons: recreational (96% of administrators), ecological (89%), and economic (81%). Most state agency administrators

also considered freshwater fisheries important or very important from a scientific research perspective (78%), but percentages were lower for cultural (59%) and nutritional (26%) perspectives. Although nutritional benefits of fisheries were not unimportant to state agency administrators, these societal values were less emphasized by state agencies whose mandated responsibilities focus on fish populations and habitats for primarily recreational, economic, and ecological purposes. However, we recognize that the distribution of our respondents—skewed towards the Midwest and South—may not have fully captured the nutritional importance of fisheries in regions with greater subsistence fishing and aquaculture (e.g., Pacific Northwest) where nutritional benefits might be expected to be more highly valued (Lynch et al. 2002). Moreover, state agency administrators in the Midwest and southern USA may recognize the nutritional significance of fisheries in their regions (e.g., Mississippi River, Gulf of Mexico), but they evidently consider it to be less important than the recreational, economic, and ecological values that represent their primary management responsibilities.

Most important fish species

The five fish species that state fisheries agency administrators designated as the most important (i.e., highest rated) in their respective states were taxonomically diverse and were, therefore, clustered into commonly associated groups (e.g., black bass) where feasible. Black bass and trout were most represented in survey responses (Table 2), reflecting the wide-ranging recreational and socioeconomic importance of these fishes (Tringali et al. 2015; Lobón-Cerviá and Sanz 2017). As expected, coolwater (e.g., Walleye *Sander vitreus*, Yellow Perch *Perca flavescens*) and coldwater (e.g., Brook Trout *Salvelinus fontinalis*) taxa were identified as important by state agency administrators from areas containing suitable thermal habitats for these species (e.g., northern, Great Lakes, and coastal states). In contrast,

warmwater species such as black bass and Channel Catfish *Ictalurus punctatus* were considered more important in warmer Midwestern and southeastern states.

Nearly all state fisheries agency administrators (97%) indicated that their state's highest-rated fishes were important or very important for recreational purposes. Many state agency administrators also indicated that highest-rated fishes were important/very important from ecological (68% of administrators) and cultural (62%) perspectives, in contrast to nutritional (31%) and commercial (17%) viewpoints. State agencies' mandated duties to conserve and protect living freshwater resources in the public trust (Lamb and Coughlan 1993) likely produced higher recreational, ecological, and cultural importance ratings than nutritional and commercial ratings. Emphasis on recreational, ecological, and cultural roles over commercial and nutritional uses suggests that sustainability of freshwater fisheries may depend more on factors shaping public and institutional valuation of natural resources than on factors shaping their utilitarian uses.

Threats to aquatic ecosystems

The majority of state fisheries agency administrators indicated that land-use change and aquatic habitat impairment (100% of administrators), water quality/quantity (96%), and invasive species (93%) were important or very important threats to freshwater ecosystems in their respective states (Table 3). A smaller majority of state agency administrators perceived fish disease/health (63% of administrators) and climate change (60%) as important or very important threats, in contrast to inadequate fisheries research (45%), inadequate wild-fish production (41%), and inadequate hatchery-fish production (29%; Table 3). These findings provide a basis for understanding threat prioritization in state fisheries agencies and developing scientifically robust solutions involving cross-agency partnerships that leverage organizational expertise and resources.

Collectively, state agency administrators in both the northern and southern states rated invasive species as a very important fisheries management issue (Figure 1a). In contrast, climate change was perceived as less important than invasive species (Figure 1b). Although half of state agency administrators from both the northern and the southern states rated climate change as a "somewhat important" issue, 17% of northern administrators rated climate change as very important, compared to 0% of southern administrators (Figure 1b). This finding could reflect real or perceived regional variability in the effects of climate change (IPCC 2018), as well as geographic differences in fish thermal guilds. For instance, climate change could have greater impacts on northern fisheries where coldwater/coolwater, climate-vulnerable fishes are relatively prevalent compared to southern states, where water bodies are already relatively warm, fish communities are primarily warmwater, and other concerns (e.g., hatchery-fish production, need for more research) predominate. This notion has some scientific support in that climate change is exerting negative effects (e.g., decreased growth and abundance, range contraction) on certain coldwater fishes (e.g.., Bull Trout *Salvelinus confluentus*, Arctic char *S. alpinus*, Cisco *Coregonus artedi*) in northern latitudes (Jacobson et al. 2012; Murdoch and Power 2013; Eby et al. 2014). In contrast, effects of climate change are neutral or positive (e.g., increased abundance, range expansion) for certain warmwater species (e.g., black bass) in the southern United States (Robillard and Fox 2006; Lynch et al. 2016b).

Collectively across the northern and southern states, there was high taxonomic diversity in the five invasive aquatic organisms that state fisheries agency administrators identified as posing the greatest threats in their respective states (Table 4). Invasive fishes were the most represented group, with 15% of state agency administrators identifying Bighead Carp *Hypophthalmichthys nobilis* and Silver Carp *H. molitrix* as threat-inducing species and 23% of administrators mentioning other invasive fishes (e.g., Sea Lamprey,

Common Carp *Cyprinus carpio*, Round Goby *Neogobius melanostomus*). Moreover, 27% of state agency administrators identified plants (e.g., Eurasian watermilfoil *Myriophyllum spicatum*, hydrilla *Hydrilla verticillata*) and 19% categorized Dreissenid mussels (i.e., quagga mussel *Dreissena bugensis*, zebra mussel *D. polymorpha*) as species posing the greatest threats to their state's freshwater ecosystems (Table 4).

The majority of state agency administrators indicated that the five greatest threat-inducing aquatic organisms in their respective states posed important or very important economic threats (86% of administrators) and ecological threats (93%). Few state agency administrators (19%) perceived these species to present important or very important threats to human health. In general, administrator perspectives aligned with estimates of the impacts (e.g., loss of biodiversity, alterations of ecosystem function, shifts in food webs) and economic repercussions of aquatic invasive species (Panlasigui et al. 2018). However, invasive species can have serious consequences for aquatic food production and human wellbeing (Pejchar and Mooney 2009), reflecting a disconnect between the importance of invasive species for human health and how state agency administrators perceive that importance. Moreover, interactions between invasive species and climate change (Rahel and Olden 2008; Nõges et al. 2016) amplify the importance of addressing these issues individually and simultaneously via research and management approaches rooted in the interdependence of these and other stressors.

Aquatic threats now and in the future

State fisheries agency administrators across the northern and southern states collectively ranked fisheries management issues according to their current importance as follows (most to least important): water quality/quantity (median rank = 1, scale 1−8), land-use change and aquatic habitat impairment (2), aquatic invasive species (3), fish

disease/health (5), fisheries research (5), wild fish production (5), hatchery fish production (6), and climate change adaptation/mitigation (7). The importance of these fisheries management issues to state agency administrators over the next decade was nearly identical; only fisheries research and wild fish production exchanged positions in order of importance. Land-use change and aquatic habitat impairment was the most important management issue for northern administrators and significantly more important in the northern states than the southern states (Mann–Whitney $U = 30$, $n_1 = n_2 = 12$, $P = 0.016$ two-tailed; Figure 2). In contrast, hatchery-fish production, water quality/quantity, and fisheries research tended to be more important issues for southern than northern administrators. Aquatic invasive species represented the third-most important issue for northern administrators and the second-most important issue for Southern administrators. State agency administrators in the North and the South ranked climate change adaptation/mitigation as the least important fisheries management issue currently over the next decade, although northern administrators rated it as more important than southern administrators (Mann–Whitney $U = 33.5$, $n_1 = n_2 = 12$, $P = 0.029$ two-tailed; Figure 2).

Overall, state fisheries agency administrators had regionally heterogeneous perspectives regarding the relative priority of fisheries management issues (e.g., greater focus on climate and land-use change in the northern states versus hatcheryfish production in the southern states). Such dissimilarities suggest that climate change may be having greater real (or perceived) effects in the northern states than the southern states (IPCC 2018), where warmer water and longer growing seasons are conducive for hatchery fish production and aquaculture (USDA 1995). Overall, climate change appears to be a relatively low priority for state agency administrators regardless of region, which does not bode well for the growth, survival, and population sustainability of certain fishes (e.g., coldwater species and those that respond negatively to floods and reduced water levels) if projected climatic warming and

extremes are realized (Hunt et al. 2016; Whitney et al. 2016). However, state fisheries agencies have an opportunity to actively prepare for long-term, persistent stressors such as climate change by developing adaptive research and management programs involving adaptation/mitigation planning to balance long-term aquatic ecosystem threats with those occurring over shorter time scales.

Agency-university interactions

All but one state fisheries agency administrator reported regular interaction with university personnel, most commonly regarding fisheries research (96% of administrators), aquatic invasive species (74%), hatchery fish production (67%), and fish disease/health (59%). In contrast, few state agency administrators reported interacting with university personnel on projects related to water quality/quantity (35% of administrators) or climate change adaptation/mitigation (19%). This finding may reflect the fact that most state agency administrators do not have the authority to independently address—much less the management capacity to control—large-scale, often long-term issues like water quality/quantity and climate change.

Employee responsibilities and budget allocation

Most state fisheries agency administrators (71%) supervised at least 51 fisheries employees, with 37% managing 51–100 employees and 34% having > 100 employees. Some state agency administrators (22%) worked for agencies that had jurisdiction over both fisheries and water quantity/quality, but the majority (78%) did not, reflecting the prevalence of state-level environmental quality agencies (e.g., Michigan Department of Environmental Quality, Minnesota Pollution Control Agency) that work separately from state fisheries agencies.

Interestingly, allocation of state fisheries agency personnel did not clearly mirror the relative priorities attributed to different issues included in the survey. Although state agency administrators perceived water quality/quantity to be a highly important issue, most (44%) worked for agencies that had only 1–5 employees assigned to work on these issues (Table 5), which likely reflects a division of labor between state fisheries and water quality agencies. Similarly, state fisheries agency administrators considered aquatic invasive species an important issue, but most administrators (65%) worked for agencies with only 1–5 employees assigned to this threat. In contrast, many state agency administrators worked for agencies with at least 11 employees working on fish production (81% of administrators) and fish habitat research or management (72%; Table 5). This relatively high level of involvement in fish production and habitat research/management corresponds with the more practical management endpoints and job duties associated with these topics (e.g., hatchery operations, habitat rehabilitation projects, habitat protection policies; Wills et al. 2004; Baumann et al. 2016) as compared to water quality/quantity, aquatic invasive species, and other larger-scale issues.

An even more complex pattern was found for climate change adaptation/mitigation, an issue that state fisheries agency administrators perceived as relatively unimportant (Figure 2), yet for which agencies had either many employees (50% of agencies with 21 or more employees) or very few employees (38% of agencies with 1–5 employees). This dichotomy, also evident for water quality/quantity, suggests that state fisheries agencies either actively confront large-scale, difficult-to-control issues or choose to invest their personnel elsewhere; there is little middle ground. Alternatively, it might suggest that some state fisheries agencies see climate change adaptation/mitigation and water quality/quantity as typical responsibilities of most staff, whereas others assign these issues to specialists or exist in states where these issues are under the purview of external organizations (e.g., state water quality agencies).

However, the latter explanation (i.e., division of labor with other agencies) is generally not applicable to climate change adaptation/mitigation and aquatic invasive species management, which are often not uniquely under the jurisdiction of any particular agency. Thus, climate change and aquatic invasive species are two issues for which fisheries agencies have an important role and must work closely with external partners (e.g., water quality agencies, AESs, NGOs) to promote healthy, productive fisheries and water resources.

Survey results indicated that state fisheries agencies currently invest a small proportion of their annual budget into issues they deem important. For example, 52% of fisheries administrators indicated that their agencies spent <1% of their budget on water quality/quantity, and 52% indicated that they spent <3% of their budget on aquatic invasive species (Table 6). In contrast, state agencies commonly spent >5% of their budget on fish production (92% of agencies), fisheries research (56%), and fish habitat improvement (56%; Table 6)—more controllable issues that agencies have a distinct mandate to address.

Although investments of personnel and budgets are complex, there does appear to be a general pattern. Specifically, state fisheries agencies tend to steer funding away from relatively unpredictable, diffuse, long-term environmental problems (e.g., climate disturbances, disease outbreaks, invasions) into more quantifiable, controllable, short-term issues related to fish production and habitat quality. This tendency is understandable given the need for agency accountability on data-driven decision making and the need to produce measurable project outcomes. Investments of personnel and funding may also reflect the priorities of cross-agency partnerships, with particular agencies allocating fewer resources toward issues addressed through agency collaborations than they would invest in the absence of such partnerships. At any rate, while state fisheries agencies are charged with protecting and enhancing fish and other aquatic populations and their habitats (Decker et al. 2008; Hubert and Quist 2010), regulatory authority and responsibility for broader environmental

factors (e.g., climate, land use, water quality/quantity) are often beyond their legal purview. Hence, while it might be tempting to presume that low investments in climate change adaptation/mitigation (where 76% of agencies spent <1% of their budget) are politically motivated, they may be symptomatic of a broader syndrome of underfunding large-scale, long-term issues that state fisheries agencies generally do not have the scope or designated authority to address. Importantly, this resource investment bias could hinder future fisheries production and sustainability. For instance, although state agency administrators perceived aquatic invasive species and fish disease/health to be important fisheries management concerns (Table 3), the relatively low allocation of personnel and funding to these issues (Table 5, 6) suggests that agencies may have difficulty addressing species invasions, fish disease outbreaks, or interactions between these and other stressors (e.g., climate change; Lõhmus and Björklund 2015).

If state fisheries agencies were granted a 25% budget increase for additional spending in any area(s) of their choice, agency administrators reported that they would invest the greatest percentage of extra funds in field technician staff (30%), followed by management staff (17%), facilities (14%), equipment (12%), research staff (9%), education and outreach (7%), administrative staff (5%), and travel (3%). These results indicate that state agency administrators place high value on having the resources (e.g., people, facilities) necessary for collecting fisheries data and completing on-the-ground monitoring and management activities. If the hypothetical 25% budget increase was earmarked for fisheries conservation issues, state agency administrators would invest extra funds in habitat projects (28% of budget), aquatic invasive species management (19%), fisheries research (17%), fish production (15%), water quality/water use (8%), fish disease/health (6%), and climate change adaptation/mitigation (3%). This order of budget allocation generally aligns with how state agency administrators ranked the relative importance of threats to freshwater fisheries.

Namely, it reflects the tendency of state agency administrators to invest resources in activities within their purview (e.g., habitat, research, fish production) rather than issues such as water quality/quantity and climate change that require long-term, large-scale adaptation/mitigation planning.

AES director results

Eleven AES directors responded to the survey, a relatively small sample size that should be interpreted carefully to avoid misrepresenting broader AES perspectives. Nonetheless, AES director responses provide important preliminary information for improving state agency–AES interactions to address current and future threats to freshwater fisheries. Much like state fisheries agency administrators, AES directors considered black bass and various trout species to be the most important fishes in their respective states (Table 2), primarily for recreational (90% of AES directors), ecological (56%), and cultural (33%) reasons, but not commercial (20%) or nutritional (11%) purposes. Similar responses between state fisheries administrators and AES directors likely reflect the widespread socioeconomic importance of Black Bass and trout (Tringali et al. 2015; Lobón-Cerviá and Sanz 2017), overlapping missions of particular AESs, and the focus of AES director interactions with state fisheries agencies and fisheries faculty (e.g., emphasis on fish ecology rather than commercial/nutritional questions). AES directors were also similar to state agency administrators in rating invasive fishes (e.g., Bighead and Silver Carp), plants (e.g., Eurasian watermilfoil, hydrilla), and mussels (e.g., quagga and zebra mussels) as the most deleterious species for ecological and economic (but not human health) reasons (Table 4). Moreover, many AES directors (73%) reported that they interact with state agencies at least once per month, similar to the frequency with which state agency administrators interact with university personnel. Overall, attitudinal similarities and personal interactions between AES

directors and state agency administrators point to the existence of common understanding and professional networks necessary for linking state agencies, AESs, and fisheries and related faculty.

However, survey responses of AES directors and state fisheries agency administrators were not universally similar. For example, whereas state agency administrators supervise many fisheries employees, most AES directors (73%) have few employees (0−10) that specialize in either fisheries management/ecology, aquaculture, or water quality. In addition, AES directors pursue a different mission and generally have different priorities than state agency administrators, as reflected in their budgetary investments. Most notably, AES directors would allocate the largest portion of a hypothetical 25% budget increase to animal agriculture (24%) and plant agriculture (21%) ahead of fisheries (16%), wildlife (16%), forestry (13%), recreation/tourism (7%), and other areas (3%). Moreover, in contrast to state agency administrators, the majority of AES directors indicated that they have personnel and financial resources sufficient to play a "very strong" or "moderate" role in water quality/quantity management (100% of directors) and climate change adaptation/mitigation (82%) by providing scientific support and advice needed to mitigate these issues. This finding suggests that compared to state agency administrators, AES directors have greater capacity to conduct water quality/quantity and climate change research resulting from their broad Land Grant mission. Thus, collaborations between state agencies, AESs, and fisheries and related faculty could provide state agencies with the necessary resources for fisheries research at broad spatial and long temporal scales. Such collaborations are particularly important for investigating large-scale, long-term issues like water quality and climate change; they would also be useful for studying fish production, fish habitat research and management, and other topics with more immediate management applications. Additional input from AES directors

will be an important step in developing a more comprehensive picture of perceived freshwater stressors.

Summary and Recommendations

The purpose of this study was to understand how state fisheries agency administrators and university-based AES directors perceive constraints to achieving sustainable freshwater fisheries management. Our initial focus on climate change and invasive species evolved into a broader assessment of freshwater ecosystem threats yielding important implications and applications for fisheries management. Results indicated that state agency administrators value—and anchor their work around—conserving and enhancing ecologically and socioeconomically productive fisheries. Although some state fisheries agencies incorporate the nutritional and commercial importance of fisheries into their management activities, agency administrators more commonly emphasize their mandated responsibilities—often specified in their mission statements or authorizing legislation—to conserve and protect fish populations and habitats for primarily recreational, economic, and ecological outcomes. Although these outcomes represent an important impetus for state agency fisheries management, they could be complemented with increased recognition of the nutritional and commercial values of fisheries (e.g., subsistence and commercial fishing, aquaculture, tourism; Lynch et al. 2002).

State agency administrators and AES directors indicated that invasive species (e.g., Bighead Carp, Silver Carp, Dreissenid mussels) pose a greater threat than climate change, likely due to the greater immediacy and practicality of responding to invasive species compared to climate change. There was regional variability in the perceived importance of climate change, but it was a low priority for state agencies and AESs, now and over the next decade. Although this finding likely reflects multiple factors (e.g., low priority of climate

change among the stakeholders agencies/AESs serve; lack of authority/capacity to control climate change; focus on short-term issues), there is growing evidence that a changing climate negatively affects freshwater fisheries ecosystems and management systems (e.g., impaired fish physiology, decreased fish growth, geographic range reduction, changes in fisher behavior and livelihoods; Hunt et al. 2016; Whitney et al. 2016). Further, interactions between climate change and other stressors (e.g., invasive species) are important to recognize and will likely require improved monitoring and coordination among entities involved in fisheries research and management (Rahel and Olden 2008). Whatever the reason(s) underlying the relatively low priority of climate change, the implication is clear: without research, policy, and management action on climate change, including investment in large-scale and long-term adaptation/mitigation planning, freshwater fisheries and their stakeholders are likely to be negatively affected (Hunt et al. 2016; Paukert et al. 2016). Given that a large majority of AES directors (82%) play an important role in climate change adaptation/mitigation, AESs and their partners in trade organizations, NGOs, and the Cooperative Extension System occupy a critical position for translating university-based climate change research into public outreach and education programs. In turn, greater public awareness and knowledge regarding climate change would likely provide necessary public support for state fisheries agencies to prioritize and actively address this complex issue.

There is an overarching need to elevate the profile of socio-ecologically critical fisheries issues (e.g., climate change, invasive species, water quality/quantity) by emphasizing large-scale, long-term adaptation/mitigation planning and enabling state fisheries agencies, AESs, and their partners (e.g., state environmental quality agencies, federal fisheries agencies) to meaningfully address these stressors. Within current budgetary constraints, fisheries managers are often restricted to projects focused on immediate stressors rather than broader, long-term issues such as climate change. Thus, resource allocation at

higher levels needs to be modified. After all, as freshwater stressors intensify (Hunt et al. 2016; Whitney et al. 2016), building and maintaining socio-ecologically resilient fisheries requires institutional capacity in staff and funding as well as partners in both the public and private sectors (Carlson et al. 2016; Paukert et al. 2016). Achieving these outcomes is not simple, but we offer the following recommendations based on insights from our surveys:

1) *Expand partnerships among state fisheries agencies, AESs, and other state, federal, tribal, and non-governmental partners* to better address large-scale, long-term issues that can be overlooked in the face of more immediate and quantifiable concerns. For example, state fisheries agencies and AESs could partner with federal fisheries agencies, Cooperative Fish and Wildlife Research Units, Cooperative Extension programs, NGOs, tribal natural resource organizations, local watershed groups, and the general public. Partnerships with these entities would allow state agencies to advance beyond their focus on select fish populations and habitats, while empowering AESs to expand their agricultural programs to fully encompass freshwater ecosystems and fisheries. Ultimately, these partnerships would broaden the scope of fisheries management to include a wider range of social-ecological issues that affect fisheries productivity and sustainability (e.g., land use, food production, tourism).
2) *Empower state agencies and AESs to learn and implement novel fisheries research and management approaches*. Historical methodologies are certainly valuable, but a spirit of innovation is necessary for productive state agency-AES collaborations and meaningful progress in many fisheries research and management areas, particularly climate change adaptation/mitigation and invasive species prevention and control.

3) *Implement predictive, anticipatory fisheries management programs.* In many cases, projections of future climatic and invasive species conditions are sufficiently accurate for state agencies and AESs to collaborate with state, federal, tribal, and non-governmental partners to implement management strategies that build social-ecological resilience (Carlson and Vondracek 2014). For example, fisheries professionals and their partners can plant riparian vegetation along river corridors to protect coldwater habitats for high-priority coldwater fishes during current (and in anticipation of future) climatic warming and thermal habitat degradation.
4) *Preserve the ability of state agencies to monitor freshwater ecosystems consistently over long time scales.* Long-term datasets are invaluable for understanding the effects of climate change, invasive species, and multiple interacting stressors. Such data are also important for testing the efficacy of short-term and long-term management actions. Interestingly, whereas many state agencies do not appear to prioritize long-term challenges like climate change, they often have valuable long-term fishery datasets for studying these challenges and should be encouraged to continue their monitoring and analysis efforts.
5) *Survey other fisheries stakeholders* beyond state agency administrators and AES directors (e.g., researchers in state/federal/tribal agencies, AESs, and universities; fisheries administrators in the U.S. Fish and Wildlife Service and National Marine Fisheries Service). State agency administrators and AES directors are likely effective indicators of regional pressures and institutional leadership priorities, but state agencies and AESs are nested within a larger realm of non-governmental and tribal interests and national and international policies that transcend fish and freshwater. Understanding how America's diverse fisheries professionals and

stakeholders perceive fisheries research and management—freshwater and marine—could provide a much deeper understanding of the profession's human capital and yield insights for creating a cohesive human–environmental framework to increase the socio-ecological resilience of fisheries management and governance.

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Table Captions

Table 1. Types of questions and measures used for the state agency fisheries administrator (FA) and Agricultural Experiment Station (AES) director surveys.

Table 2. Percentage of state fisheries agency administrators (% Admin, *N* = 27) and AES directors (% AES, *N* = 11) who designated particular groups or species of fish as one of the five most important in their respective states. Similar taxonomic groups (e.g., black bass) are designated where appropriate.

Table 3. Percentage of state fisheries agency administrators (*N* = 27) who rated various threats to aquatic ecosystems in their respective states as very important, important, somewhat important, or unimportant. Land-use change/habitat impairment includes both watershed and in-stream spatial scales.

Table 4. Percentage of state fisheries agency administrators (% Admin, *N* = 27) and AES directors (% AES, *N* = 11) who designated particular groups or species of invasive aquatic organisms as one of the five most ecologically threatening in their respective states. Similar taxonomic groups (e.g., plants) are designated where appropriate.

Table 5. Percentage of fisheries administrators (*N* = 27) from state agencies that employ various numbers of employees who address fisheries management responsibilities listed alphabetically below.

Table 6. Percentage of fisheries administrators (N = 27) from state agencies that invest various budget percentages toward fisheries management responsibilities listed alphabetically below.

Table S1 (Supplementary Table 1). Copy of the state agency fisheries administrator survey.

Table S2 (Supplementary Table 2). Copy of the AES director survey.

Figure Captions

Figure 1. Percentage of state fisheries agency administrators who believe (A) invasive species and (B) climate change are unimportant, somewhat important, important, or very important issues in their respective states. Different colored bars represent state agency administrators from the northern USA (white bars; Indiana, Kansas, Michigan, Nebraska, North Dakota, South Dakota) and the southern USA (gray bars; Arkansas, Delaware, Oklahoma, Tennessee, Texas, West Virginia).

Figure 2. Box-and-whiskers plot displaying state fisheries agency administrators median rankings of fisheries management issues (dark bands) currently and over the next decade. Note the y-axis scale, where lower numbers correspond with higher rankings (i.e., more important management issues). Asterisks denote statistically significant differences ($P < 0.05$, Mann–Whitney U Test) in median rankings between state agency administrators in the

northern USA (white boxes; Indiana, Kansas, Michigan, Nebraska, North Dakota, South Dakota) and the southern USA (gray boxes; Arkansas, Delaware, Oklahoma, Tennessee, Texas, West Virginia). Abbreviations are as follows: WQQ (water quality/quantity), LUH (land-use change and aquatic habitat impairment), AIS (aquatic invasive species), FDH (fish disease/health), FRS (fisheries research), WFP (wild-fish production), HFP (hatchery-fish production), CLC (climate change adaptation/mitigation).

Table 1.

Topics	Survey	Measures
Agency budget allocation	FA	Current and projected future budget allocation for fisheries management
Aquatic threats	FA	Relative importance of aquatic threats (water quality/quantity, land-use change, disease, climate change, inadequate research, inadequate fish production, invasive species)
Fisheries importance	FA	Relative importance (economic, ecological, recreational, cultural, scientific, nutritional)
Agency location	FA	Optional question about U.S. state where employed
Water quality	FA	Description of agency water quality management responsibilities
AES budget allocation	AES	Current and projected future budget allocation for agriculture and natural resource issues
Expertise	AES	Description of areas of expertise
External funding	AES	Annual grants and contracts received
Fish consumption	AES	Frequency of fish consumption in the last week and year
Fisheries funding	AES	Annual grants and contracts received that are fisheries-related
Fisheries involvement	AES	Strength of involvement (strong, moderate, minor, none) in fisheries issues
Recreational fishing	AES	Frequency of recreational fishing in the last year
Tenure	AES	Years served as AES director
University affiliation	AES	Optional question about university affiliation
Aquatic species	Both	Five invasive species that pose greatest threats (economic, human health, food web)
Comments	Both	Optional comments about survey

Ecosystem evaluation	Both	Optional description of ways agency/AES is improving freshwater ecosystem health assessment
Fish species	Both	Five most important fish species and why (commercial, recreational, ecological, subsistence, cultural)
Staffing	Both	Number and percentage of agency/AES employees with fisheries job duties
University interactions	Both	Description of agency/AES interactions with universities

Table 2.

Taxa	% Admin	% AES	Species included in group
Black Bass	23	17	Largemouth Bass *Micropterus salmoides*, Smallmouth Bass *M. dolomieu*
Trout	20	18	Brook Trout *Salvelinus fontinalis*, Brown Trout *Salmo trutta*, Rainbow Trout *Oncorhynchus mykiss*, Lahontan Cutthroat Trout *O. clarkii henshawi*, Redband Trout *O. mykiss gairdnerii*, Steelhead *O. mykiss*
Catfish	14	8	Channel Catfish *Ictalurus punctatus,* Flathead Catfish *Pylodictis olivaris*
Crappie	11	2	Black Crappie *Pomoxis nigromaculatus*, White Crappie *P. annularis*
Sunfish	8	6	*Lepomis* spp.
Walleye	7	8	*Sander vitreus*
Pike	5	2	Chain Pickerel *Esox niger*, Muskellunge *E. masquinongy*, Northern Pike *E. lucius*
Salmon	4	4	Chinook *Oncorhynchus tshawytsch*, Coho *O. kisutch*, Kokanee *O. nerka*
Temperate Bass	4	4	Striped Bass *Morone saxatili*, White Bass *M. chrysops*
Yellow Perch	2	4	*Perca flavescens*
Alligator Gar	1	NA	*Atractosteus spatula*
Paddlefish	1	2	*Polyodon spathula*
Bluehead Sucker	NA	2	*Catostomus discobolus*
Cyprinids	NA	17	Hornyhead Chub *Nocomis biguttatus*, Humpback Chub *Gila cypha*, Roundtail Chub *Gila robusta*, Sacramento Splittail *Pogonichthys macrolepidotus*, Suckermouth Minnow *Phenacobius mirabilis*
Delta Smelt	NA	2	*Hypomesus transpacificus*
Sturgeon	NA	2	*Acipenser* spp.
Tilapia	NA	2	*Tilapia* spp.

Table 3.

Threat	% Very important	% Important	% Somewhat important	% Unimportant
Land-use change/habitat impairment	93	7	0	0
Water quality/quantity	85	11	4	0
Invasive species	74	19	7	0
Disease/fish health	26	37	33	4
Climate change	19	41	33	7
Inadequate fisheries research	4	41	52	3
Inadequate wild-fish production	15	26	37	22
Inadequate hatchery-fish production	7	22	52	19

Table 4.

Taxa	% Admin	% AES	Species included in group
Plants	27	34	Brazilian waterweed *Egeria densa*, common reed *Phragmites australis*, cordgrass *Spartina spp*., creeping water primrose *Ludwigia peploides*, curlyleaf pondweed *Potamogeton crispus*, Eurasian watermilfoil *Myriophyllum spicatum*, flowering rush *Butomus umbellatus*, giant cane *Arundo spp*., giant salvinia *Salvinia molesta*, hydrilla *Hydrilla verticillata*, purple loosestrife *Lythrum salicaria*, salt cedar *Tamarix spp*., starry stonewart *Nitellopsis obtusa*, water chestnut *Trapa natans*, water hyacinth *Eichhornia crassipes*
Fishes (not Bighead and Silver Carp)	23	16	Alabama Bass *Micropterus henshalli*, Alewife *Alosa pseudoharengus*, Black Carp *Mylopharyngodon piceus*, Blue Catfish *Ictalurus furcatus*, Blue Tilapia *Oreochromis aureus*, Brook Trout *Salvelinus fontinalis*, Brown Trout *Salmo trutta*, Common Carp *Cyprinus carpio*, Flathead Catfish *Pylodictis olivaris*, gar *Lepisosteus* spp., Gizzard Shad *Dorosoma cepedianum*, Grass Carp *Ctenopharyngodon idella*, Green Sunfish *Lepomis cyanellus*, Lake Trout *Salvelinus namaycush*, Largemouth Bass *Micropterus salmoides*, Northern Snakehead *Channa argus*, Sea Lamprey *Petromyzon marinus*, Red Shiner *Cyprinella lutrensis*, released baitfish, Round Goby *Neogobius melanostomus*, White Perch *Morone americana*
Mussels and snails	19	22	Quagga mussel *Dreissena bugensis*, zebra mussel *D. polymorpha*
Bighead and Silver Carp	15	14	*Hypophthalmichthys nobilis*, *H. molitrix*
Nuisance algae	5	NA	Cyanobacteria, *Didymosphenia geminata*, golden algae (Chrysophyceae)
Other invasive invertebrates	5	10	Island apple snail *Pomacea insularum*, New Zealand mud snail *Potamopyrgus antipodarum*, red swamp crayfish *Procambarus clarkii*, virile crayfish *Orconectes virilis*
Diseases/viruses	4	2	Infectious pancreatic necrosis, ranavirus, viral hemorrhagic septicemia, whirling disease
Spiny water flea	1	2	*Bythotrephes longimanus*
Wild hogs	1	NA	*Sus scrofa*

Table 5.

	Employees			
Responsibility	1-5	6-10	11-20	21 or more
Climate change mitigation/adaptation	38	8	4	50
Disease/fish health	73	8	4	15
Fish production	11	8	31	50
Fisheries research	27	31	23	19
Habitat	24	4	40	32
Invasive species	65	15	12	8
Water quality/quantity	44	12	12	32

Table 6.

	Budget			
Responsibility	<1%	1-3%	3-5%	> 5%
Climate change mitigation/adaptation	76	4	0	20
Disease/fish health	40	40	16	4
Fish production	0	4	4	92
Fisheries research	8	12	24	56
Habitat	4	8	32	56
Invasive species	16	36	24	24
Water quality/quantity	52	28	8	12

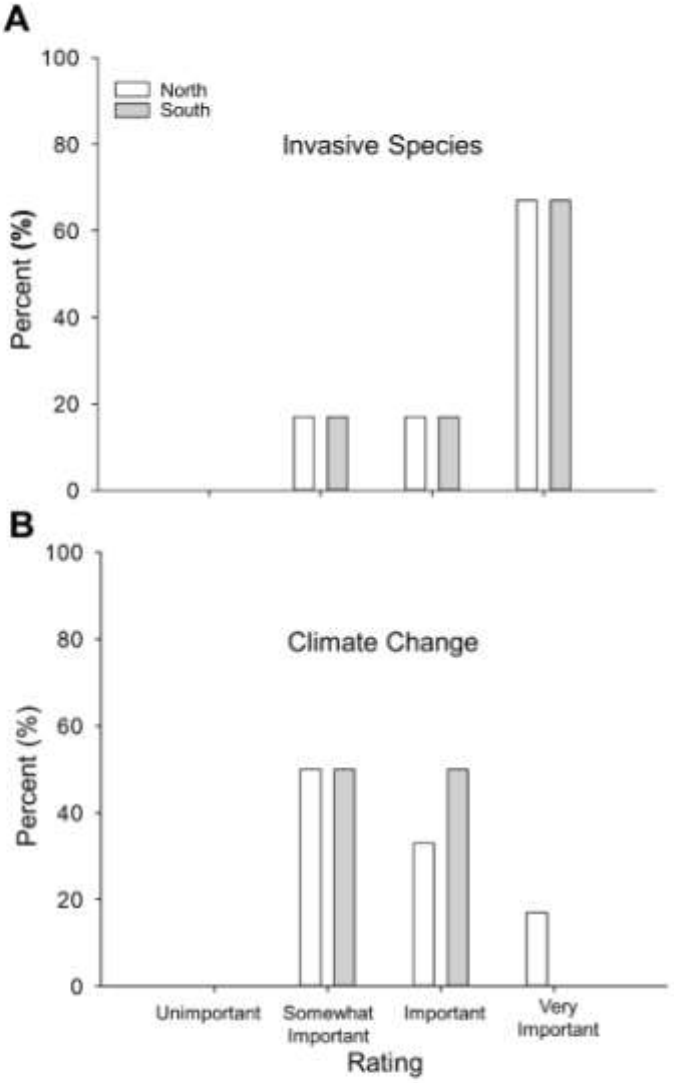

Figure 1.

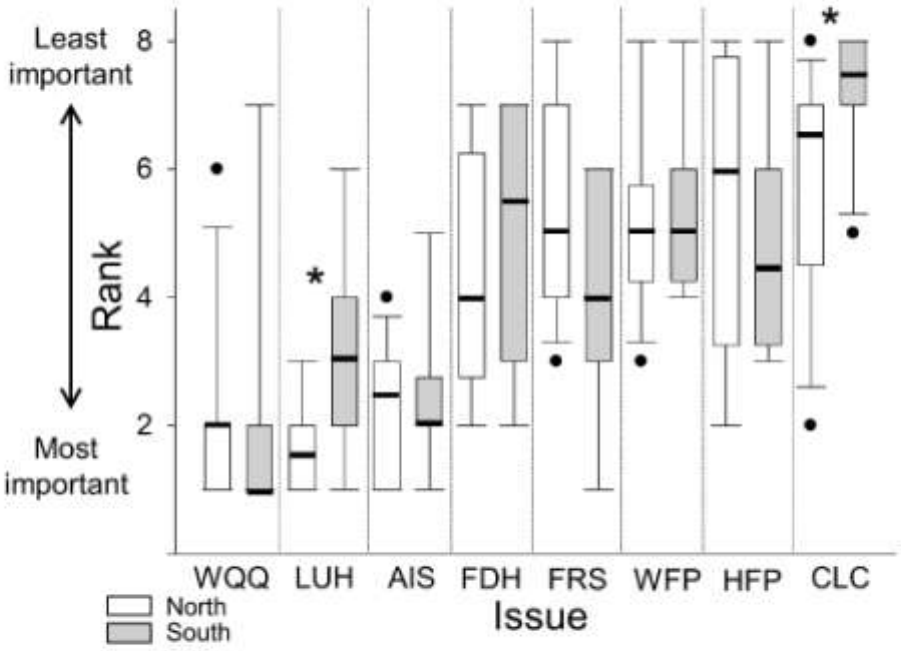

Figure 2.