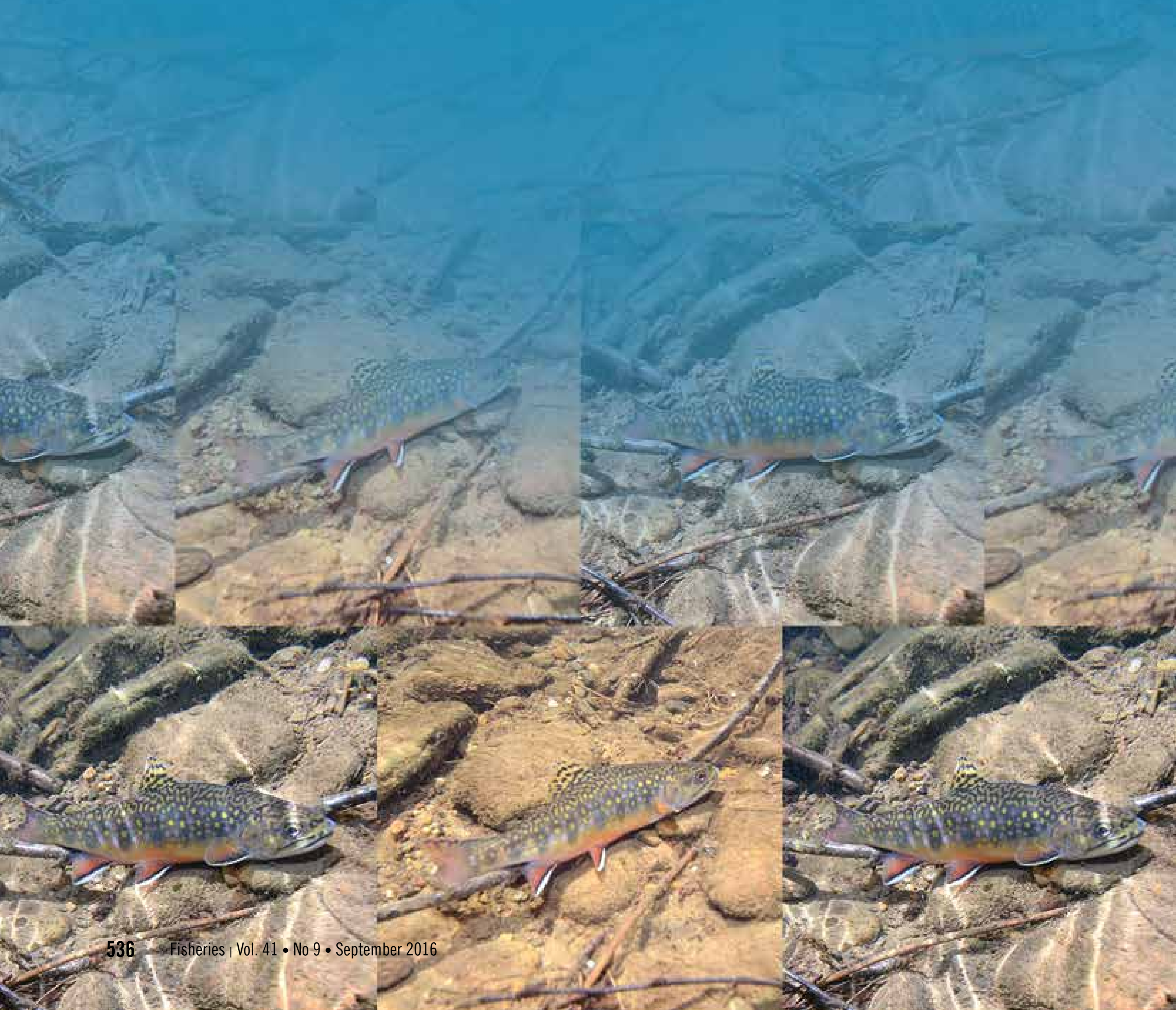
FEATURE

# Transboundary Fisheries Science:
## Meeting the Challenges of Inland Fisheries Management in the 21st Century



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Managing inland fisheries in the 21st century presents several obstacles, including the need to view fisheries from multiple spatial and temporal scales, which usually involves populations and resources spanning sociopolitical boundaries. Though collaboration is not new to fisheries science, inland aquatic systems have historically been managed at local scales and present different challenges than in marine or large freshwater systems like the Laurentian Great Lakes. Therefore, we outline a flexible strategy that highlights organization, cooperation, analytics, and implementation as building blocks toward effectively addressing transboundary fisheries issues. Additionally, we discuss the use of Bayesian hierarchical models (within the analytical stage), due to their flexibility in dealing with the variability present in data from multiple scales. With growing recognition of both ecological drivers that span spatial and temporal scales and the subsequent need for collaboration to effectively manage heterogeneous resources, we expect implementation of transboundary approaches to become increasingly critical for effective inland fisheries management.

### Ciencia pesquera transfronteriza: enfrentando los retos del manejo de pesquerías continentales en el siglo 21

El manejo de las pesquerías de aguas interiores en el siglo 21 presenta varios obstáculos que incluyen la necesidad de analizar las pesquerías desde distintas escalas espaciales y temporales, lo cual normalmente implica poblaciones y recursos que rebasan las fronteras sociopolíticas. Si bien la colaboración no es algo nuevo en la ciencia pesquera, los sistemas acuáticos continentales han sido históricamente manejados a nivel local y entrañan retos que son diferentes a los del medio marino y a los de grandes sistemas de agua dulce como Los Grandes Lagos. Por lo tanto, se propone una estrategia flexible que considera a la organización, cooperación, análisis e implementación como piezas fundamentales para abordar de forma efectiva los asuntos relativos a las pesquerías transfronterizas. Adicionalmente se discute el uso de modelos jerárquicos bayesianos (dentro de la etapa analítica) debido a su flexibilidad en cuanto al tratamiento de la variabilidad de los datos en múltiples escalas. Tomando en cuenta la creciente aceptación tanto de los forzantes ecológicos, en las dimensiones espacial y temporal, y la subsecuente necesidad de colaboración para manejar eficientemente recursos heterogéneos, se espera que la implementación de enfoques transfronterizos se vuelva cada vez más importante para un manejo efectivo de las pesquerías en aguas interiores.

### Sciences halieutiques transfrontalières: relever les défis de la gestion des pêches continentales au 21e siècle

La gestion des pêches continentales au 21e siècle présente plusieurs obstacles, y compris la nécessité de considérer la pêche à partir de multiples échelles spatiales et temporelles, ce qui implique généralement des populations et des ressources réparties sur plusieurs frontières sociopolitiques. Bien que la collaboration ne soit pas quelque chose de nouveau pour la science de la pêche, les systèmes aquatiques continentaux ont toujours été gérés à l'échelle locale et présentent des défis différents des grands systèmes d'eau douce ou marins comme les Grands Lacs laurentiens. Par conséquent, nous présentons une stratégie souple qui met en évidence l'organisation, la coopération, l'analyse et la mise en œuvre en tant que blocs de construction afin de traiter efficacement les questions de pêche transfrontières. De plus, nous discutons de l'utilisation de modèles hiérarchiques bayésiens (au sein de la phase d'analyse), en raison de leur flexibilité dans le traitement de la variabilité présente dans les données de plusieurs échelles. Avec la reconnaissance croissante des facteurs écologiques qui couvrent des échelles spatiales et temporelles, et la nécessité d'une collaboration ultérieure pour gérer efficacement les ressources hétérogènes, nous nous attendons à ce que la mise en œuvre d'approches transfrontalières devienne de plus en plus critique pour une gestion efficace de la pêche continentale.

## INTRODUCTION

Inland fisheries managers often work at relatively small spatial scales (e.g., a single lake or watershed) corresponding to their local or regional authorities. Local influences, objectives, regulations, and enforcement have traditionally guided protection, enhancement, and sustainability of fish populations within an individual water body, stream reach, or watershed. Likewise, management objectives often have a brief temporal window (e.g., months or years). Correspondingly, applied inland fisheries research has predominantly attempted to reduce uncertainties at these small spatial and temporal scales. Many issues can be addressed at spatial and temporal scales consistent with local management objectives—such as harvest rates and fishing effort. Other critical questions are untenable or misleading at small scales. For this suite of issues, a broader spatial or temporal approach is needed. For example, large-scale processes, such as climate and land-use change, can alter physiochemical and biological properties of aquatic and terrestrial ecosystems and shift linkages among habitat types (Frissell et al. 1986; Fausch et al. 2002; Soranno et al. 2009). Elucidating links between multi-scale phenomena is critical for integration of existing data to inform management of resources that respond to both local and large-scale influences.

Fisheries (and ecological) research has been generally expanding to include larger-scale questions coincident with a greater appreciation that natural resources are sensitive to large-scale phenomena via complex and dynamic pathways (e.g., Wenger et al. 2011; Pépino et al. 2012; Muhlfeld et al. 2014). Although the appreciation of large-scale dynamics in fisheries is not new (e.g., Frissell et al. 1986), common challenges remain in addressing research questions across multiple spatial and temporal scales and diverse inland fisheries. In particular, reducing large-scale uncertainties often requires data from multiple and disparate sources. As such, efforts based on collaboration and coordination of data across jurisdictional management boundaries are increasingly important in fisheries management, within the contexts of several key issues (e.g., barriers to migration, habitat loss, and climate change).

Recent scientific and management efforts emphasize a growing focus on interdisciplinary and holistic approaches for understanding and managing ecosystems across broad scales. Among notable examples are the U.S. Fish and Wildlife Service (USFWS) Landscape Conservation Cooperatives (fws.gov/landscape-conservation/lcc.html), U.S. Department of Interior Climate Science Centers (doi.gov/Csc/index.cfm), the National Fish Habitat Action Plan (fishhabitat.org ), and associated fish habitat partnerships such as the Eastern Brook Trout Joint Venture (easternbrooktrout.org). Each of these efforts spans spatial and temporal boundaries that might otherwise impede traditional approaches for conservation and natural resource management. Concurrent to these interdisciplinary organizational structures are a growing number of freely available databases for fisheries and aquatic scientists (e.g., McManamay and Utz 2014), along with active discussions in the literature about improving interdisciplinary research and incorporating the information produced into decision making (Pennington 2008; Goring et al. 2014). Despite the valuable and extensive research products today's interdisciplinary units provide, transboundary fisheries science (TFS) efforts still encounter challenges, which may become increasingly apparent when either influences or outcomes of management no longer adhere to the short term and local scale.

In this article, we consider limitations, advantages, logistical challenges, and strategies for collaboratively engaging in TFS. For our purposes, we define TFS as "fisheries science that crosses two or more sociopolitical boundaries (e.g., state, provincial, tribal, or national) in order to secure useable information for management action." We focus on inland fisheries because transboundary questions and approaches are relatively new to inland fisheries compared to other systems. Diadromous and marine fisheries have long been recognized as interjurisdictional, large-scale functional units (McGinnis 1994; Thébaud 1997). Ecosystem-based fisheries management has been advanced in marine systems (Francis et al. 2007; Espinosa-Romero et al. 2011), and transboundary approaches are being discussed, for example, by Makino and Sakurai (2014), who outline the need for more end-to-end approaches regarding marine fisheries. The Great Lakes of North America are inherently transboundary, with research efforts having addressed questions of international scope for some time (e.g., through efforts of the Great Lakes Fishery Commission and Council of Lake Committees). There are certainly lessons to be learned from transboundary efforts within these large systems. However, inland lakes and rivers are unique systems with their own conservation and management priorities that historically have operated at a small scale. For example, the implications of broad-scale phenomena like climate change, species introductions, and changes to watersheds are likely to only be understood at transboundary scales; smaller scales may obscure the larger pattern.

We illustrate a conceptual framework for performing TFS by characterizing four components common to these efforts: organization, cooperation, analytics, and implementation. Scale is critical to each component and requires explicit consideration in order to successfully address the many issues affecting fisheries and aquatic ecosystems over large spatial extents. Our goals are to (1) formalize a discussion about the process of TFS in order to highlight its utility and provide a common ground for cultivating future opportunities, and (2) provide researchers and managers with approaches and strategies to address challenges when implementing TFS.

## ORGANIZATION: INITIATING TRANSBOUNDARY RESEARCH

Transboundary research activities typically begin with recognizing and defining a problem, which is often broad in spatial extent and complex in scope. Although clearly outlining a problem might be considered the first step of any decision-making effort, concurrent identification of project leadership is required for transboundary research in order to best delineate issue complexity and to assemble the appropriate team. Therefore, the initiation of transboundary research requires strong leadership to work with decision makers to define the problem, form long-term group and individual goals, and maintain progress. Identifying an appropriate team leader (or leaders) for a transboundary project is critical for success. Selin et al. (2000) identified effective leadership as the most important predictor of successful collaborations. Leadership assets include strong organizational skills and credibility. Although leaders may not be experts in everything, they ensure that subject-matter experts are included and engaged. The leader(s) will be the face of the project, interact with stakeholders, and lead conference calls, webinars, or other media outreach.

**The initiation of transboundary research requires strong leadership to work with decision makers to define the problem, form long-term group and individual goals, and maintain progress.**

Leaders often identify stakeholders and team members of the project. Stakeholders are those individuals or groups with a vested interest in the resource or outcome of a management decision. Team members are individuals actively involved in the process of TFS (while noting that the membership in one is not exclusive to the other). Team members are likely to be selected based upon their ability to contribute to accomplishing project objectives, their areas of expertise, and, in some cases, a need for representation. Because of the large spatial extent of many TFS questions, integrating across scientific disciplines is often necessary, and broad stakeholder representation is critical to collaboration success (Selin et al. 2000). Team members often have complementary skills sets (e.g., knowledge of the ecology of the species of interest, database and geographic information systems experts, and quantitative and landscape ecologists) and have a demonstrated ability to work with others. If successful, the assembled team will have the characteristics of a productive collaborative research team, including synergistic efforts of team members, effective communication, and individual and group accountability (Cheruvelil et al. 2014). If representatives from the agencies/organization where the data were collected are not part of the team, the team leader must ensure that those agencies and organizations are kept abreast of the project and have the proper permission to use data. Subsequent communication to those groups will help provide buy-in of the project and use of the results.

Perhaps most importantly for project success, leaders and team members need a clearly articulated vision and measurable objectives. These objectives need not be elaborate or complicated. Effectively crafted objectives are quantifiable so that progress toward reaching them can be determined. In practice, project planning is initiated by transparently defining a problem and establishing common expectations among project participants (Figure 1). A conceptually simple vision, for example, might be to compile fish species richness or abundance from stream electrofishing survey data over a given geographic range to determine the effects of land use and climate change on

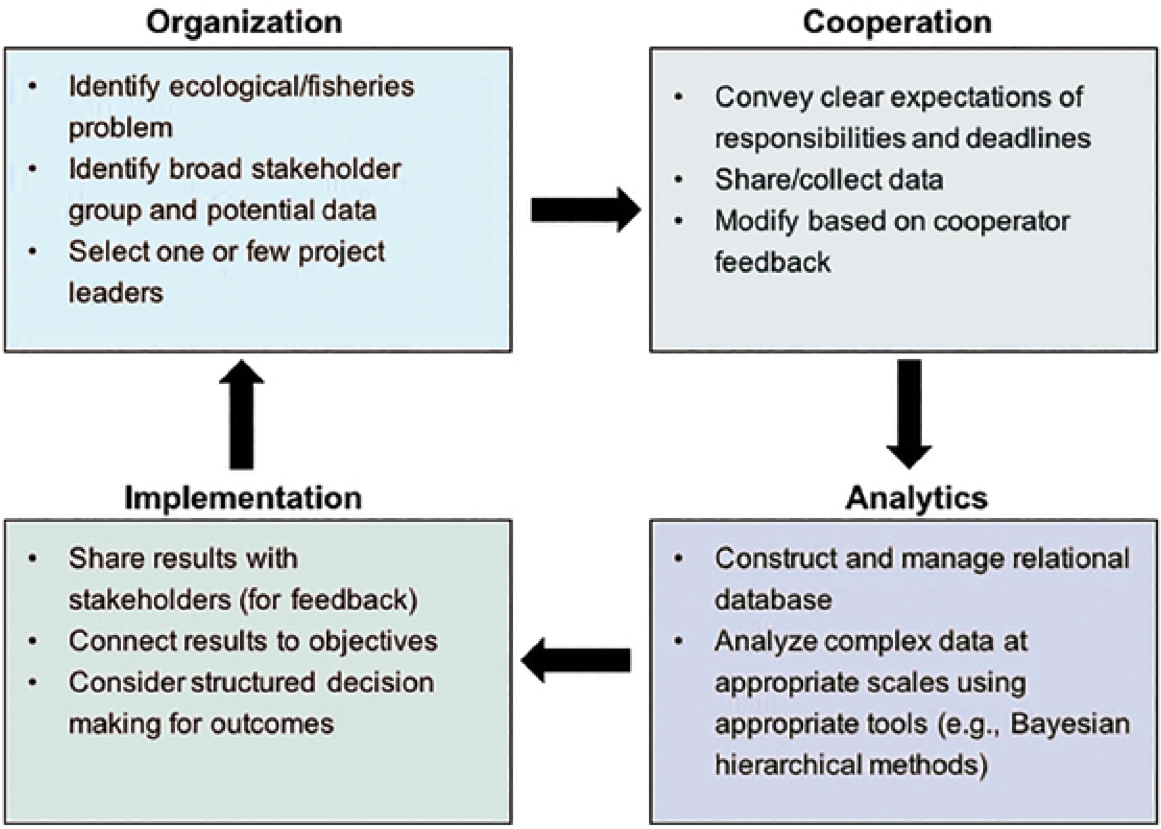


Figure 1. Four-component conceptual model for TFS. Although a highly specific and sequential process may not be required based on the nature and scope of the problem, TFS issues can be approached with this four-part model in which most or all of the component steps will need to be considered. The cycle will generally begin with the organization component.

fish species richness or abundance.

Assessment of native fishes of the Upper Colorado River Basin (srlcc.databasin.org/galleries/f9c4a86d785147f595159ce533d42710) is an informative case study of successful TFS organization (Whittier and Sievert 2014). Over a six-state region, native species conservation priorities were developed for conservation partners in the Desert Fish Habitat Partnership, which is part of the National Fish Habitat Partnership. Individual fish habitat partnerships receive funds from USFWS to conduct projects to protect and restore fish habitat. Allocation of these funds is partially performance based, and the basic criterion to receive these funds is that each partnership needs to compile a scientific assessment of fish habitats within their boundaries. The scientific assessment in the Upper Colorado River Basin developed by Whittier and Sievert (2014) used procedures developed by Strecker et al. (2011) for the five-state Lower Colorado River Basin so that there is a consistent assessment of fish habitat throughout the entire Colorado River Basin. These assessments are a direct result of transboundary research to meet stakeholder needs and required input (including data) from state and federal agencies and nongovernmental organizations.

## COOPERATION: ENGAGING PARTNERS AND SHARING DATA

Fostering active and effective cooperation between and among partners—including user groups, nongovernmental organizations, state agencies, and federal and academic institutions—demands clear communication of goals, expectations, outcomes, and products, including a timeline and plans for individual and agency recognition (e.g., publication authorship). Cooperation is critically important when working across boundaries, where local politics may drive motivations. In some cases, this communication is formalized through the linking of funds to specific deliverables, cooperative agreements, and memoranda of understanding, in order for the agency collecting the data to retain oversight of the data. However, usually only a small percentage of participants who receive funding or data are responsible for contractual obligations. Keeping data providers in the loop (assuming that they desire to be) as results are generated and products are finalized will help to ensure that the research is relevant to management and that the results will be used by those agencies. Such interactions may also foster trust between the team leaders and agencies that may lead to future collaborations that are mutually beneficial to the participants and the groups they represent. If funding is available across multiple boundaries, coordination of timelines and data collection may be one of the bigger challenges early in the project development. Funding agencies typically fund projects to meet their own specific objectives or needs, and they may have certain timelines or criteria for support and deliverables. An example of the possible mismatch in allocation of funds is the difference between a federal fiscal year and a state fiscal year. A project funded by federal dollars may begin (and end) on October 1 of a given year, whereas a state-funded project may begin (and end) on the state's fiscal year (e.g., July 1). For research projects involving students, academic calendars impose additional constraints. Therefore, team leaders need to understand these logistical challenges to ensure that all supporting agencies' criteria are met.

For at least the short term, transboundary work is likely to rely on information that was collected for purposes other than the transboundary goal, commonly long-term monitoring or standard lake or stream fish assessments. Therefore, understanding how existing data were collected and for what purpose is critical to using these data to answer the research or management question. Though on-the-ground practitioners may have access to or have collected data, use of the data beyond their intended purpose can have limited attraction. It is simply not in most managers' job descriptions to find and then dig through decades of data (that may still be in written form) and hand it over to a would-be, out-of-region collaborator. Support from administrators to collaborate across boundaries may be limited. Such efforts can be viewed by supervisors as distractions and may limit collaboration beyond their boundaries. The fact that, more often than not, fisheries biologists freely collaborate speaks volumes to the work ethic of those in the field. In our experiences, hard-earned data are usually generously shared with little expectation of reciprocation.

Ongoing efforts are attempting to compile data over large spatial scales and provide public access to these data (e.g., Multistate Aquatic Resources Information System 2008). Such efforts are anticipated to minimize the required efforts of individual agency personnel to respond to future data requests. Participation and buy-in by data providers is critical to ensure the usefulness of data compilation resources. The growing effort and production of transboundary biological and habitat databases will certainly facilitate inquiry of future transboundary questions.

Being unquestionably clear about expectations and outputs is imperative, particularly in an effort to maintain a sense of progress toward goals shared by different groups. For those in academia and/or research, publication of a product is an obvious means toward the objective of reaching a project's goal. Inclusion of authors—or, more likely, exclusion—can be a sensitive issue among participants. Before the first bytes of data are exchanged, knowing expectations for inclusion in eventual publications is essential to retaining good working relationships among cooperators. There are a number of resources available to determine suitable authorship (e.g., Weltzin et al. 2006; see also the American Fisheries Society 2016 and the Ecological Society of America 2013), which may be helpful when discussing authorship with team members, stakeholders, and collaborators. At a minimum, acknowledging indispensable information and individuals who have contributed to the project is merited in both public presentations and publications. Providing feedback to cooperators as to the potential management relevance of publications is both a deliverable and a means of increasing the probability of informed management action. Providing feedback to administrators can lead to a culture of data sharing in the future.

Providing deliverables to a cooperator early in a project is valuable, and their propagation can help to forge lasting cooperation. Asking what might be useful to the cooperators and following through are positive moves that help avoid problems or concerns in the future of the project. Likewise, keeping researchers abreast of pressing management questions can help allow for timely delivery of actionable information—data or results that can help inform a management action. Providing access to the compiled data may be of interest and utility to the cooperators or their colleagues. For example, is there any screening, quality assurance, georeferencing, or other data management that researchers can conduct once data are provided to them? Our experience is that data stewards (loosely defined as anyone who manages, curates, or holds data) are interested in knowing whether possible outliers were identified, which may help providers in establishing quality control procedures for their databases. Ultimately, uncirculated, regional data sets are the building blocks of TFS, so ensuring their quality and importance lays the foundation for strong TFS.

## ANALYTICS: BIG DATA AND COMPLEX DATA STRUCTURES

The compilation of diverse data necessitates database skill commensurate with scale. A simple spreadsheet may be sufficient for some applications but grossly inadequate for others. Because of the need to integrate many sources of information, a common initial step for TFS analyses is to create a transboundary relational database, which is often composed of or compiled from several smaller, local-scale databases. Triage of what data exist, are made available, and are appropriate is frequently necessary. Local-scale databases (e.g., collected by state or federal agencies or universities) usually must be manipulated for consistency such that they can be compiled in a meaningful way. This task includes, at a minimum, having common variable names across data sets, geographic location data, and general information about sampling methods, including gear type, water temperature, season, and target species (see Kolb et al. 2013 for overview of database construction and management in fisheries science).

Inconsistencies among databases usually fall into one of two categories: (1) failure to record/report information (i.e., missing information) and (2) inconsistencies in recording, reporting, and methodologies (e.g., data entry errors). Often the data will need to be converted or aggregated because of data limitations. For instance, relative abundance data may need to be converted to presence–absence data because of biases associated with different sampling gears (e.g., Schloesser et al. 2012). The data acquisition and compilation often takes a considerable amount of time and can represent a substantial proportion of overall personnel time and fiscal resources devoted to any given project. When initiating TFS, do not assume that data are easily obtainable or organized in a useful way. In short, it is not prudent to underestimate data management issues at the outset of TFS and include data management in project budgets.

The development and use of large-scale data sets creates big data challenges, similar to those encountered by scientists in other fields of ecology (e.g., Hampton et al. 2013; Rüegg et al. 2014). Fortunately, however, access to diverse transboundary data sets and the sharing of data and computer code within the scientific community is increasing, largely facilitated by the creation of online data repositories (e.g., DataOne [Michener et al. 2012], U.S. Geological Survey 2016, and web-based hosting services such as GitHub, Inc. 2016). Online data repositories and open science may eventually reduce the proportion of projects that need to start "from scratch" when compiling data across a region and reduce the time burden put on data providers (e.g., state agencies) as a result of data requests. Regardless of the initial intent, care and transparency need to follow every step of the data curation process—there are often products later in the project that can be informed by well-managed data, in addition to the fact that journals are increasingly requesting that data, and sometimes computer code, be provided with manuscripts.

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Although several analytical challenges may arise when analyzing transboundary data sets, two specific challenges worth mentioning are spatially varying processes and spatial data imbalance. Scaling up inferences based upon fisheries data collected at local spatial scales (or varying temporal scales) and merged to address transboundary questions requires a re-evaluation of assumptions regarding how systems may function. This is recommended due to the potential for many processes that are assumed spatially homogenous or invariant at smaller spatial scales to be dynamic and require spatially explicit representation at larger spatial scales. For example, occurrence of Brook Trout *Salvelinus fontinalis* in relation to watershed urbanization is relatively constant at smaller spatial scales, yet the proportion of urbanization in a watershed that results in an abrupt change in occurrence probability of Brook Trout increases with increasing water temperatures across the species Eastern U.S. range (Wagner and Midway 2014).

In addition, driver variables of fish distribution or abundance may interact across scales, resulting in cross-scale interactions and potentially unanticipated nonlinear patterns and dynamics (Soranno et al. 2014). Such dynamics are also seen with Brook Trout, where watershed soil permeability was found to be an important landscape attribute that varied among ecological drainage units (DeWeber and Wagner 2015). These complexities can be detected and accounted for in transboundary research if the effects of covariates are allowed to vary spatially—for example, in models with explicit spatially varying parameters—and subsequently modeled at larger spatial extents (Wagner et al. 2011; Soranno et al. 2014). Because quantifying spatially varying parameters requires data that span the transboundary study area of interest, a related issue is that there is often an uneven spatial distribution of observations across large spatial extents, resulting in data-rich and data-poor areas. One particular challenge is how to deal analytically with data-poor regions, particularly when results from the regional analysis will be used to make management decisions at subregional (e.g., state) or local (e.g., river reach) scales.

## IMPLEMENTATION: LINKING TRANSBOUNDARY RESEARCH WITH REGIONAL AND LOCAL MANAGEMENT

Addressing research questions that can be linked to make better informed management decisions is often the purpose of applied research. Applying this principle to TFS is no different. Large-scale data analysis demands time and effort but holds the potential for fundamental shifts in fisheries management that exceed the scale of existing management authorities. After defining the natural resource problem, outlining quantifiable objectives is a critically important step in the decision-making process (Irwin et al. 2011; Conroy and Peterson 2013). During TFS, however, management is likely to occur at multiple spatial scales and, thus, management objectives are likely to be scale dependent. For example, research across a species' native range may be used to inform management goals that are concerned with maintaining a certain number of viable populations. Within that native range, a local management agency may be interested in using the same research to inform harvest regulations at the catchment scale. In addition, objectives are required at multiple stages of performing TFS (e.g., from objectives of the funding agency to specific management objectives that may vary from state to state), and the potential for conflicting objectives within and across domains is possible.

For example, Paddlefish *Polyodon spathula* are found throughout much of the Mississippi River and cross interjurisdictional boundaries during migrations (Jennings and Zigler 2009). However, Paddlefish are not considered a sport fish in Minnesota and Wisconsin, whereas other states (e.g., Illinois, Missouri; Bettoli et al. 2009) have sport fisheries for this species. Thus, a result of transboundary research that explores outcomes and uncertainty for various harvest regulations may only be relevant to the states that actually harvest Paddlefish. Therefore, we suggest that performing TFS within a structured decision-making framework is likely to increase the likelihood that relevant objectives are included from the initiation of TFS (Martin et al. 2009). Adopting structured decision making for performing TFS also has the benefit of explicitly linking management and research components by ensuring a collaborative development of tools (e.g., models) that address the diverse values of stakeholders, which will create a transparent process and greatly increase the likelihood of management success (Irwin et al. 2011). The importance of stakeholders is also critical at the implementation stage. Stakeholders may be the ones who physically carry out a management recommendation, navigate local or regional politics, or play other roles required for successful TFS.

## SUMMARY AND GUIDANCE FOR MOVING FORWARD WITH TFS

Transboundary fisheries science, like other fields of ecology that can broadly be described as macrosystems ecology (Heffernan et al. 2014), deals with large volumes of diverse data types. From a technical perspective, storing and managing large volumes of data no longer need be a concern. However, Rüegg et al. (2014) stated that macrosystems projects would benefit from integrated information management, which would lead to "improved communication, and sharing of knowledge among diverse project participants, better science outcomes, and more transparent (i.e., "open") science" (p. 24). An important component of integrated information management is publishing well-documented data sets in an effort to help foster open science, ensuring that data are available for future use. This notion is especially relevant to TFS, where there are often a large number of diverse stakeholder and user groups.

Though notation and nomenclature of data collection represent serious logistical impediments to transboundary work, methodological differences across boundaries can be ruinous. Data collection techniques can be region, agency, or person specific. In one case, one of the authors was informed

**Box 1. Example of hierarchical Bayesian model used to link spatially varying occurrence (and uncertainty) of Brook Trout at local and regional scales (Wagner and Midway 2014).**

Eastern Brook Trout (Figure 2) are an ecologically and economically valuable stream-dwelling salmonid that occurs natively across eastern North America. Brook Trout have declined throughout their native range in eastern North America (Hudy et al. 2008), where it ranges from being a locally abundant and popular sport fish to being at risk of local extirpation. Knowing that land use and land cover can be large-scale drivers linked to local species occurrence thresholds, Wagner and Midway (2014) parameterized a hierarchical Bayesian threshold model that allowed for simultaneous inferences about local catchment-scale occurrence probabilities and regional inferences about large-scale effects of land use on occurrence. This model also allowed land-use change points (and other parameters) to vary spatially and included cross-scale interactions, where the effects of catchment-scale land use on Brook Trout occurrence was affected by larger-scale stream thermal characteristics. The model produced results highlighting that (1) some drainages had substantially different change point estimates; (2) some change points were fairly certain, whereas others were uncertain (Figure 3); and (3) change points based on percentage of urban land use covaried with a regional covariate—change point values increased with increased stream water temperatures. This example highlights that (1) change points would not have been estimable for all regions within the Brook Trout's native range using traditional (nonhierarchical) modeling (i.e., often too little data to fit a threshold response); (2) in those areas with little data, uncertainty in estimates was properly accounted for; (3) allowing for spatially varying parameters provided insight into drivers of Brook Trout occurrence and allowed for the estimation and modeling of cross-scale interactions; and (4) local and regional inferences were possible from a single model fit.

Figure 2. Brook Trout (top) and Rainbow Trout *Oncorhynchus mykiss* (bottom). Transboundary fisheries issues by definition not only span political boundaries but may deal with ecologically complex topics, such as protection of native species (e.g., Brook Trout), competition of introduced species (e.g., Rainbow Trout), and management of stocked populations. Photo credit: B. J. Irwin.

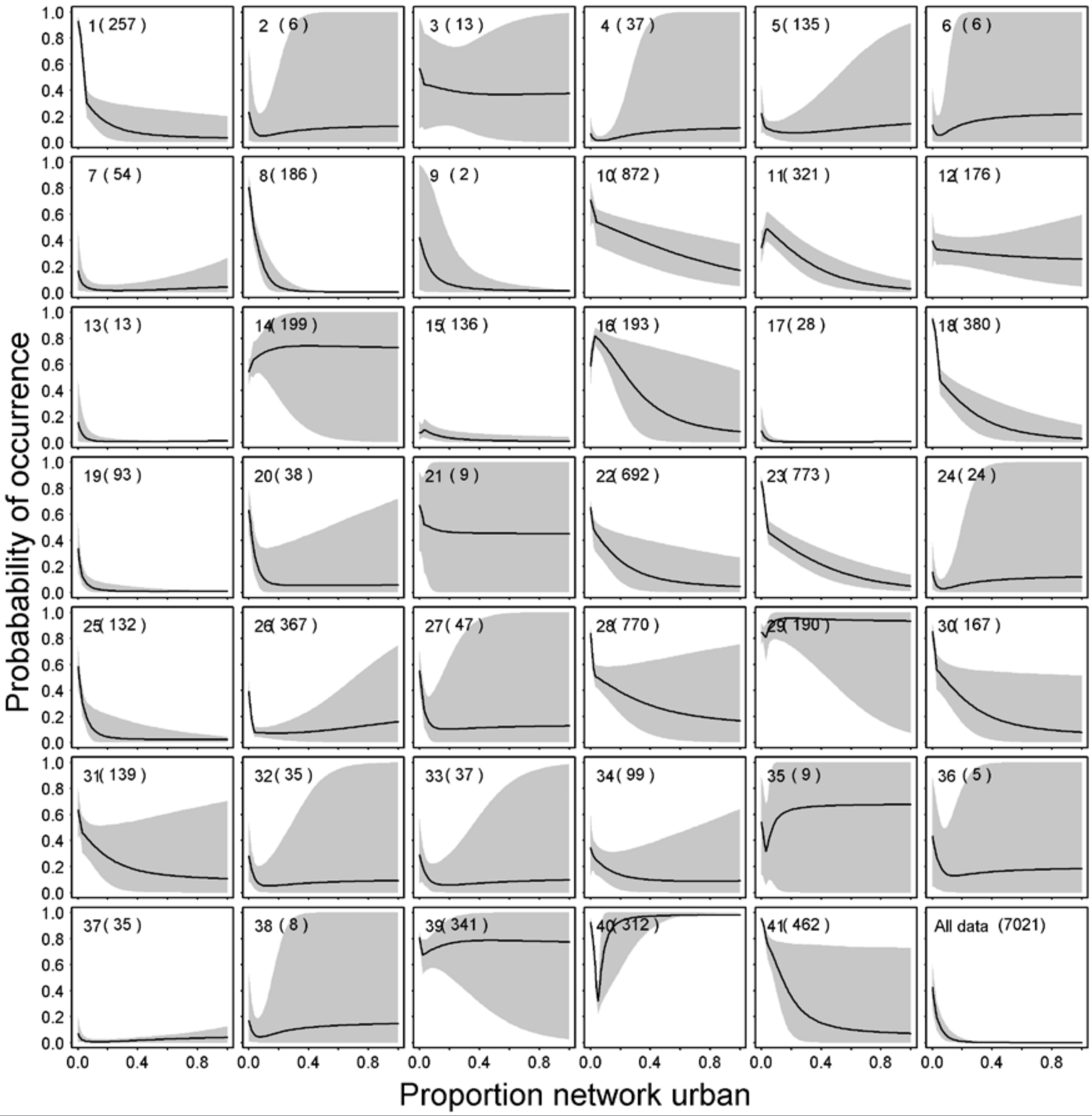


Figure 3. Reprinted from Wagner and Midway (2014), this figure shows ecological drainage unit–specific threshold relationships (black lines) with 90% credible regions (shaded area) for Brook Trout occurrence probability in response to proportion of network catchment urban land use. Number of observations is in parentheses, and numbers 1–41 reference ecological drainage units. Transboundary products such as this are not possible without large-scale cooperation, well-documented data management procedures, and hierarchical Bayesian models that generate spatially varying estimates that would otherwise not be estimable.

that rather than counting individuals, fish species were listed as rare, infrequent, or abundant in lakes. However, the qualitative measure differed from lake to lake (i.e., if the catch were fewer than expected in a given lake, it was recorded as infrequent). Standardization across boundaries is challenged by the lack of structure to decide how to proceed. With a keen eye to the implications of this problem, the Fisheries Techniques Standardization Committee, from the Fisheries Management Section of AFS, consolidated and published a compilation of techniques for freshwater fisheries (Bonar et al. 2009). This book and the accompanying website (fisheriesstandardsampling.org) are valuable assets in working to collect future data that would be likely able to contribute to TFS.

Though standardized methods are the most desired strategy for TFS, the reality is that interdisciplinary and interjurisdictional management approaches have established ways of collecting data that may be unlikely to be modified. Because we view the strength of TFS by the linkage between the ecology and data to the management outcomes, a concern for any TFS undertaking is how mismatched data sets can be combined to produce inference greater than the sum of the parts. With this in mind, we put forth that Bayesian hierarchical methods provide a uniquely flexible framework to accommodate the complex data structures and questions observed in TFS. The flexibility of hierarchical models is essential to TFS if spatially varying and imperfectly collected data are the raw materials from which TFS must inform management decisions.

Although fisheries scientists and managers may successfully use a variety of statistical methods to help guide the management and conservation of inland fish populations and their habitats, a hierarchical framework provides unique analytical properties well suited to complex data structures. Hierarchical models are particularly well suited to resolving the complexities of multi-scale fisheries data (Wagner et al. 2006;

Thorson and Minto 2014). Hierarchical models cover a broad class of statistical models, ranging from (non)linear regression models to time series models and population dynamic models, and offer flexibility in model formulation. In fact, nearly all models in use can be extended in a hierarchical way, meaning that we are not necessarily suggesting a complete revision of existing tools but rather a framework in which they can be effective for TFS. In particular, hierarchical Bayesian methods are extremely useful for accommodating the aforementioned challenges (Cressie et al. 2009; Levy et al. 2014). Hierarchical Bayesian methods have been used to address a variety of questions related to fish growth (Helser and Lai 2004; Midway et al. 2015) and abundance (Kanno et al. 2012) and for performing stock assessments (Jiao et al. 2011). They represent a very powerful tool amenable to innovative application. For example, hierarchical Bayesian models can allow for spatially varying model parameters to account for spatially varying process, such as variation in a stressor–response relationship. This is important because a single model can then be used to help inform local management, through identification of local-scale processes and drivers, and regional implementation, through the identification of regional patterns and drivers. See Box 1 for an example of modeling spatially varying parameters with Brook Trout.

## CONCLUSIONS

Nearly all freshwater systems are now directly linked to social systems, and many important sociological systems are under much pressure from anthropogenic stressors that affect fish populations and their habitats over broad spatial extents. Because global demands on aquatic resources are likely to increase into the future, with the potential for disrupting the social–ecological linkages, we posit that TFS will become increasingly necessary to address the growing challenges associated with managing inland fisheries at local and regional scales. Additionally, global stressors may alter system dynamics in unpredictable ways, and a baseline transboundary approach will provide a more robust understand for future work. Inland systems are heterogeneous and, thus, homogeneous responses to large-scale stressors are unlikely.

Though any successful TFS project will likely be complex, approaches and strategies are emerging to increase successful outcomes. Namely, strong leadership of a broad range of stakeholders is a critical backdrop to any project (Selin et al. 2000). With that in place, attention to detail and open communication are essential to manipulating various data sources into a common, useful resource. Finally, expanding on other reviews of collaborations (e.g., Makino and Sakurai 2014; Kark et al. 2015), we highlight the broad utility of hierarchical Bayesian methods as one promising approach for overcoming complex data structures and questions that traditional statistical models often cannot accommodate. With these tools in hand and the growing number of transboundary databases openly available, we see a growing volume and scale of important fisheries ecological questions that can be meaningfully addressed in the near future.

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