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June 2021

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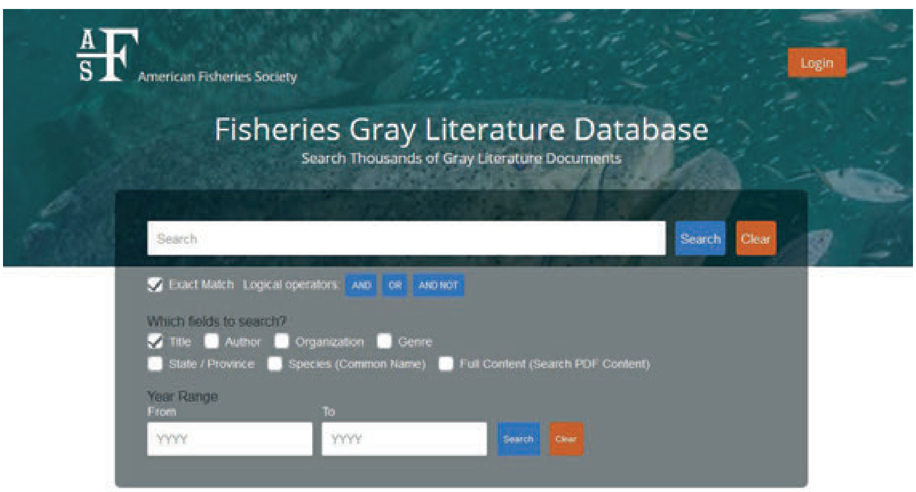

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The American Fisheries Society (AFS), founded in 1870, is the oldest and largest professional society representing fisheries scientists. The AFS promotes scientific research and enlightened management of aquatic resources for optimum use and enjoyment by the public. It also encourages comprehensive education of fisheries scientists and continuing on-the-job training.

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COVER

A Walleye *Sander vitreus* fights on the line after taking an angler's lure. Walleye are the topic of two papers in this issue of fisheries, including Bruner and Feiner et al. Photo credit: Stammphoto.

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COLUMN
PRESIDENT'S HOOK

Transformative Action for Diversity, Equity, and Inclusion

Brian R. Murphy | AFS President. E-mail:bmurphy@fisheries.org

President's Note: I have written several times in this column of the critical need for us to amplify efforts to improve diversity, equity, and inclusion (DEI) within both AFS and our profession. Those columns spurred a number of responses from members, including the letter below to AFS officers from three long-term AFS members, all recipients of the AFS Emmeline Moore Prize for their leadership in DEI efforts. While talk of DEI raises awareness, progress can only be made with concrete actions: here members have responded to the calls for action with specific recommendations. Their suggestions offer new paths and strategies that could help supercharge our DEI efforts, and AFS leadership will take them under close advisement as we work to develop a DEI strategic plan. I invite you to review their letter, and to share your related comments and suggestions with your fellow members in the new "Letters" section of this magazine, or directly with AFS leadership.

To AFS Leadership: We were inspired by President Murphy's editorial, "What Would John Do?" in *Fisheries* (August 2020). We appreciate the end quote from the Dalai Lama, "When you talk, you are only repeating what you already know. But when you listen, you may learn something new." We provide in this letter, our perspectives regarding ways to listen, learn, and address racial and environmental justice.

First of all, congratulations for the outstanding sessions sponsored by the AFS Equal Opportunities Section at the 2020 Annual Meeting. Their focus on making the attendees more effective in their equal opportunity efforts is commendable. You have much to be proud of. There is an old saying of the Freedom Movement that goes "We aren't where we want to be, and we aren't where we should be, but thank the Lord we aren't where we used to be."

In the year of Black Lives Matter the importance of addressing systemic racism has moved into mainstream politics. The movement calls on all of us to finally address racism. In addition to the Equal Opportunities Section and DEI efforts to educate people of the realities of barriers, we urge you to look at AFS efforts holistically.

Racism was openly evident at the 1967 meeting of the Southern Division of AFS in New Orleans as part of the annual meeting of the Southeastern Association of Game and Fish Commissioners. There was one African American fisheries graduate student in attendance. The governor opened the plenary session with a vivid description of what he would do to those trying to "destroy the South's way of life" and personified his view by calling out youthful civil rights activist H. "Rap" Brown. The audience was receptive, particularly the armed law enforcement attendees, many of whom seemed to welcome the opportunity to assist the governor. There was no significant counter view presented personally to the one African American attendee during the fisheries sessions. During this same period, the laboratory director who hired of one of the first African American scientists in the Bureau of Commercial Fisheries was asked how that hire was going, and his response was "It's going fine, he has not bothered any of the women."

For more than 4 decades, multiple efforts by AFS members have addressed the need for change in our approach and goals for increasing and including people of color. Members have organized, catalyzed, and provided panels and sessions emphasizing equity and access. A session at the 1980 Annual Meeting (Wallace et al. 1981) included a "call to action" for AFS to increase the introduction, education, and professional development of women and minorities in the fisheries profession. The summary of this panel cautioned that the recruitment process may be hampered because "we are not listening to the nonwhites and women …gaining the insights of individuals who understand both the needs of the profession and what it is to be nonwhite and/or a woman." The result of that meeting was the formation of the Equal Opportunity Committee.

The message of inclusion was repeated by the Equal Opportunity Committee in 1987, with a panel focused on status of Blacks in the fishery profession and the opportunities for establishing linkages with Historically Black Colleges and Universities (HBCUs; Brown 1988). Foster et al. (2011) provided a guest editorial in *Fisheries* regarding the potential for growth in utilizing partnerships within HBCUs and other minority-serving institutions. If we are to take the calls of the Black Lives Movement to do things differently, there are changes that must be made. Instead of continuing to force everyone into white-dominant institutions like typical internship programs, we need to listen to the perspectives of leaders in organizations and institutions like the National Technical Association, HBCUs, and others that have proven networks.

The HBCUs are well known for punching above their weight class when it comes to graduating African American students with degrees in STEM (science, technology, engineering, and mathematics) and numbers receiving doctorates. The National Science Foundation has funded research to look for educational approaches that can be duplicated (Rankin 2019).

The attention to utilization of HBCUs in federal efforts began in the 1960s with every U.S. President, beginning with Jimmy Carter issuing a proclamation, first for a Federal

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Program and then for a White House Initiative on Historically Black Colleges and Universities (in 1981). There is currently a renewed understanding and recognition of their value in equity efforts. A partnership with the National Association for Equal Opportunity in Higher Education (Washington, D.C.), the organization of HBCU presidents, could provide a transformative opportunity for AFS.

Fortunately, when it comes to working with HBCUs there is an additional closely aligned mechanism. The Centers for Coastal and Marine Ecosystems (CCME) and the Living Marine Resources Science Center (LMRSC) were established in 2001 by NOAA's Educational Partnership Program with Minority Serving Institutions. The Centers are led, respectively, by an HBCU with doctoral authority (Florida A&M University) and the University of Maryland Eastern Shore (UMES), and the consortium involves other HBCUs with or without doctoral authority and one or more majority research universities (including Hispanic Serving Institutions). The LMRSC program partners include Delaware State University, Hampton University, Oregon State University, Savannah State University, University of Maryland Center for Environmental Science Institute of Marine and Environmental Technology, and the University of Miami Rosenstiel School of Marine and Atmospheric Sciences. Partner institutions of the CCME include Bethune–Cookman University, Jackson State University, University of Texas Rio Grande Valley, Texas A&M University Corpus Christi, and California State University Monterey Bay. These programs have significantly increased the number of African American doctorates and have links to high schools to increase the pipeline.

Using the organizational structures to support planning AFS Annual Meetings also can be an effective tool to increase the visibility of and engagement of targeted underserved minorities. The 2021 Annual Meeting in Baltimore is located near a significant number of HBCUs. The last time an AFS Annual Meeting had a focus on HBCUs was in 1987 in North Carolina. The Director of the LMRSC at UMES, Paulinus Chigbu, supports the UMES AFS Student Subunit within the Tidewater Chapter. Additional opportunities are possible at Morgan State University in Baltimore, and their research lab on the Chesapeake Bay, which receives research funding from NOAA, U.S. Fish and Wildlife Service, and Maryland Department of Natural Resources.

Strategic educational partnerships within AFS can help catalyze the already dynamic young professional development within the student subunit programs. The University of California at Santa Cruz is recognized as a Hispanic Serving Institution and has an excellent graduate program. The UCSC partners with nearby Cal State Monterey (a partner in CCME) in marine programs. The student-led Santa Cruz/Monterey Bay AFS Subunit could be instrumental in increasing interactions that can assist with recruitment and retention of Hispanic and other minority students into graduate programs in fisheries and related fields (Fryxell et al. 2018).

Finally, we suggest that a similar approach regarding recruiting other underrepresented sectors into AFS and into fisheries and aquatic science could be paralleled at future AFS meetings in other geographical locations to include Tribal Colleges and Universities, e.g. the Northwest Indian College, which now offers a BS in Native Environmental Science (www.nwic.edu). The Initiative on American Indian and Alaska Native Education began within the U.S. Department of Education in 2011, with now more than 30 fully accredited Tribal Colleges and Universities located in regional locations.

Our final suggestion for the officers and Governing Board concerns the staffing of the AFS office. As well articulated in the Green 2.0 report (Taylor 2014), virtually all conservation agencies and NGOs have staff and directors dominated by white Americans. In a more recent essay for the Sierra Club, Taylor points out that little has changed since 2014 (Taylor 2020). Our AFS Officers now include women and men of color, but our staff and Governing Board are much less diverse. A staffing process needs to be developed with diversity as a priority, given the demographics of the metropolitan–D.C. area. The time/moment is right and we/AFS cannot afford to wait any longer—transformative action needs to be taken. We look forward to actionable and transformative progress.

Most Sincerely,

Bradford Brown, Ambrose Jearld, Jr., Christine Moffitt

REFERENCES

Brown B. E. 1988. Establishing linkages with Historically Black Colleges and Universities: a report on a panel discussion at the 1987 American Fisheries Society Annual Meeting. Fisheries 13(5):26–27.

Foster M. J., C. Bennett, E. J. Sterling, and N. Bynum. 2011. Fostering the development of conservation leadership at minority-serving institutions. Fisheries 36:461–463.

Fryxell D. C., K. M. Kobayashi, K. N. McElroy, and H. Nuetzel. 2018. Creating outreach and restoration programs to promote the development of fisheries professionals: the primacy of cross-institutional collaboration. Fisheries 43(1):11–12.

Rankin C. 2019. HBCUs and Black STEM student success. Peer Review 21(1/2). Available: https://bit.ly/3vqJwUy (April 2021).

Taylor D. E. 2014. The state of diversity in environmental organizations. Report for Green 2.0. Available: https://bit.ly/3vlWpiT (April 2021).

Taylor D. E. 2020. Dorceta E. Taylor on environmental justice. Sierra (December 22). Available: https://bit.ly/3vn8hBk (April 2021).

Wallace D. N., A. O. Smith, S. M. Malcolm, C. K. Barton, B. Gilliard-Payne, and B. E. Brown. 1981. Panel presentations on equal opportunity in the fisheries profession: 1980 AFS Annual Meeting. Fisheries 6(4):2–11. AFS

PERSPECTIVE

Mentoring and Leadership in Aquatic Field Sciences During Unjust, Unsettling, Unpredictable, and Unprecedented Times

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CONTEXT

Science in a traditional university setting is commonly perceived as a place for pedagogy, a setting for intellectual freedom, and an anchor for theoretical and applied research that can lead to innovations and advancements across a wide range of disciplines. Professors in this context lead the charge by teaching in the classroom, the laboratory, and sometimes "off-campus" (e.g., field trips), as well as writing grants, conducting research, and communicating their findings. What professors teach is often based on curricula aimed at providing undergraduate and graduate students with fundamental and practical knowledge and skills that can assist in furthering their intellectual development and careers. The same goes for the engagement of graduate students, and sometimes undergraduates, in research, with professors providing training in experimental design, engaging with external partners, executing laboratory/field work, performing data analyses, and communicating science at a number of levels. In these roles, professors are expected to be mentors and leaders to those whom they teach and guide through the research process. Based on the common perceptions of students, we use the term "professor" broadly to include tenure and non-tenure track faculty, adjuncts who contribute to the academic mission (e.g., a government scientist who holds an unpaid academic appointment who mentors graduate students), research faculty who may not teach, and lecturers, all whom are influential and may be inspiring to students and others they lead.

What is often unseen and unappreciated is the level of responsibility professors shoulder when it comes to ensuring the safety and wellbeing of undergraduate students, graduate students, postdoctoral fellows, and technical staff they employ or otherwise supervise or mentor. Similarly, what also may be overlooked is that a university is a "workplace," and depending on an employee's duties, they are subjected to administrative and regulatory requirements to keep them physically safe, avoid discrimination, and be part of a productive, congenial work environment. As such, it is mandated to take university-sanctioned training courses such as basic first aid, laboratory safety, diver safety, animal care, working with human subjects, and diversity and inclusion. It is also mandated institutionally for all to know and follow laws that protect students from gender discrimination and sex-related harassment and assault (e.g., Title IX civil rights laws and the Clery Act laws, respectively, in the United States). However, for professors there is much more behind the scenes when it comes to anticipating and planning for risks to themselves and those they lead and mentor. Where this becomes exemplified is when teaching and research happen off campus, and especially in remote settings, out of range of 9-1-1 service, more than a few hours from definitive healthcare, and without the ability to consult with the professor in real time (i.e., via cell phone or two-way radio). These responsibilities and realities of being a professor are frequently not communicated to those they mentor and lead, which can create tensions related to why things need to be done in a certain way, or even what the legal ramifications are if negligence is implicated when (not if) an incident occurs. Moreover, these issues can be exacerbated in the broad disciplines of fisheries and aquatic sciences, largely because of the hazards of being near, on, and in the water, which present inherent risks.

Although our personal context is nested in experiences within a university setting, individuals in fisheries and aquatic sciences at government agencies, non-government organizations, and consulting companies who oversee and mentor field crews are also faced with planning for risks and dealing with unexpected challenges. For field research in fisheries and aquatic sciences, potential risks can be quite stressful for a seasoned individual or team, from the threat of drowning, wading and boat navigation in fast flowing rivers and streams, to dealing with complex coastal hazards, waves, tides, and unpredictable weather. Moreover, travel to aquatic environments requires traversing the land, thus those engaging in fisheries and aquatic sciences require an understanding and appreciation of terrestrial-based risks as well. This added complexity can elevate the need for due diligence, planning, preparedness, and associated responsibilities of professors, but even more so when extrinsic, unpredictable, and unprecedent events occur, such as the global COVID-19 pandemic in 2020/2021. These are indeed stressful times that are pushing the limits and capacities of individual professors, collaborative research teams (including graduate and undergraduate students), and the very institutional framework and foundations of the universities under which they are housed. In fact, to say these are unprecedented times seems to be an understatement, since what seems unprecedented one day is soon topped by unforeseen changes and the need to adapt again soon after plans are updated. Unprecedented times are periods or sequences of events that are well beyond what any training and experience can provide, however the way

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we cope can be shaped by what was experienced during the "old normal." Given the path of humanity, learning from past challenges and how we are dealing with the current crisis can help prepare us for the next hurdle—big or small.

With collectively over 30 years of trial and error as mid-career professors, educators, and mentors in fisheries and aquatic sciences, we write this perspective because we believe that by sharing our strategies, experiences, and personal challenges, those entering academia or similar mentorship and leadership roles particularly in fisheries and aquatic sciences can better understand and appreciate why and how certain decisions are made, and what can keep us up at night, beyond preparing lectures and writing grant proposals. Although some of this may seem elementary, we feel that many of the points below may simply serve as important reminders for even the seasoned professor or anyone in a mentorship or leadership role in fisheries and aquatic sciences. Lastly, and most importantly, we write this fully acknowledging that we are two privileged, cisgender, straight, white men in a discipline plagued by injustices related to diversity, inclusion, gender, and race, and hope that much of what we reflect on brings to light additional challenges for underrepresented groups in the field of fisheries and aquatic sciences.

DEFINING UNJUST, UNSETTLING, AND UNPREDICTABLE

What do we mean by unjust, unsettling, and unpredictable? An unjust situation is one in which statements or decisions are made or actions are taken that may be perceived by students and team members as unfair or inequitable. In our experience, this is most often manifested in our labs as biases that are imposed on team members by external factors, by the educational system, the institution, and peers. For example, sometimes how a team member is treated by stakeholders in the field is dictated by gender. From having team members spit on by community members to unwanted sexual advances (harassment)—our team members have seen a lot. Bullying or other forms of verbal harassment are also common as team members are blamed for wasting public funds or their failure to "make fishing better" in a given location.

An unsettling situation can arise from injustices, such as when tensions created by disparities in values and inherent biases erode the working relationship among team members. At times this is influenced by the composition or actions of team members, and whether discretion is used when making decisions that could be risky. It can also be quite unsettling to stumble across a body floating in the water (this has happened twice) or having a police SWAT team commandeer a research vessel in darkness for reasons they cannot discuss. Unsettling times also occur when broader societal and political crises happen, such as being at a remote field station when the 9/11 terrorist attacks occurred in the United States, or, more recently, with the rapid escalation of racial tensions and incidences of police brutality against protestors. These factors can rattle even the most experienced research team, making "everyday" risk management and the nuances of remote (or even urban) settings more challenging and stressful.

Unpredictability is woven into this via the probability that something dangerous or threatening will happen, or how certain risks are simply unforeseen. When planning field work, there are things that an individual or team can prepare for, such as equipment failure or the weather rapidly changing from benign to inclement. This also includes pre-existing medical conditions of team members, such as allergies to insect bites and stings, and the need to carry an Epi-pen and how to deal with anaphylaxis. For these, training and preparedness can help reduce risks and ensure individual and team safety. However, the level of risk and its influence on safety escalates when the field environment is highly dynamic and keeping people safe depends on how an individual or team copes with unforeseeable risks, crises, or "acts of god." This also includes individual variation in experience and tolerance to field work; e.g., long days, repetitive duties, and isolation. Even the most seasoned team members can become physically and mentally exhausted from field work, even though it is an enjoyable activity that many live for.

What we strive to avoid are unpredictable situations that put our students at high risk of physical injury, emotional strife, or both. Essentially, we want and need our students and teams to stay safe, and we must also lead by example, as well as uphold many layers of responsibility as a leader, mentor, and employer. We both still shake our heads in disbelief when it comes to the myriad of risks and safety concerns our teams face. Driving vehicles remains among the most dangerous thing our team members do—especially working in remote and rural locations where moose and deer collisions are more common, and in the north where roads can be snow covered. We also work on water, so drowning and other hazards are possible. Unpredictable dangers extend to much more insidious things, including when three of our team members were intentionally shot at in a location that was over an hour from the nearest police station. Sadly, two of our team members have been sexually assaulted at field sites. And then there are elephants, poachers, ticks, military and political roadblocks, civil unrest, tear gas, death threats (usually from online sources), small storms rapidly turning into hurricanes, and the list goes on. Most unpredictable was the emergence of a pandemic that has now added much uncertainty to all of our lives. Included in this are recent experiences with graduate students conducting field work in another part of the country as states and provinces began locking down in an attempt to isolate from the COVID-19 outbreak, all as university administrative travel restrictions were being established and amended as the context of the pandemic rapidly changed.

STRATEGIES FOR DEALING WITH UNJUST, UNSETTLING, AND UNPREDICTABLE TIMES

Although unjust, unsettling, and unpredictable times can also create safety issues on campus, we will continue to focus on the context of being off campus and doing field work in fisheries and aquatic sciences as we reflect on the strategies we have developed over the years to reduce risks and manage expectations for ourselves and those we lead, mentor, supervise, and employ. We also preface this section by acknowledging and embracing that we both tend to lead our lives with a growth mindset, and value how personal and professional growth can be enhanced when we are "outside our comfort zone" and through diverse experiences. For us, halting field work and adjusting our research portfolios so that they are more on campus is not an option. Implicit with field work is the strong probability that we will not be with a team member when they experience and respond to situations that are unjust, unsettling, and unpredictable. At times, we could be only a phone call or short drive away from where our teams are, but our work is also global, meaning the potential for much less accessibility whether for basic advice or to deal with an extreme crisis.

We add that our perception of risk and concerns for the wellbeing of those we mentor have been amplified after becoming parents ourselves and realizing that our students are somebody's child or loved one. We desperately want to protect our team members, but still want them to grow personally and professionally, and have the opportunity to experience the joys and inherent challenges of field work and everything else our world has to offer. We also still vividly remember the experiences, good and bad, that we had when conducting field work as students, and hope that through our guidance those we mentor will stay safe well beyond the time in our labs.

So how does one develop a strategy for mentoring those we lead and try to inspire them without becoming a "helicopter" mentor or micro manager? We have both at times said "I will never send a team member back to that region or country" after something awful has happened to a team member, only to have them lobby to go back. It isn't easy, and below are some strategies that we have developed over time. These are presented recognizing that they remain imperfect and a work in progress, but we hope that they stimulate thinking for those with relevant experiences and expertise to share, or for those who are thinking about entering a career that includes mentoring others and having the responsibility and sincere desire to keep everyone safe and healthy (physically and mentally).

We also acknowledge that our perceptions of potential risks are likely biased because of who we are and our lived experiences, even though we make considerable efforts to learn about and include in our strategies differences in the threats and challenges among different groups based on race, gender, sexual orientation, religion, and past personal experiences. Providing students and others we lead with tools that allow them to cope and be resilient when situations arise must be derived from diverse experiences. We also feel that it is valuable to offer words of encouragement and support, and to be there for those we lead and mentor.

Embrace Transparency in Decision Making

Making sure that all team members have a voice and opportunity to contribute to projects is (or should be) the norm in field work. Yet, there is a hierarchy of responsibility in any workplace and liability such that although consultation is essential, it is the ultimate responsibility of the leader to make decisions and be accountable for them. Recognizing that any decisions that are made (e.g., cancelling a field trip) will have impacts on team members, it is essential to embrace transparency in the decision-making process. That is to say, although the decision making itself may not always be democratic, the basis for a decision (relative to alternatives) should always be openly discussed with team members. There have been tough decisions that we have had to make where a team member or entire team does not like a given decision, but we do our best to be transparent as to why a decision was made. This is fortunately a rather uncommon path and, in most instances, decisions are achieved through extensive discussion and consensus. Nevertheless, a culture of transparency must be developed and maintained, not only in decision making, but with any aspect of field work that could elevate risks.

Create an Atmosphere of Mutual Respect and Trust

It is a natural extension from a culture of transparency to one of mutual respect and trust. Although academia can be hierarchical because of different levels of training and responsibility, we certainly try to foster respect and trust when it comes to the fact that both mentor and mentee are human, that people make mistakes, and that life can be unfair at times. Tied to this is an assumption of good will. We also approach mentoring as simply being more experienced and further along in our careers than most we lead, but are still very open-minded about learning from those in our labs even if our ages are separated by decades or degrees. Transparency, respect, and trust also apply when personal or family matters influence someone's physical and emotional wellbeing, and how that can be translated into difficulties in the field as well as how decisions are made. Sometimes we are put in the difficult situation of not legally being allowed to ask about pre-existing conditions (medical, psychological, or otherwise), yet if we are aware of them, we can then make any accommodation needed. We have had team members enter into situations that are a danger to themselves and others because we did not know of and were not legally able to ask about pre-existing conditions. In remote field locations, this can create huge problems and really calls for trust and transparency. Also related to trust is creating a culture where our students know that we will "have their back" if a situation arises, unless true negligence or irresponsible behavior is evident. This can build mutual respect that can bolster self confidence in those who are being mentored, and foster greater success whether in the field, or when back behind a desk, at a conference, or as a mentor themselves.

Acknowledge the Blurred Lines between Work and Life

Field work can be extremely exciting and rewarding, but it is not a hobby. It is a work activity undertaken by trainees and professionals. Yet, field work is an activity where there is often a blurred line between work and life (or work and play). Consider a scenario where a team of four are working at a remote field site for 2 months. They live under the same roof, they cook together, they socialize together, and they do field work together. They are not technically working 24/7, but at the same time the situation they are in (i.e., shared living) is entirely dictated by the work. In such situations, transparency, respect, and trust outlined above are critical, not only between us and the individual team members, but among the team members as well. Simple inconveniences and differences in the way individuals cope can transform what is normally something that is easy to shrug off into a matter that creates rifts in the team, resulting in unjust decisions and unsettled situations. This is when being transparent with our teams about our expectations and broader awareness is critical, whether it is regarding personal and professional behavior, respecting differences among team members, or unconscious biases. For instance, chores and cooking meals while in the field should not default to female team members, and similarly trailering and piloting the boats should not default to male team members. We also try to encourage compassion and understanding, and trust that those we mentor and lead will also understand how we strive to promote finding work–life balance. Woven into all of this are pressures for students to succeed by fulfilling not only their own expectations, but those of their mentors, partners, stakeholders, and peers. Such pressures can leave those we mentor and lead to be especially vulnerable to "burnout," as well as psychological distress and even self-harm. As mentors it is important to be aware of this, identify the signs, and intervene when necessary, but this also has to be something that is part of team dynamics (i.e., watching out for and taking care of each other) when the mentor or leader is not around or available, as in a remote field work setting.

Develop a Plan

It is impossible to plan for every scenario, yet the planning process prepares team members to consider the things that they may encounter and then develop strategies for dealing with them. This is really where a detailed appreciation of what the scope of foreseeable risks may be, determining the probability that the risks could manifest into an issue of health and safety, and devise the best means to reduce the chances of an incident or crisis occurring. Planning takes time and effort, and this must be built into any timeline. Planning early can help identify need for specialized training, safety equipment, and contingencies. The general approach to risk assessment planning is transferrable so even though there may be instances that were entirely unanticipated (e.g., example of being shot at per above), it is possible to adapt in real time. In our labs, we work to create a culture that acknowledges that what we do in the field can be risky, that there can be a difference between perceived and actual risks, and that planning and continuously evaluating risks in real time are an essential part of doing field work. We also work collaboratively with those we mentor to think through solutions and contingencies to mitigate risk and adequately respond if something unpredictable occurs.

Engage in Frequent Communication

When the people we mentor and lead are conducting field work, we have a policy where in the case of emergencies (no matter how large or small) it is imperative we are contacted (by phone, if possible) at any time of day or night. Even if the issue seems manageable and the team is able to solve it on their own, we work to instill in our teams that we must remain in the loop. We also try to schedule regular check-ins with team members, both as a group and individually, to help identifying problems before they arise. Even if we have teams halfway around the world, we make sure to plan ahead and ensure that there are adequate ways to communicate. Sometimes it means getting up extremely early, staying up very late, adding to or beefing up line items to budgets for communications, and asking our families to be extra patient, but in the end, being accessible to those we mentor and lead is critical to keeping individuals and teams safe.

Empower Team Members to Act

Team members will have to make real-time decisions that influence their wellbeing and safety. It is important that team members are empowered to do so and know that they will be supported. Likewise, we acknowledge that how we perceive and respond to risk in the field can be different than how our mentees will perceive and respond to risk. Creating an atmosphere that allows those we mentor and lead to make choices in the moment and vocalize their perceptions of potential and observed risks without fear of judgement is a must. Action often has consequences, such as spending money or impacting the ability to do the field work, which can make team members hesitate when action is urgently needed. In our labs we have a policy that team members can spend lab money (not their own money) related to safety at any time without consulting us, such as needing to purchase new brakes or tires for a field vehicle when it is away from campus or changing a flight or buying an entirely new ticket to get out of an unsafe situation. Similarly, we do not believe that field work should happen no matter the cost. There is always tomorrow, so if an action (e.g., taking a few days off to recharge or pausing a field project due to inclement weather) impedes field work, in most cases there will be another opportunity later. It is also important for team members to know that they can seek assistance from first responders as needed. We have observed a reluctance to contact relevant authorities (e.g., police, medical professionals) for an issue without first checking in to see if they are "allowed to do so." As such, we hope that through adequate planning and discussion, including ample transparency, that individuals and teams will feel that they have the capacity to work and respond independently, but also know we are available to consult and support as needed.

Learn from and Get Help from Others

What sets university-based field research apart from other groups that send people into the field, is that we, as principal investigators and mentors, end up being the main coordinating body for nearly all aspects of the field work. This requires some level of independence about how we set up guidelines, policies, and expectations for teams. However, it does not preclude us from learning from other individuals and groups, since there is no need to reinvent the wheel, so to speak. Organizations that regularly deploy hundreds if not thousands of people around the world, such as the Peace Corps, various charities, the diplomatic service, and the military, have more formal structures, prescribed policies, and many decades of experience when it comes to planning for risks and successfully responding to incidents. Taking the time to review how others deal with unjust, unsettling, and uncertain times, especially as they relate to individual and team health and safely, should certainly be a priority. In learning and appreciating this, a key take-away is the importance of not being hesitant to use local assets for help. For example, we had an issue where a team member was assaulted in a different state/province but did not want to abandon their field work. The solution was found by reaching out to a local university so that the team member could connect with their counseling services for support.

Tied to all of this is feeling comfortable with openly sharing our experiences about how we have personally dealt with situations, and not just the mechanics behind it, but how we felt emotionally, the administrative aspects of reporting incidences, and how we personally learned and adapted based on past challenges in the field. There is great value in fostering peer-to-peer support networks within the lab and among students, creating a culture of awareness for the wellbeing of others. This also applies to how students observe their mentors and leaders, and the mutual removal of barriers that may inhibit revealing emotional struggle. Thankfully, things are changing in the way our society views mental health, with greater awareness and resources available. In fact, in addition to physical first aid training, it would be wise to conduct psychological first aid training, especially for teams that can be in remote settings for long periods of time, and/or under challenging conditions. Whether through formal team meetings, informal conversations, or even classes we teach on field work and risk management, we feel that it can only help those we mentor, teach, lead, and inspire if we share the personal and professional realities of doing field work and how we cope with unjust, unsettling, and unpredictable times.

CONCLUDING REMARKS

It is a constant and evolving struggle knowing that the people we mentor and lead are put into situations that are unjust, unsettling, and unpredictable during their field work. Knowing and appreciating that our students and teams are exposed to stresses and risks certainly contributes to sleepless hours, knots in our stomachs, and replaying scenarios over and over in our heads. This all differs from an on-campus experience where there is easier access to resources and where there might be more familiarity as to how support systems work. When it comes to field research in fisheries and aquatic sciences, we want our teams to have formative and positive experiences with their journey as trainees eager to learn and budding scientists embarking on exciting careers—not be physically and emotionally scarred by their field work.

For many in fisheries and aquatic sciences, as well as the broader disciplines of ecology, evolution, and environmental science, field work is a big part of why they entered the profession. As one of our mentors used to say, it is about embracing whether you want to be a "lab coat" or a "plaid shirt," or more specifically, whether you are willing to eat your lunch in the pouring rain, being eaten by bugs, and smelling since you haven't showered for days. When individuals are making this decision, it is important to remember that although field work can be enamoring, it is different than hiking for fun. Field research still needs to be treated as a work activity involving the same necessary responsibilities and planning as working in a chemistry lab on campus, but there must be physical and emotional room for additional layers of planning and risk assessment. We are not saying that one is better than the other, and in some cases both on-campus and off-campus research is part of a particular research project or career tract. What we do emphasize is that those excited by the idea of field work need to embrace and respect the additional complexities related to risk, especially in remote settings.

Knowing that we cannot completely ensure the wellbeing and safety of our team members is personally stressful, because we care about them deeply and we are personally and professionally liable. Dealing with this can be emotionally draining for those mentoring and leading, especially when field work is far afield, and as human societies are faced with seemingly more unjust, unsettled, and unpredictable times, such as what we are currently experiencing with the COVID-19 pandemic and racial injustices. Even since first drafting this perspective, the challenges related to COVID-19 have ebbed and flowed as waves of infections continue to emerge. We ourselves are reaching out to peers and institutional administrations to help wade through current challenges, especially since there is no pre-existing roadmap as to how best to cope. What is a solution one day changes the next, and not only do those that mentor and lead have to adapt, but they have to be able to effectively communicate the challenges to those they supervise, who are also dealing with personal issues related to COVID-19. We submit that our community is poorly prepared for all that field work entails, especially in these unprecedented times. An additional emerging challenge is addressing long term planning tied to our own ambitions as well as the ambitions of our students. Managing expectations will continue to be difficult, especially when we begin asking deeper philosophical questions related to what the future of field research should look like, especially for those who have established a strong international research program. Nevertheless, given the nature of fisheries and aquatic sciences, field research will remain essential, and this sentiment is true for many other disciplines in the natural (and social) sciences. With that, the ideas shared here will hopefully help others to be more proactive and ensure that field work can be conducted in a way that develops coping strategies and resiliency for both the mentor and mentee as unjust, unsettling, and unpredictable times continue to ebb and flow.

Figure 1. Challenges faced by our teams during field work: **(A)** boat trailer issues and associated troubleshooting; and **(B)** teaching a field course in a tropical storm.

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We greatly thank feedback and input from our students and staff when it comes to our continued learning to be good mentors and leaders. We are also indebted to our past and present mentors who shared their experiences as well as providing us with the freedom to learn from our own mistakes, survive, and be able to foster a growth mindset with those we lead. We also thank several anonymous reviewers for critiquing our perspective and helping to shape the final manuscript. AFS

FEATURE

Empirical Evidence for Depensation in Freshwater Fisheries

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A closeup of a fingerling Walleye *Sander vitreus*.
Photo credit: Sam Stukel, U.S. Fish and Wildlife Service.

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Inland fisheries face increasing threats to their sustainability. Despite speculation that depensation may exacerbate the effects of stressors on population resiliency, depensation has not been empirically explored in freshwater fisheries. Declining productivity of Walleye *Sander vitreus* populations in northern Wisconsin foreshadows an underlying change in naturally reproduced juvenile Walleye survival. We used long-term stock and recruitment data from lakes in the Ceded Territory of Wisconsin to quantify density-dependent trends in juvenile Walleye survival and tested for the prevalence of depensation using the *q* parameter of Liermann and Hilborn (1997). Of 82 Walleye populations evaluated, about half exhibited depensatory recruitment. An analysis of the global *q* for all populations examined suggested that the posterior probability of depensatory dynamics was about 0.89. In addition, there were few clear cases of compensation—most populations exhibited weak density dependence. The general lack of strong compensatory recruitment across Walleye populations could leave these stocks vulnerable to stressors and unresponsive to rehabilitation. We present multiple lines of evidence to suggest that depensation is a plausible phenomenon explaining declines in Walleye populations in the Ceded Territory of Wisconsin and may be implicated in other invisible collapses of freshwater fisheries.

INTRODUCTION

Inland fisheries are recognized as important sources of food, recreation, and economic value. These systems face an increasing number of threats to their resilience and sustainability, including overexploitation (Post et al. 2002; Embke et al. 2019), habitat degradation due to global (e.g., climate change) and local (e.g., watershed development, shoreline alterations) change (Sass et al. 2019), species invasions, and shifts in fish community dominance due to unbalanced fisheries practices (e.g., cultivation by preferentially harvesting some species, while practicing catch-and-release for others; Walters and Kitchell 2001; Sass and Shaw 2019). The ability of fish populations to maintain resiliency in the face of multiple stressors is regulated by their compensatory response to increased mortality or reduced population productivity (i.e., surplus production; Ricker 1975; Goodyear 1980; Cahill et al. 2018). The absence of compensation results in lost population productivity and poor recovery potential, necessitating increased expansion of stocking and/or use of restrictive regulations to maintain populations (Shertzer and Prager 2007). These practices may become a more common feature of inland fisheries in the face of natural production declines.

Depensation, wherein mortality increases or productivity decreases with decreasing population size, has been implicated in the collapse of fish populations for decades (Ricker 1954; Goodyear 1980). Most fisheries production and management models assume compensatory responses to harvest or population declines above a critical depensation point. In the absence of a compensatory response (depensation below a critical threshold), management paradigms may fail and populations become more difficult to rehabilitate (Quinn and Deriso 1999; Liermann and Hilborn 2001; Post et al. 2002; Hilborn and Walters 2013; Neuenhoff et al. 2018; Figure 1). Thus, a lack of compensation could be underlying unsuccessful management objectives in depleted fish populations. To date, however, empirical evidence for depensatory dynamics is relatively sparse and almost entirely limited to commercially exploited marine stocks (Ricker 1954; Myers et al. 1995; Liermann and Hilborn 1997). This may be due to the difficulty of identifying depensatory dynamics when relying on fishery-dependent data or data that lacks observations at very low population abundances (Myers et al. 1995). Evidence of regime shifts in population productivity in many marine species may suggest that depensation is occurring in some populations even if it was not directly measured (Britten et al. 2016). Depensatory recruitment has not been empirically explored in freshwater fisheries, despite speculation that depensation may exacerbate the effects of stressors like overexploitation, climate change, or species invasions in these systems (Walters and Kitchell 2001; Post et al. 2002).

Walleye *Sander vitreus* in lakes of the Ceded Territory of Wisconsin (CTWI) have exhibited declining abundance and productivity (Rypel et al. 2018) linked to production overharvest (Embke et al. 2019) and changes in climate and fish community composition (Hansen et al. 2015b, 2017). Managers had previously assumed a relatively strong compensatory response in juvenile survival for Walleye populations and managed accordingly. Managers have attempted rehabilitation for declining populations by expanding stocking programs, liberalizing harvest regulations on Largemouth Bass *Micropterus salmoides*, and restricting Walleye harvest, even closing Walleye fisheries in some cases (Raabe et al. 2020). However, a continued lack of recovery in many Walleye populations over time may be evidence for depensation occurring in these fisheries. We empirically tested for depensatory dynamics influencing naturally reproduced juvenile Walleye survival across CTWI populations. Specifically, we used stock–recruitment relationships to quantify density-dependent trends in age-0 Walleye survival across populations over time, tested for the prevalence of depensation using the *q* parameter of Liermann and Hilborn (1997) and the Ricker β parameter, and evaluated

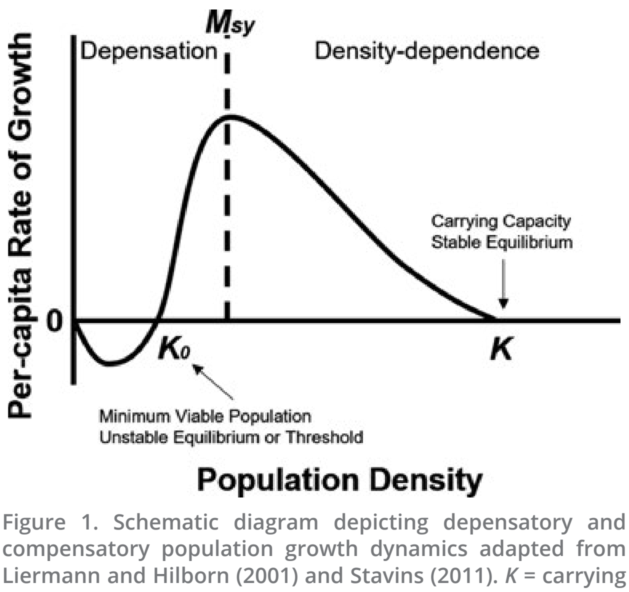

Figure 1. Schematic diagram depicting depensatory and compensatory population growth dynamics adapted from Liermann and Hilborn (2001) and Stavins (2011). *K* = carrying capacity and a stable equilibrium. K_0 = minimum viable population and an unstable equilibrium or threshold. M_{sy} = maximum sustainable yield.

a global q_μ to test for the probability of depensatory dynamics across all populations examined. We present multiple lines of evidence to suggest that depensation is a plausible phenomenon explaining declines in Walleye populations in the CTWI. Similar trends in other fish populations could mean management based on commonly assumed compensatory relationships above a critical depensation point (Ricker 1975) may result in poor recovery of overexploited stocks and potentially increase the risk of nearly irreversible collapse (Quinn and Deriso 1999; Liermann and Hilborn 2001; Post et al. 2002; Hilborn and Walters 2013; Neuenhoff et al. 2018).

MATERIALS AND METHODS

Study Area and Data Collection

Walleye population data for CTWI lakes included mark–recapture population estimates of adult Walleye (≥ 381 mm or sexable) and age-0 Walleye relative abundance estimates (Figure 2). Data was collected by Wisconsin Department of Natural Resources (WDNR) and Great Lakes Indian Fish and Wildlife Commission biologists (GLIFWC) during 1990–2018. Standardized population assessments for Walleye in the CTWI have been conducted jointly by GLIFWC and WDNR since 1990 in order to monitor the recreational angling and tribal spearing fisheries that co-occur in the area (Beard et al. 1997). A standardized lake survey rotation is in place that ensures 20–30 lakes are sampled in any given year (Beard et al. 2003; Mrnak et al. 2018), but not all lakes are sampled in all years. However, several trend lakes have been sampled annually or more frequently since the early 1990s. Outside of the trend lakes, the goal of the rotation is to sample all Walleye populations at least once every 5–10 years. An annual standardized sampling protocol has also existed on Escanaba Lake, Wisconsin, since the 1950s due to it being an experimental fisheries research lake and part of a long-term compulsory creel census (Kempinger et al. 1975). The entire available dataset from Escanaba Lake (1958–2018) was used

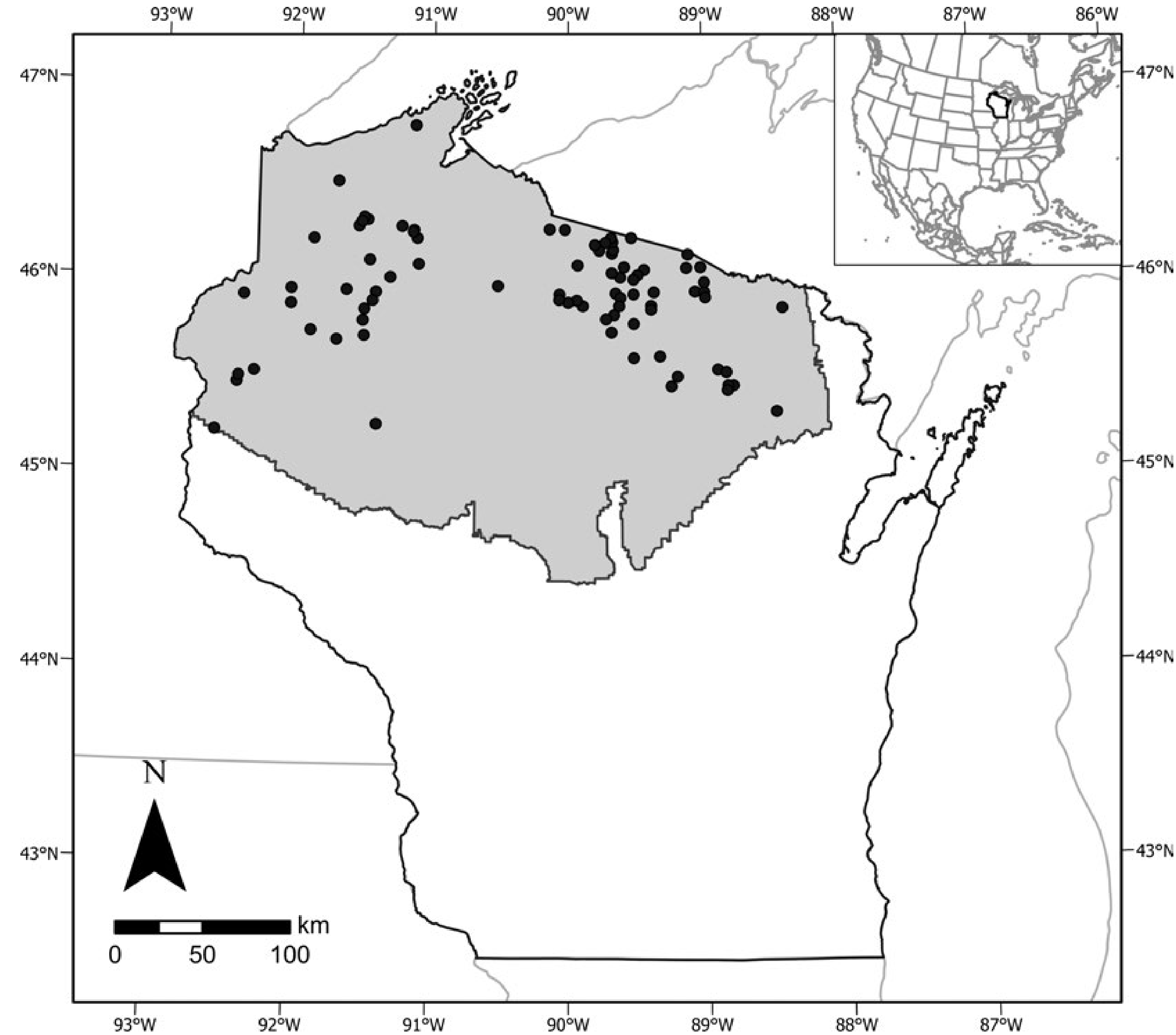

Figure 2. Map of Wisconsin, USA displaying the Ceded Territory of Wisconsin (shaded) and locations of the study lakes (black dots, n = 82) where Walleye recruitment dynamics were examined during 1990–2018.

for this population only due to the long-term use and comparability of standardized methods. We used data from lakes that had adult mark–recapture population estimates and juvenile Walleye (fall age-0) relative abundance estimates available during the same year beginning in 1990.

Wisconsin Department of Natural Resources adult Walleye population estimates were conducted in the spring of each year using a combination of fyke netting and nighttime electrofishing surveys. Fyke nets were set immediately after ice-out to target spawning adult Walleye and all adults captured were marked with a year-specific fin clip and released. Fyke net surveys continued daily until about 10% of the previously estimated population size was marked. The recapture event in each lake and year included electrofishing the entire lake shoreline during the peak of the Walleye spawn immediately after the marking event. Great Lakes Indian Fish and Wildlife Commission adult Walleye population estimates were conducted similarly; however, electrofishing was used as the mark and recapture gear. Adult density was estimated for each lake and year using Chapman's modification of the Petersen estimator (Ricker 1975). Population estimates were only considered acceptable if they had a coefficient of variation ≤40%. Only acceptable population estimates were considered for this study.

Walleye age-0 recruit surveys were conducted in the fall of each year and were conducted independent of recruitment status. Relative abundance of age-0 Walleye (i.e., catch per km of shoreline electrofished; CPE) was quantified by lake and year. In general, one electrofishing survey covering the entire lake shoreline (including islands) was conducted when water temperatures ranged between 10–18°C and catch-at-age (i.e., differentiating age-0 from age-1 Walleye) was determined by examination of length–frequency histograms validated by ageing fish using scales (Beard et al. 2003). Walleye recruitment in CTWI lakes is maintained in one of three ways and classified accordingly: solely or primarily natural reproduction (NR), a combination of natural reproduction and supplemental stocking (C-ST), or primarily stocking (ST). Some lakes used in our study may have been undergoing supplemental stocking or the stocking status changed over time (e.g., from NR to C-ST). Stocking of Walleye primarily occurs in the fall. If a lake was stocked, fall age-0 surveys were supposed to occur prior to the stocking event in order to estimate natural recruitment. Thus, lakes used in our study may have been undergoing stocking, but if this was the case, lake years were only included where fall age-0 surveys could be confirmed to have occurred prior to the stocking event and were thus an estimate of natural recruitment. Therefore, all Walleye age-0 data analyzed in our dataset was solely from natural recruitment.

Trends in Density-Dependent Age-0 Walleye Survival

We tested for the prevalence of compensatory or depensatory density-dependent survival in age-0 Walleye recruitment from CTWI lakes. For the purposes of these analyses, we used lake/years that had five or more sampling events that included a spring adult Walleye density estimate (number of adult fish/ha) and a fall age-0 Walleye estimate (CPE) in the same lake/year (similar to Tsehaye et al. 2016 where a minimum of 5 lake/years was required to estimate a stock–recruitment relationship for a population; Supplementary Material, Table S1).

We compared the utility of five different plausible stock–recruitment models to assess the strength of evidence for density-dependent dynamics in Walleye recruitment across lakes. Because of the benefits of improved precision in fitting complex models using hierarchical approaches and examination of the posterior distributions of parameters of interest, all models were fit using Bayesian inference (Myers and Mertz 1998; Cahill et al. 2018, 2020). Recruitment was modeled in log-space to improve model convergence and allow for comparability of model fit across models. Specifically, we fit variations of Ricker and Beverton–Holt models ignoring and including depensatory dynamics, namely:

$$(1)\quad log_e\left(R_{ij}\right)=log_e\left(\alpha_i\right)+log_e\left(S_{ij}\right), \text{assuming density} -\text{independent recruitment},$$

$$(2)\quad log_e\left(R_{ij}\right)=log_e\left(\alpha_i\right)+log_e\left(S_{ij}\right)+\beta_i S_{ij}, \quad \text{Ricker with compensatory recruitment}, \beta i<0,$$

$$(3)\quad log_e\left(R_{ij}\right)=log_e\left(\alpha_i\right)+log_e\left(S_{ij}\right)+\beta_i S_{ij}, \quad \text{Ricker allowing for depensation}, -\infty >> \beta i<\infty,$$

$$(4)\quad log_e\left(R_{ij}\right)=log_e\left(\frac{a_i S_{ij}}{b_i+S_{ij}}\right), \text{Beverton–Holt assuming compensation, and}$$

$$(5)\quad log_e\left(R_{ij}\right)=log_e\left(\frac{a_i S_{ij}{}^{d_i}}{b_i{}^{d_i}+S_{ij}{}^{d_i}}\right), \text{Beverton–Holt allowing for depensation},$$

where R_{ij} is age-0 CPE (recruitment) and S_{ij} is adult Walleye/ha (stock) for each lake i and year j, α_i is a Ricker stock productivity parameter, β_i is the density-dependent survival rate of recruits, a_i is the Beverton–Holt productivity parameter, b_i is the density-dependent parameter, and d_i is a modifier to account for depensation. We used vague priors with wide variances for each parameter (Table 1).

Models 1, 4, and 5 were fit using a hierarchical, non-centered parameterization (Carpenter et al. 2017a; Stan Development Team 2018) to improve model convergence, minimize divergent transitions, and to provide more precise parameter estimates about model dynamics at low stock sizes. All Stan code has been made available in the Supplementary Material (Supplement S1), so we only briefly describe our approach herein. Each lake-specific parameter (e.g., a_i, b_i, d_i for Models 4 and 5, or α_i for Model 1) was transformed to have a standard normal prior, e.g.,:

$$(6)\quad \tilde{a}_i \sim N(0,1)$$

from which true parameter estimates were derived as

$$(7)\quad a_i=\mu_a+\sigma_a\tilde{a}_i$$

to allow for more efficient sampling of parameter space, where μ_a and σ_a are the mean and variance of the hyperprior from which lake-specific a_i are drawn, $a_i \sim N(\mu_a, \sigma_a)$. For the same reasons, hyperprior variances (σ) were reparameterized to draw from a uniform distribution, then transformed for true parameter estimates as:

$$(8)\quad \tilde{\sigma}_a \sim Uniform\left(-\frac{\pi}{2},\frac{\pi}{2}\right)$$

$$(9)\quad \sigma_a=\left|\tan\tilde{\sigma}_a\right|$$

which equates to a half-Cauchy prior, $\sigma_a \sim Cauchy(0, 1)$.

Table 1. Priors, hyperpriors, and relevant transformations used in Bayesian stock–recruitment modeling. Subscript *i* denotes lake-specific parameter estimates. See Supplementary Material S1 for full Stan code.

Model	Parameter	Prior	Transformation
Density-independent model (1)	$log_e(\tilde{\alpha}_i)$	$N(0, 1)$	
	μ_a	$N(0, 10)$	
	σ	$Cauchy(0, 5)$	
	σ_a	$Cauchy(0, 5)$	
	$log_e(\alpha_i)$	$\mu_a + \sigma_a log_e(\tilde{\alpha}_i)$	
Ricker models (2 and 3)	$log_e(\alpha_i)$	$N(0,10)$	
	β_i	$N(0,10)$	Truncated to $\beta_i < 0$ in Model 2
	σ	$Cauchy(0,5)$	
Beverton-Holt models (4 and 5)	$\tilde{a}_i$	$N(0, 1)$	
	$\tilde{b}_i$	$N(0, 1)$	
	$\tilde{d}_i$	$N(0, 1)$	
	μ_a	$N(100, 10)$	
	μ_b	$N(100, 10)$	
	μ_d	$N(1, 5)$	
	$\tilde{\sigma_a}$	$Uniform(-\frac{\pi}{2}, \frac{\pi}{2})$	
	$\tilde{\sigma_b}$	$Uniform(-\frac{\pi}{2}, \frac{\pi}{2})$	
	$\tilde{\sigma_d}$	$Uniform(-\frac{\pi}{2}, \frac{\pi}{2})$	
	a_i		$\mu_a + \sigma_a \tilde{a}_i$
	b_i		$\mu_b + \sigma_b \tilde{b}_i$
	d_i		$\mu_d + \sigma_d \tilde{d}_i$
	σ_a		$\lvert tan(\tilde{\sigma_a}) \rvert$
	σ_b		$\lvert tan(\tilde{\sigma_b}) \rvert$
	σ_d		$\lvert tan(\tilde{\sigma_d}) \rvert$
	σ	$Cauchy(0,5)$	

Hierarchical methods for the Ricker models (Models 2 and 3) yielded poor convergence and severe shrinkage of lake-specific parameter estimates toward the global mean, limiting their utility to describe density dependence in Walleye recruitment. We instead used a non-hierarchical model estimating separate α_i and β_i parameters for each lake, which provided satisfactory model performance and improved parameter interpretability. Models were run in four chains, each using 2,000 warmup steps followed by 10,000 iterations thinned to take every 10th step. Parameter trace and density plots, $\hat{R}$ statistics, and effective sample sizes were checked to ensure mixing of all chains and model convergence. The distribution of predicted recruitment from 1,000 draws of the posterior was compared against the distribution of observed recruitment as a posterior predictive check of model performance (Supplemental Material, Figure S1) in addition to visually assessing lake-specific model fits. Analyses were conducted in Program R (R Core Team 2017) and Stan (Carpenter et al. 2017a) using package "rstan" (Stan Development Team 2018). Comparison of these models using leave-one-out cross validation and stacked Bayesian model averaged weights (R package "loo"; Vehtari et al. 2017, 2019; Yao et al. 2018) suggested that models accounting for depensation, particularly Model 5, were most useful to address our objectives (Supplemental Material, Tables S2–S7). Therefore, we report results based on the models allowing for depensation (Models 3 and 5), based on their ability to address our specific objectives, and overall utility in describing Walleye recruitment in our study lakes.

Because of its utility in interpreting β as an indicator of density-dependent dynamics in recruit survival (Quinn and Deriso 1999; Walters and Martell 2004), we used trends in the slope of Model 3 (i.e., positive or negative β) to characterize the type of density-dependence observed in age-0 Walleye survival, where compensation was identified as a negative slope and depensation as a positive slope. As an additional indicator of potential depensation, we fit Model 5 (the Beverton–Holt model accounting for depensation) and calculated the depensation parameter q using methods defined by Liermann and Hilborn (1997). Depensation, as q, is the ratio of the depensatory and the standard Beverton–Holt stock–recruitment models at 10% of the maximum observed spawner level. For $q < 1$, the stock–recruitment model is depensatory. For $q > 1$, the stock–recruitment model is compensatory (Liermann and Hilborn 1997). The value of q should not necessarily be interpreted as either depensatory or compensatory, but rather as an indicator of density independence and that recruitment may exist across a gradient of compensation and depensation. For the purpose of our manuscript, we have defined values of $q < 1$ as depensatory and values of $q > 1$ as compensatory. We calculated q_i for each study lake to evaluate among-lake patterns in density-dependent recruitment. As an indicator for the tendency of an average CTWI Walleye population to exhibit depensatory or compensatory recruitment patterns, we also calculated a global mean q (q_{μ}) from the hyperpriors μ_a, μ_b, and μ_d, and the average maximum stock size observed across all lakes in the dataset (Liermann and Hilborn 1997) and determined the posterior probability that $q_{\mu} < 1$.

RESULTS

Trends in Density-Dependent Age-0 Walleye Survival

A total of 82 CTWI Walleye populations had five or more stock–recruitment observations during 1990–2018 (Figure 2; Supplementary Material, Table S1). Using the Ricker model allowing depensation, 35 populations (43%) were classified as exhibiting depensatory juvenile survival, where age-0 Walleye survival declined with declining adult density (Figure 3a; Supplementary Material, Table S5, Figures S2, S3, S5a). The remaining 57% of populations (n = 47) exhibited on average compensatory age-0 survival with increasing age-0 Walleye survival as adult density declined. However, most of the slope estimates were near zero with wide confidence intervals, suggesting generally weak stock–recruitment relationships across populations even when the average trend was for compensation or depensation. Only a few populations were clearly depensatory or compensatory (Figure 3a; Supplementary Material, Table S5).

The depensation parameter q followed similar overall trends across lakes. Slightly more than half of the populations (n = 42) were depensatory ($q < 1$) and slightly less than half (n = 40) compensatory ($q > 1$) (Figure 3b; Supplementary Material, Table S7, Figure S4, S5B). Most lakes exhibited high uncertainty in q suggesting weak density-dependence in recruitment, although there were more lakes with strong

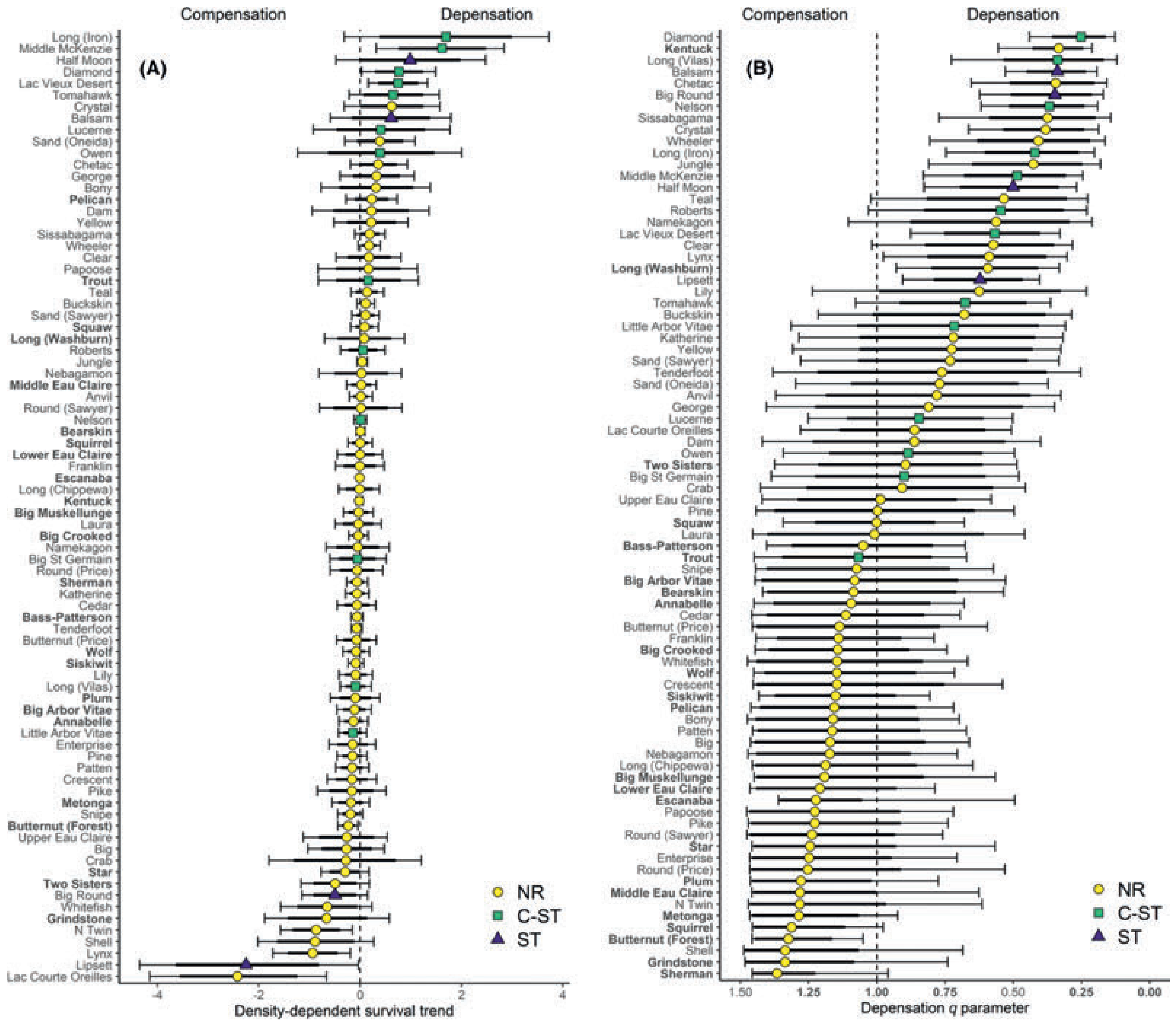

Figure 3. Posterior distributions of parameters, including posterior means (points), 80% credible intervals (heavy inner line), and 95% credible intervals (light outer line) quantifying density dependence in age-0 Walleye density-dependent survival represented as: (A) the slope of the Ricker regression β; and (B) the stock–recruitment depensation parameter q from the Beverton–Holt relationship accounting for depensation for Ceded Territory of Wisconsin Walleye populations. A depensatory population is represented by a positive β (juvenile survival declines with declining stock size) or $q<1$. Gold circles = populations supported primarily by natural reproduction (NR); green squares = populations supported by a combination of stocking and natural reproduction (C-ST); and dark blue triangles = populations supported primarily by stocking (ST). Trend lakes and Escanaba Lake are bolded.

evidence for depensation than compensation (Figure 3b, 4; Supplementary Material, Figure S4B, S5). Characterizations of recruitment dynamics based on mean recruit survival trends and q parameter estimates agreed in 70% of lakes (Supplementary Material, Tables S5, S7). Disagreements were characterized by lakes with uncertain or near-zero age-0 survival trends, but stronger depensatory dynamics in the Beverton–Holt model. Both metrics shared a pattern with a higher proportion of ST or C-ST lakes exhibiting depensatory recruitment than NR lakes. Overall, examination of the global q_{μ} posterior distribution showed a probability of about 0.89 for depensatory dynamics occurring in an average CTWI Walleye lake based on the populations examined (Figure 5).

DISCUSSION

Depensation (reduced juvenile survival at low adult stock sizes) has been implicated in the collapse or slow recovery of overexploited marine fisheries (Myers et al. 1995; Liermann and Hilborn 1997; Walters and Kitchell 2001; Hilborn et al. 2014); however, empirical evidence for this phenomenon is lacking overall and particularly for freshwater fisheries (e.g., Post et al. 2002). Walleye natural recruitment, adult density, biomass, production, and production:biomass ratios have declined significantly over time in the CTWI (Hansen et al. 2015a; Rypel et al. 2018; Embke et al. 2019). Further, climate change and associated lake warming is predicted to exacerbate these declines and potentially favor centrarchid species dominance (e.g., Largemouth Bass; Hansen et al. 2015b). Therefore, we tested for depensation (or a lack of compensation) with declining adult Walleye density as a phenomenon leading to observed declines in Walleye natural recruitment in the CTWI over time. Based on our definition of compensation and depensation (see Methods), we found that depensatory recruitment dynamics were evident in about one-half of the Walleye populations examined during 1990–2018, with a global q_{μ} posterior probability distribution suggesting that CTWI Walleye populations on average exhibit depensatory dynamics. To our knowledge, this is the first empirical evidence of this phenomenon in a freshwater fishery.

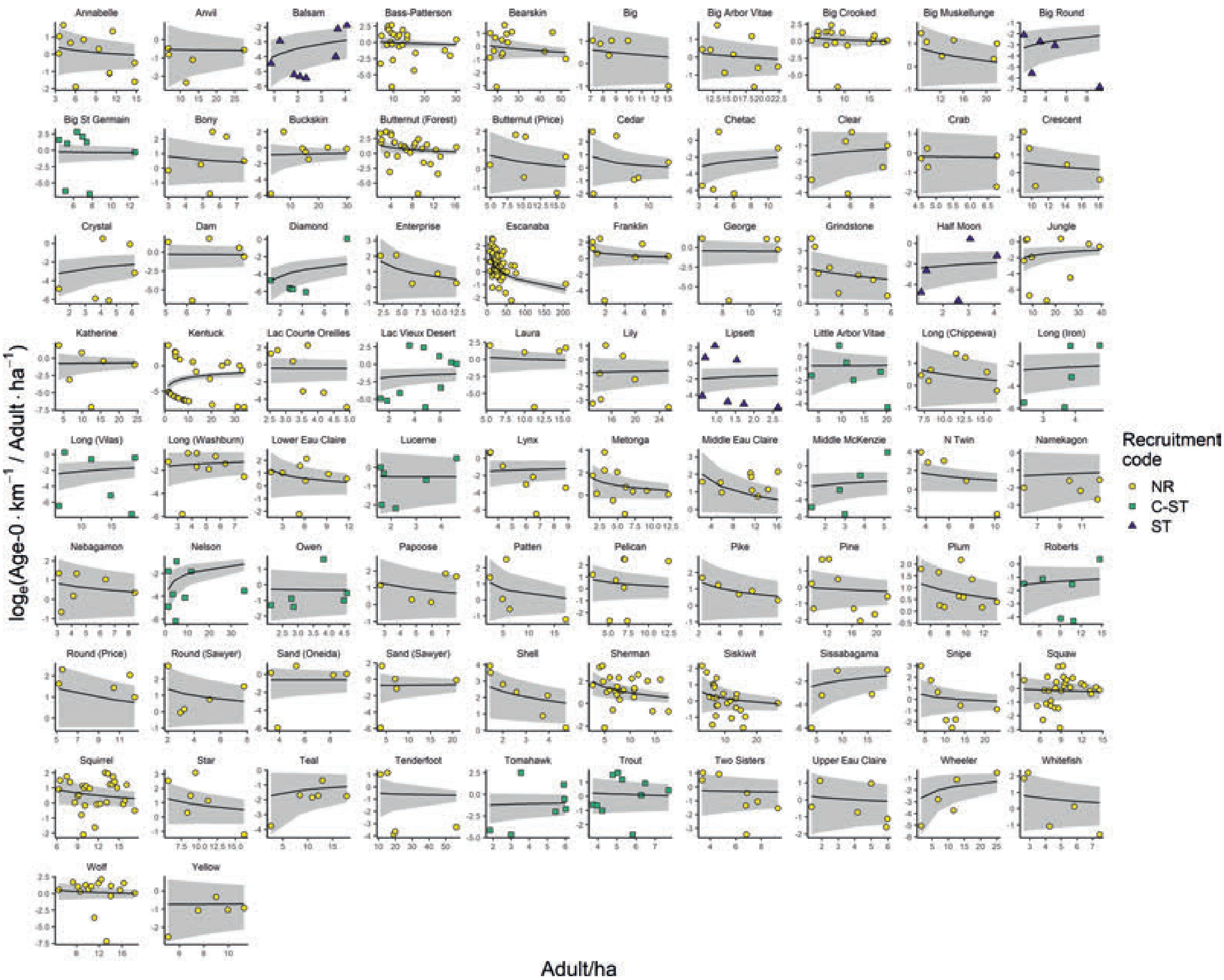

Figure 4. Lake-specific fits of the Beverton–Holt stock–recruitment model allowing for depensation (Model 5) transformed to predict observations of Walleye recruit survival ($\log_e$(age-0·km^{-1}/adults·ha^{-1})) against adult density (adults·ha^{-1}) in Ceded Territory of Wisconsin lakes. Points represent current lake recruitment status code (NR = naturally reproducing, gold circle; C-ST = combination of stocking and natural recruitment, green square; ST = stocked only, blue triangle), lines are mean predicted model fit, and shaded areas represent 95% credible intervals. Positive trends are indicative of depensatory recruit survival, while negative trends suggest compensation.

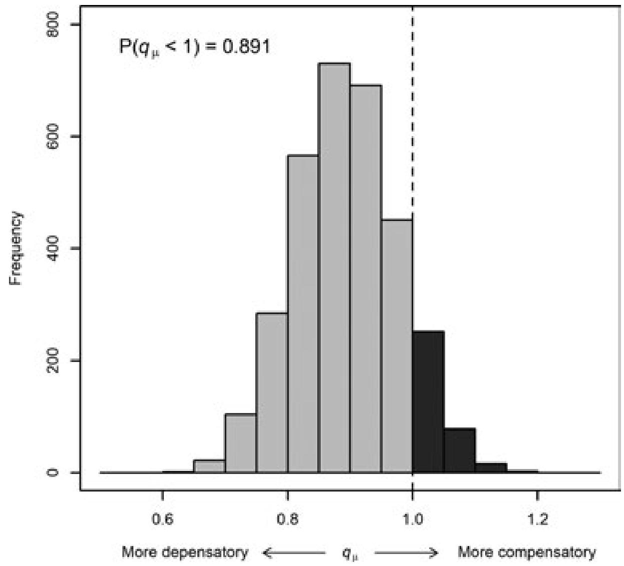

Figure 5. Frequency distribution of global average q_μ from 3,200 draws of the posterior distribution of the Beverton–Holt model allowing for depensation (Model 5). The probability that $q_\mu < 1$ is shown and indicates the probability for an average Walleye population to exhibit depensatory density-dependence in recruitment.

Depensation has been implicated as a factor leading to fishery collapse or lack of recovery through mechanisms such as Allee effects (e.g., inability to find a mate, inbreeding), predator–prey interactions (e.g., cultivation–depensation), or habitat loss. Allee effects have been used interchangeably with depensation to describe a positive correlation observed between juvenile survival and adult stock size (Hutchings 2014). A strong Allee effect suggests that there is a critical adult population size at which further reductions in population size lead to negative population growth (Allee 1931; Kramer et al. 2009). We reasoned that Allee effects due to the inability to find a mate were not a likely mechanism causing depensatory recruitment dynamics in CTWI Walleye populations. Walleye aggregate to spawn (Feiner and Höök 2015; Raabe et al. 2020) and show hyperstable relationships between harvest rates and adult stock size in tribal spear fisheries that target spawning fish (Mrnak et al. 2018). Due to this aggregatory spawning behavior, the inability to find a mate is unlikely. Further, stocking is a pervasive tool used to enhance Walleye abundance such that adult abundance decline below a critical threshold or inbreeding is unlikely in the absence of other mechanisms proposed to cause depensation (Raabe et al. 2020).

The depensatory recruitment dynamics observed in CTWI Walleye populations were more likely related to predator–prey interactions and environmental change; two common mechanisms often implicated to lead to depensation and commonly linked to Walleye declines in Wisconsin (Walters and Kitchell 2001; Post et al. 2002; De Roos and Persson 2002; Carpenter et al. 2017b). De Roos and Persson (2002) and Walters and Kitchell (2001) provided two examples of predator–prey interactions leading to population collapse or inability to recover following fishery closure. Using Atlantic Cod *Gadus morhua* as an example, Walters and Kitchell (2001) suggested that overharvest of adults reduced predatory control of predators of juvenile cod (e.g., trophic triangle, cultivation–depensation) leading to the inability of the adult population to recover due to persistent food web change. De Roos and Persson (2002) predicted a similar outcome when two top predators foraged on one another's juveniles and one top predator was reduced in abundance due to overexploitation or environmental change. Similar predator–prey dynamics may be influencing CTWI Walleye. Recent increases in centrarchid abundance, especially Largemouth Bass due to climate change (Hansen et al. 2015b) and prevalence of voluntary catch-and release in angling fisheries (Fayram et al. 2005; Hansen et al. 2015b; Sass and Shaw 2019), could potentially increase predatory or competitive interactions with juvenile Walleye. Evidence for negative interactions between Walleye and Largemouth Bass in Wisconsin lakes have been mixed. Fayram et al. (2005) found that survival of stocked Walleye was negatively correlated with Largemouth Bass relative abundance and provided evidence of diet overlap between juveniles of the two species as well as some predation on juvenile Walleye by Largemouth Bass. Kelling et al. (2016) found little evidence for direct predation of juvenile Walleye by Largemouth Bass. Coincident high exploitation of Walleye and/or habitat loss in these systems (Carpenter et al. 2017b; Embke et al. 2019) could have also reduced the ability of adult Walleye to control centrarchids via predation, releasing additional predation pressure on juvenile Walleye. Additional study of these inter-specific interactions is needed to further support this plausible depensatory mechanism negatively influencing Walleye populations.

A critical adult population size, along with suitable spawning and juvenile habitat, is required for population sustainability and to keep fisheries in a "safe operating space" (Carpenter et al. 2017b). Another plausible mechanism for depensatory recruitment dynamics in CTWI Walleye populations is the loss or degradation of suitable spawning and juvenile rearing habitat manifested through climate change (e.g., loss of thermal-optical habitat, species dominance, drought), lakeshore residential development, and invasive species. Specifically, climate change is predicted to reduce thermal-optical habitat availability for Walleye (Lester et al. 2004), while promoting other warmwater species (i.e., centrarchids; Hansen et al. 2015b, 2017). Warmer waters and increased growing seasons may also increase vegetation growth and biomass in littoral zones, altering water clarity and reducing littoral spawning and rearing habitat suitability for Walleye (Feiner and Höök 2015). Increasing severity of drought conditions resulting in lower lake levels will expose essential littoral spawning habitat and reduce recruitment and productivity (Gaeta et al. 2014). Lakeshore residential development could have similar effects by degrading littoral habitats and fishery productivity through the loss of allochthonous nutrient inputs (Sass et al. 2019), removal of coarse woody habitat (Sass et al. 2006), and reductions in gravel/cobble habitats important for spawning (Raabe et al. 2020). Although each of these factors and/or interactions among them could erode the productivity of Walleye populations and result in declining recruitment with declining adult abundance (Rypel et al. 2018; Embke et al. 2019), we can only speculate on the precise mechanisms resulting in depensatory dynamics of CTWI Walleye populations. Further study is required to test for their respective influences on Walleye sustainability.

Our results and those of Embke et al. (2019), Rypel et al. (2018), and Tsehaye et al. (2016) suggest that CTWI Walleye populations operate along a gradient of depensatory/

compensatory recruitment dynamics and productivities. Walleye populations in the CTWI ranged from highly compensatory to highly depensatory with mean age-0 Walleye survival trend and q values ranging from −2.48 to 1.80 and 0.25 to 1.35, respectively. Similarly, Tsehaye et al. (2016) found a wide range of resilience to fishing in CTWI Walleye populations, which is supported by the range of density dependence we observed in this study. Populations with a strong compensatory recruitment response should be most resilient to exploitation, which is demonstrated by certain Walleye populations in Tsehaye et al. (2016) and by a trend toward populations maintained by natural reproduction to exhibit compensatory recruitment via age-0 survival and q. On the other hand, populations with depensatory (juvenile survival, $q < 1$) or weakly compensatory recruitment dynamics may not be as resilient to exploitation, with higher probabilities of collapse even at relatively low exploitation rates. For example, our results and those of Tsehaye et al. (2016) suggested that Lac Vieux Desert, Vilas County, showed highly depensatory recruitment dynamics and was weakly resilient to collapse with exploitation. Conversely, Grindstone Lake, Sawyer County, exhibited strong compensatory recruitment and was robust to high levels of exploitation. Interestingly, the trend lakes and Escanaba Lake (lakes with the highest sample sizes in our dataset) showed similar β and q values to other lakes with less data. The trend lakes and Escanaba Lake have the most monitoring data because they generally maintain stable, naturally reproducing populations and are some of the most important to the tribal and recreational fisheries of northern Wisconsin. The similarity of these lakes in β and q with other less monitored lakes further suggests that adult abundance is not a strong predictor of Walleye recruitment (Madenjian et al. 1996; Hansen et al. 1998; Beard et al. 2003; Shaw et al. 2018; Feiner et al. 2019). Because CTWI Walleye populations vary widely in their recruitment dynamics and productivities (Rypel et al. 2018; Embke et al. 2019), and subsequently their resilience to exploitation (Tsehaye et al. 2016), identification of critical thresholds in adult population size may be key for preventing the elicitation of depensatory recruitment dynamics that would push Walleye populations outside of a "safe operating space" (Carpenter et al. 2017b), particularly given our finding of the posterior probability distribution of a global q_{μ} being about 0.89 and skewed towards depensatory dynamics among the populations examined. Fishing pressure and population productivity are integral to defining the "safe operating space" for fisheries management (Carpenter et al. 2017b); thus, understanding how environmental variables and harvest drive recruitment dynamics is crucial for protecting valuable fisheries with varying resilience to exploitation.

To date, most examinations of depensation in fish stocks have derived from marine commercial fisheries (Myers et al. 1995; Liermann and Hilborn 1997; Hilborn et al. 2014). Even then, clear evidence for depensation as a driver of collapse or failed recovery from overexploitation has been weak (Walters and Kitchell 2001; Liermann and Hilborn 2001; Hilborn et al. 2014). In freshwater fisheries, depensation as a phenomenon causing fisheries collapse has largely been speculative outside of a few case studies (Post et al. 2002; De Roos and Persson 2002). It is likely that data limitations have prevented the identification of depensatory dynamics in many freshwater and marine fisheries. For example, most fisheries datasets do not have sufficient long-term fishery-independent recruitment and abundance data across many discrete populations or stocks to test for depensation, particularly when stock sizes are low (Myers et al. 1995). Further, the use of marine commercial landing fishery-dependent data may preclude the identification of depensation simply due to necessary assumptions made about recruitment processes (e.g., uncertain stock–recruitment relationships) and actual abundance (e.g., commercial landings are proportional to actual abundance) required to manage these fisheries. In contrast, our study examined recruitment dynamics across many discrete Walleye populations using fisheries-independent data spanning 3 decades and a wide range of adult densities and recruitment levels. Our findings suggest that depensatory recruitment dynamics may be more prevalent in broadcast, non-parental guarding, freshwater and marine species where the primary drivers of recruitment are environmental and highly variable (e.g., water temperature, forage availability); however, additional research is needed to support this assertion. Further, we reason that depensation may be more likely in inland lake freshwater fishes due to their general inability to disperse to find more suitable environmental conditions and habitat (Lynch et al. 2016; Sass et al. 2017). Therefore, our results provide some of the clearest empirical evidence to date for depensatory recruitment dynamics in an exploited freshwater fishery.

In general, fisheries management relies upon compensatory recruitment to rebuild exploited fish stocks (Ricker 1954). However, many examples of collapsed fisheries or those that only slowly or never recovered following fishery closure exist (Walters and Kitchell 2001; Post et al. 2002). These observations of invisible collapses or irreversibility following fishery closures could be attributed to unidentified depensation or at least a lack of compensatory recruitment at low adult stock size, potentially caused by factors such as exploitation, predator–prey interactions, and/or habitat loss (Walters and Kitchell 2001; Post et al. 2002). Given the observations in our study, it is important to point out that many populations exhibited weak density dependence in recruitment. Even though depensation was only clearly indicated in a few populations, the general lack of strong compensatory dynamics across Walleye populations could leave these stocks vulnerable to environmental fluctuations, overexploitation, and slow or no response to rehabilitation efforts through the same mechanisms outlined above. Thus, the identification of population-specific critical population sizes below which depensatory recruitment dynamics may occur, and prioritizing conservative management to avoid these thresholds, may be imperative for sustaining and managing fish stocks in a "safe operating space" for the long term (Carpenter et al. 2017b). Unresponsive or delayed management may result in the inability of stocks to recover in the absence of labor intensive and expensive management actions (e.g., chemical rehabilitation, whole-lake fish removals; Shertzer and Prager 2007). Our results suggest that depensation should be considered in fisheries stock assessments, particularly those where the primary drivers of recruitment are environmental, variable, and uncertain, as suggested previously by Ricker (1954).

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REFERENCES

Allee, W. C. 1931. Co-operation among animals. American Journal of Sociology 37(3):386–398.

Beard, T. D., S. W. Hewett, Q. Yang, R. M. King, and S. J. Gilbert 1997. Prediction of angler catch rates based on Walleye population density. North American Journal of Fisheries Management 17(3):621–627.

Beard, T. D., P. W. Rasmussen, S. Cox, and S. R. Carpenter 2003. Evaluation of a management system for a mixed Walleye spearing and angling fishery in northern Wisconsin. North American Journal of Fisheries Management 23(2):481–491.

Britten, G. L., M. Dowd, and B. Worm 2016. Changing recruitment capacity in global fish stocks. Proceedings of the National Academy of Sciences 113(1):134–139.

Cahill, C. L., S. C. Anderson, A. J. Paul, L. MacPherson, M. G. Sullivan, B. van Poorten, C. J. Walters, and J. R. Post 2020. A spatial–temporal approach to modeling somatic growth across inland recreational fisheries landscapes. Canadian Journal of Fisheries and Aquatic Sciences 77(11):1822–1835.

Cahill, C. L., S. Mogensen, K. L. Wilson, A. Cantin, R. N. Sinnatamby, A. J. Paul, P. Christensen, J. R. Reilly, L. Winkel, A. Farineau, and J. R. Post 2018. Multiple challenges confront a high-effort inland recreational fishery in decline. Canadian Journal of Fisheries and Aquatic Sciences 75(9):1357–1368.

Carpenter B., A. Gelman, M. D. Hoffman, D. Lee, B. Goodrich, M. Betancourt, M. Brubaker, J. Guo, P. Li, and A. Riddell 2017*a*. Stan: a probabilistic programming language. Journal of Statistical Software 76(1):1–32.

Carpenter, S. R., W. A. Brock, G. J. A. Hansen, J. F. Hansen, J. M. Hennessy, D. A. Isermann, E. J. Pedersen, K. M. Perales, A. L. Rypel, G. G. Sass, T. D. Tunney, and M. J. V. Zanden 2017b. Defining a safe operating space for inland recreational fisheries. Fish and Fisheries 18(6):1150–1160.

De Roos, A. M., and L. Persson 2002. Size-dependent life-history traits promote catastrophic collapses of top predators. Proceedings of the National Academy of Sciences 99(20):12907–12912.

Embke, H. S., A. L. Rypel, S. R. Carpenter, G. G. Sass, D. Ogle, T. Cichosz, J. Hennessy, T. E. Essington, and M. J. V. Zanden 2019. Production dynamics reveal hidden overharvest of inland recreational fisheries. Proceedings of the National Academy of Sciences 116(49):24676–24681.

Fayram, A. H., M. J. Hansen, and T. J. Ehlinger 2005. Interactions between Walleyes and four fish species with implications for Walleye stocking. North American Journal of Fisheries Management 25(4):1321–1330.

Feiner, Z. S., and T. O. Höök. 2015. Environmental biology of percid fishes. Pages 61–100 *in* P. Kestemont, K. Dabrowski, and R. C. Summerfelt, editors. Biology and culture of percid fishes, first edition. Springer Netherlands, Dordrecht.

Gaeta, J. W., G. G. Sass, and S. R. Carpenter 2014. Drought-driven lake level decline: effects on coarse woody habitat and fishes. Canadian Journal of Fisheries and Aquatic Sciences 71(2):315–325.

Goodyear, C. P. 1980. Compensation in fish populations. Pages 253–280 *in* C. H. Hocutt, and J. R. Stauffer, Jr., editors. Biological monitoring of fish. Lexington Books, DC Heath and Company, Lexington, Massachusetts.

Hansen, G. J. A., S. R. Carpenter, J. W. Gaeta, J. M. Hennessy, and M. J. Vander Zanden 2015a. Predicting Walleye recruitment as a tool for prioritizing management actions. Canadian Journal of Fisheries and Aquatic Sciences 72(5):661–672.

Hansen, G. J. A., S. R. Midway, and T. Wagner 2017. Walleye recruitment success is less resilient to warming water temperatures in lakes with abundant Largemouth Bass populations. Canadian Journal of Fisheries and Aquatic Sciences 75(1):106–115.

Hansen, J. F., G. G. Sass, J. W. Gaeta, G. J. A. Hansen, D. A. Isermann, J. Lyons, and M. J. Vander Zanden. 2015b. Largemouth Bass management in Wisconsin: intra-and inter-specific implications of abundance increases. Pages 193–206 *in* M. D. Tringali, J. M. Long, and T. W. Birdsong, editors. Black bass diversity: multidisciplinary science for conservation. American Fisheries Society, Bethesda, Maryland.

Hilborn R., D. J. Hively, O. P. Jensen, and T. A. Branch 2014. The dynamics of fish populations at low abundance and prospects for rebuilding and recovery. ICES Journal of Marine Science 71(8):2141–2151.

Hilborn, R., and C. J. Walters 2013. Quantitative fisheries stock assessment: choice, dynamics and uncertainty. Springer Science and Business Media, Berlin.

Hutchings, J. A. 2014. Renaissance of a caveat: Allee effects in marine fish. ICES Journal of Marine Science 71(8):2152–2157.

Kelling, C. J., D. A. Isermann, B. L. Sloss, and K. N. Turnquist 2016. Diet overlap and predation between Largemouth Bass and Walleye in Wisconsin lakes using DNA barcoding to improve taxonomic resolution. North American Journal of Fisheries Management 36(3):621–629.

Kempinger, J. J., W. S. Churchill, G. T. Priegel, and L. M. Christensen 1975. Estimate of abundance, harvest, and exploitation of the fish population of Escanaba Lake, Wisconsin, 1946–1969. Wisconsin Department of Natural Resources, WDNR Technical Bulletin 84, Madison.

Kramer, A. M., B. Dennis, A. M. Liebhold, and J. M. Drake 2009. The evidence for Allee effects. Population Ecology 51(3):341–354.

Lester, N. P., A. J. Dextrase, R. S. Kushneriuk, M. R. Rawson, and P. A. Ryan 2004. Light and temperature: key factors affecting Walleye abundance and production. Transactions of the American Fisheries Society 133(3):588–605.

Liermann, and Hilborn 2001. Depensation: evidence, models and implications. Fish and Fisheries 2(1):33–58.

Liermann, M., and R. Hilborn 1997. Depensation in fish stocks: a hierarchic Bayesian meta-analysis. Canadian Journal of Fisheries and Aquatic Sciences 54(9):1976–1984.

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

Mrnak, J. T., S. L. Shaw, L. D. Eslinger, T. A. Cichosz, and G. G. Sass 2018. Characterizing the angling and tribal spearing Walleye fisheries in the Ceded Territory of Wisconsin, 1990–2015. North American Journal of Fisheries Management 38(6):1381–1393.

Myers, R. A., N. J. Barrowman, J. A. Hutchings, and A. A. Rosenberg 1995. Population dynamics of exploited fish stocks at low population levels. Science 269(5227):1106–1108.

Myers, R., and G. Mertz 1998. Reducing uncertainty in the biological basis of fisheries management by meta-analysis of data from many populations: a synthesis. Fisheries Research 37(1):51–60.

Neuenhoff, R. D., D. P. Swain, S. P. Cox, M. K. McAllister, A. W. Trites, C. J. Walters, and M. O. Hammill 2018. Continued decline of a collapsed population of Atlantic Cod (*Gadus morhua*) due to predation-driven Allee effects. Canadian Journal of Fisheries and Aquatic Sciences 76(1):168–184.

Post, J. R., M. Sullivan, S. Cox, N. P. Lester, C. J. Walters, E. A. Parkinson, A. J. Paul, L. Jackson, and B. J. Shuter 2002. Canada's recreational fisheries: the invisible collapse? Fisheries 27(1):6–17.

Quinn, T. J., and R. B. Deriso 1999. Quantitative fish dynamics. Oxford University Press, Oxford, UK.

R Core Team. 2017. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna.

Raabe, J. K., J. A. VanDeHey, D. L. Zentner, T. K. Cross, and G. G. Sass. 2020. Walleye inland lake habitat: considerations for successful natural recruitment and stocking in North Central North America. Lake and Reservoir Management 1–25.

Ricker, W. E. 1954. Stock and recruitment. Journal of the Fisheries Research Board of Canada 11(5):559–623.

Ricker, W. E. 1975. Computation and interpretation of biological statistics of fish populations. Bulletin of the Fisheries Research Board of Canada 191.

Rypel, A. L., D. Goto, G. G. Sass, and M. J. Vander Zanden. 2018. Eroding productivity of Walleye populations in northern Wisconsin lakes. Canadian Journal of Fisheries and Aquatic Sciences.

Sass, G. G., J. F. Kitchell, S. R. Carpenter, T. R. Hrabik, A. E. Marburg, and M. G. Turner. 2006. Fish community and food web responses to a whole-lake removal of coarse woody habitat. Fisheries 31(7):321–330.

Sass, G. G., A. L. Rypel, and J. D. Stafford. 2017. Inland fisheries habitat management: lessons learned from wildlife ecology and a proposal for change. Fisheries 42(4):197–209.

Sass, G. G., and S. L. Shaw. 2019. Catch-and-release influences on inland recreational fisheries. Reviews in Fisheries Science and Aquaculture 28:211–227.

Sass, G. G., S. L. Shaw, T. P. Rooney, A. L. Rypel, J. K. Raabe, Q. C. Smith, T. R. Hrabik, and S. T. Toshner. 2019. Coarse woody habitat and glacial lake fisheries in the Midwestern United States: knowns, unknowns, and an experiment to advance our knowledge. Lake and Reservoir Management 35(4):382–395.

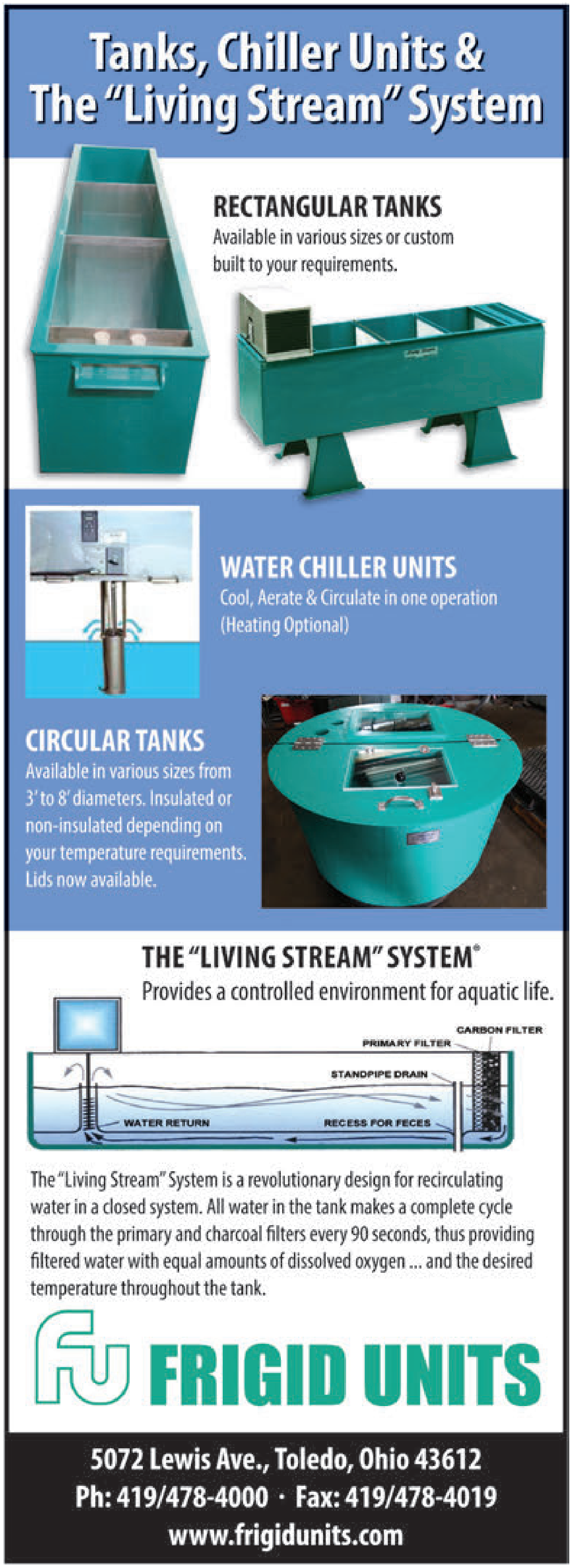
Shertzer, K. W., and M. H. Prager. 2007. Delay in fishery management: diminished yield, longer rebuilding, and increased probability of stock collapse. ICES Journal of Marine Science 64(1):149–159.
Stan Development Team. 2018. RStan: the R interface to Stan.
Stavins, R. N. 2011. The problem of the commons: still unsettled after 100 years. American Economic Review 101(1):81–108.
Tsehaye, I., B. M. Roth, and G. G. Sass. 2016. Exploring optimal Walleye exploitation rates for northern Wisconsin Ceded Territory lakes using a hierarchical Bayesian age-structured model. Canadian Journal of Fisheries and Aquatic Sciences 73(9):1413–1433.
Vehtari, A., J. Gabry, M. Magnusson, Y. Yao, P. Bürkner, T. Paananen, and A. Gelman. 2019. loo: Efficient leave-one-out cross-validation and WAIC for Bayesian models.
Vehtari, A., A. Gelman, and J. Gabry. 2017. Practical Bayesian model evaluation using leave-one-out cross-validation and WAIC. Statistics and Computing 27(5):1413–1432.
Walters, C., and J. F. Kitchell. 2001. Cultivation/depensation effects on juvenile survival and recruitment: implications for the theory of fishing. Canadian Journal of Fisheries and Aquatic Sciences 58(1):39–50.
Walters, C. J., and S. J. D. Martell. 2004. Fisheries ecology and management. Princeton University Press, Princeton, New Jersey.
Yao, Y., A. Vehtari, D. Simpson, and A. Gelman. 2018. Using stacking to average Bayesian predictive distributions (with discussion). Bayesian Analysis 13(3):917–1007.

SUPPORTING INFORMATION

Additional supplemental material may be found online in the Supporting Information section at the end of the article.

Table S1-7

Supplementary Material AFS



FEATURE

Mexican Small-Scale Fisheries Reveal New Insights into Low-Carbon Seafood and "Climate-Friendly" Fisheries Management

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Fishing at sunset. Photo credit: Octavio Aburto/Mares Mexicanos

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As a society, we are confronted with the question of how best to feed an expanding human population, and some have pointed to seafood as a "climate-friendly" option. To date, the contributions of small-scale fisheries (SSFs) have been largely excluded from studies on food footprint. Here, we calculated the Emission Intensity profiles for seven seafood types generated by Mexican SSFs. Based on these results—which indicate that there exist several low-carbon SSFs in Northwestern Mexico—we provide a coarse approximation for the total carbon footprint of Mexico's motorized small-scale fleet. Finally, we scrutinize the utility of non-fuel data (such as GPS data) in predicting fuel consumption/carbon emissions across SSFs. To our knowledge, this is the first life-cycle assessment to compare multiple seafood products generated by Mexican SSFs, and the first published link between tracking data and carbon accounting for SSFs specifically. We discuss how these results, in combination with insights gained from monitoring efforts in Northwestern Mexico, might be used to inform and incentivize "climate-friendly" fisheries management. While carbon footprint represents just one component of sustainability, this article serves as a helpful case study for those preoccupied with carbon accounting and fishers sustainability in traditionally data-limited scenarios.

INTRODUCTION

Social–ecological functioning on our planet faces radical disruption due to anthropogenic climate change (IPCC 2018; IPBES 2019), with nature, Indigenous peoples, and low-income communities projected to bear severe climate injustices (IPCC 2018; IPBES 2019; Whyte 2019). Simultaneously, we are confronted with the question of how best to feed an expanding human population on a planet where increasing climate instability already threatens food security (IPCC 2018; FAO 2019). Some studies point to seafood as a source of "climate-friendly" protein (Hilborn et al. 2018)—that is, protein which has a negative, neutral, or low carbon footprint—while others are less conclusive (Nijdam et al. 2012).

Of the research that provides estimates for carbon dioxide (CO_2) or CO_2-equivalent (CO_2e) emissions associated with food, only a handful report information about seafood landed in small-scale fisheries (SSFs; Kelleher and Mills 2012; Alder et al. 2018). This underrepresentation of SSFs in the footprint literature is remarkable, given their contributions to the global food system. Worldwide, SSFs provide about one-half of all seafood landed for direct consumption, directly employ over 40 million people, and support many more millions in the post-production sector (Kelleher and Mills 2012; Alder et al. 2018). Their exclusion from the footprint literature is primarily attributed to lack of data (e.g., Hilborn et al. 2018; Parker et al. 2018), and because it can be difficult to make "generalizable" conclusions about them (Smith and Basurto 2019). Further, we speculate that emissions from SSFs are understudied due to the incorrect assumption that SSFs are too small to substantively contribute to food security (see Too Big to Ignore; Chuenpagdee 2019).

Here, we explore the carbon footprints associated with seafood from Mexico's SSFs, based on over 4,900 catch records reported by fishers (Mascareñas-Osorio et al. 2020). We provide Emission Intensity estimates per kilogram of wet weight and kilogram of protein, followed by a coarse approximation for the carbon footprint produced by the country's motorized (marine) small-scale fleet (defined as boats <12 m; FAO 2003, 2019). Finally, we demonstrate that GPS data can be used to predict the fuel footprint of SSF activities as a proxy for carbon emissions. To the best of our knowledge, this is the first carbon assessment of SSF products in Mexico, and the first published link between geospatial tracking data and carbon accounting in SSFs specifically. We conclude with a discussion about how this information might be leveraged to inform climate-friendly fisheries management in Mexico and beyond.

METHODS

Collecting GPS, Fuel Use, and Landings Data

Scientists with the Gulf of California Marine Program (GCMP) have worked collaboratively with small-scale fishers for over a decade to collect fisheries data from eight communities along the Baja California peninsula and around the Gulf of California, Mexico (Figure 1). This fisheries monitoring program employs portable GPS tracking devices to populate an SSF database with thousands of fishing tracks (> 25,000). Many of these tracks are appended with catch data reported by fishers. Approximately 4,900 of these records were single-species trips with information about geospatial movement, catch, and fuel consumption, collected from the years 2013–2018; these records represent the universe of data we used as our primary sample (Figure 2). The GCMP dataset (Mascareñas-Osorio et al. 2020) is assumed

Figure 1. A map showing the eight different communities in which we work and have collected samples from. (Map of Baja California Peninsula courtesy of Wikimedia commons, available: http://bit.ly/3uZ6keZ)

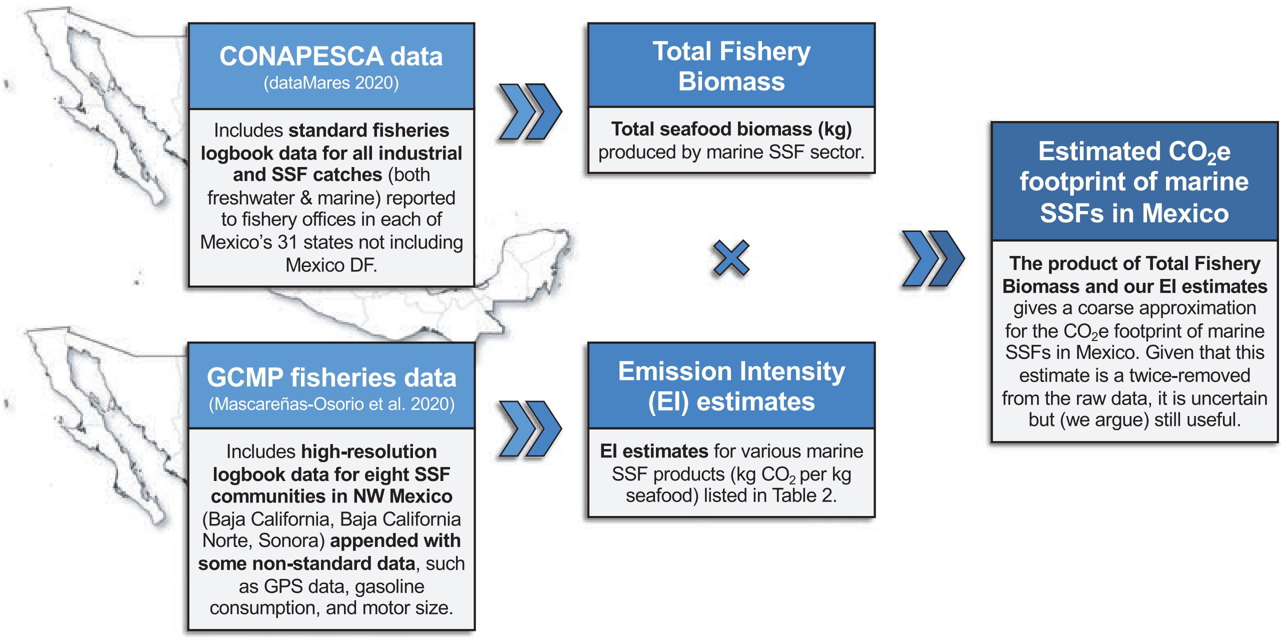


Figure 2. Shows the flow of data used throughout our analyses. Here, SSF = small-scale fisheries, GCMP = Gulf of California Marine Program, and CONAPESCA = Comisión Nacional de Acuacultura y Pesca.

to be representative of SSFs in Mexico (see Supplemental Material) and is available by request at dataMares.ucsd.edu.

Classing Organisms

In both the data set we collected (Mascareñas-Osorio et al. 2020), and in a supporting data set provided by Mexico's Comisión Nacional de Acuacultura y Pesca (CONAPESCA; dataMares 2020; Figure 2), taxa are reported to lowest taxonomic level possible. We grouped each taxa into 1 of 11 organismal classes: (1) small pelagic fishes (<30 cm), (2) large pelagic fishes (> 30 cm), (3) residential demersal fishes, (4) non-residential demersal fishes, (5) demersal molluscs, (6) non-shrimp crustaceans, (7) shrimp/prawns (hereafter shrimp), (8) cephalopods, (9) echinoderms, (10) primary producers, or (11) other.

In most cases, the class to which an organism was assigned was obvious and indisputable. However, some of the demersal fishes were difficult to class, given the diversity of life-history strategies these fish do, or could theoretically, employ. For some demersal fishes, their behavior and natural history are not well known. Here, "resident" refers to demersal fishes with high site fidelity and/or those consistently associated with complex substrate or biogenic structure (e.g., reefs, kelp forests, seagrass meadows, or mangroves). These fishes do not frequently traverse pelagic waters. We assigned resident versus non-resident status to demersal fishes based on: (1) known life history; (2) a preponderance of evidence one way or another, plus consensus among authors using FishBase (https://www.fishbase.se/; Froese and Pauly 2020) as well as other publicly available sources; or, as a last resort, (3) the known life history of the species' congener or family member. To give two examples of how this worked, a study by TinHan et al. (2014) found that, of individuals sampled, 50% of Leopard Grouper *Mycteroperca rosacea* showed high site fidelity, versus only 25% of Yellow Snapper *Lutjanus argentiventris*; we classified these fish as resident and non-resident species, respectively.

The CONAPESCA data included records pertaining to 527 distinct taxa spanning all 11 classes, 462 of which we included in this analysis. The remaining 65 taxa (which comprised 7.0% of landed biomass) were identified as (11) other and omitted from our analysis; this catch-all category consisted of freshwater species, unidentified bycatch, unspecified organisms, and a small number of cnidarians. Within the data we collected (Mascareñas-Osorio et al. 2020), 39 taxa were observed (Table 1), representing classes (1)–(7) and 32 genera. Of all landed biomass reported to CONAPESCA (dataMares 2020), 28.6% of biomass was derived from these genera specifically.

Calculating Emission Intensity Estimates for Different Types of Seafood

An Emission Intensity (EI) estimate tells us the emission rate of CO_2e, or the global warming potential per kilogram of product. These estimates are useful for comparing carbon footprint between foods and allow us to approximate the total emissions generated by a fishing fleet, using landings data alone (see Figure 2). Very often, EI estimates refer to the live/wet weight of product, but can also refer to butchered/filleted weight (Nijdam et al. 2012). We calculated EI estimates for each class of organism based on samples of seafood *wet weight* and fuel consumption (Mascareñas-Osorio et al. 2020). To encourage comparison between our EI estimates and those previously published, we applied estimation methods approximately consistent with Parker et al. (2018), with some minor caveats outlined below.

Out of 5,295 trips complete with gasoline data, less than 8% were flagged as multi-species trips. Thus, to avoid the numerous uncertainties associated with portioning fuel consumption among multiple species (Vázquez-Rowe et al. 2012), we only considered single-species trips ($n_{\text{single-species trips}}$ = 4,939 samples). Unlike Parker et al. (2018), whose EI estimates are global but largely informed by industrial fleets powered by marine diesel,

Table 1. Lists the 39 taxa represented by the samples we collected in Northwestern Mexico (Mascareñas-Osorio et al. 2020), grouped by class.

Small pelagic fish (< 30 cm)	Non-resident demersal fish
Clupeidae spp.	*Cynoscion othonopterus*
Sardinops sagax	*Cynoscion* spp.
	Gnathanodon speciosus
Large pelagic fish (> 30 cm)	*Lutjanus peru*
Atractoscion nobilis	*Lutjanus* spp.
Isurus oxyrinchus	*Micropogonias megalops*
Mobula thurstoni	*Mulloidichthys dentatus*
Mustelus californicus	*Paralichthys californicus*
Prionace glauca	*Stereolepis gigas*
Rhinoptera steindachneri	
Scomberomorus concolor	**Demersal molluscs**
Seriola lalandi	*Chione californiensis*
unspecified sharks	*Hexaplex* spp.
	Panopea generosa
Resident demersal fish	*P. globosa*
Balistes polylepis	
Caulolatilus princeps	**Non-shrimp crustaceans**
Epinephelus labriformis	*Callinectes bellicosus*
Hyporthodus niphobles	*Panulirus interruptus*
Mugil spp.	
Mycteroperca jordani	**Shrimp**
M. rosacea	*Farfantepenaeus californiensis*
Paralabrax maculatofasciatus	*Litopenaeus stylirostris*
P. nebulifer	
Paranthias colonus	
Sphoeroides annulatus	

we calculated emissions borne from the combustion of gasoline (used by Mexican SSFs). We assumed a fuel-to-emissions conversion of 2.8 kg CO_2e/L of gasoline, accounting for the direct (2.3 kg CO_2e/L; Natural Resources Canada 2014) and indirect (0.5 kg CO_2e/L; DEFRA 2011) emissions associated with combustion and upstream production. We assumed that non-fuel emissions directly associated with fishing contributed an additional 10% to total fishing emissions (supported by Gulbrandsen 2012), accounting for CO_2e sources like the production/consumption of ice. All data analysis was performed using R version 4.0.3, and graphs were generated using ggplot2.

To obtain EI estimates for each class of organism, we first generated EI estimates for individual trips by multiplying reported fuel consumption (L) by a factor of 3.11 CO_2e/L and dividing by the wet weight of catch (kg) reported for each entry. To limit the influence of outliers, we applied a 95% winsorization to all EI estimates (R DescTools package), except for small-pelagic fishes where n = 7. Using this data set, we produced mean EI estimates for classes (1)–(7) and bootstrapped a 95% confidence interval for each (R boot package). Due to lack of data, we were unable to generate EI estimates for classes (8) cephalopods, (9) echinoderms, and (10) primary producers, which are fished throughout Mexico and account for 22.7% total landed biomass reported to CONAPESCA (dataMares 2020).

Comparing to Other Types of Animal Protein

To contextualize our results for seafood landed by SSFs, versus other sources of protein, we provide an approximation for CO_2e emissions per kilogram of protein, derived from each class of organism (Table 2), employing methods approximately consistent with Nijdam et al. (2012) and Parker et al. (2018). We assumed protein content was equal to 20% of total edible catch (Nijdam et al. 2012; Parker et al. 2018), which we approximated as 40% of landed biomass (Nijdam et al. 2012; Parker et al. 2018), unless the catch was marked as prepared in some way. For example, about half of all entries were reported as having been "gutted," "deshelled," "beheaded," or otherwise butchered. We treated these landings as *de facto* edible catch, while all other records were assumed to report unprocessed wet weight. Following this transformation, we multiplied the CO_2e estimate for edible catch by a factor of 0.2 to obtain kg CO_2e/kg protein. As was the case for our EI estimates, we winsorized estimates for CO_2e per kilogram of protein at the 95% level (grouped by class, sans small pelagics).

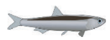
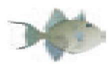
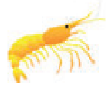
Unlike Parker et al. (2018)—though consistent with other "cradle-to-gate" life-cycle assessments (Vázquez-Rowe et al. 2012)—we assumed that the downstream emissions associated with processing and distribution of these products were equal to zero, primarily because the value chains of Mexican SSF products are non-uniform and poorly resolved. Thus, the estimates for EI per kilogram of protein reported here are conservative and may not reflect a 100% assessment of life-cycle emissions, but close to it. (Note that, when approximating the CO_2e emissions per kg of edible protein, Parker et al. [2018] added an additional 0.5 kg per landed kg of seafood. If we were to apply this extra source of emissions to our calculations, our estimates for emissions per kg of protein would increase by ~16%.)

Estimating Carbon Footprint of Mexico's Marine SSFs

To calculate the carbon footprint for marine SSFs in Mexico, we utilized our EI estimates in combination with SSF data reported in the country's 17 coastal states (Figure 2; dataMares 2020). We grouped records for SSF catch by class (total biomass, kg), and then multiplied these observations by the best available estimate for EI. For classes (1)–(7), we used the EI estimates produced directly by our analysis, and for classes (8)–(10) we supplied a "best guess" estimate.

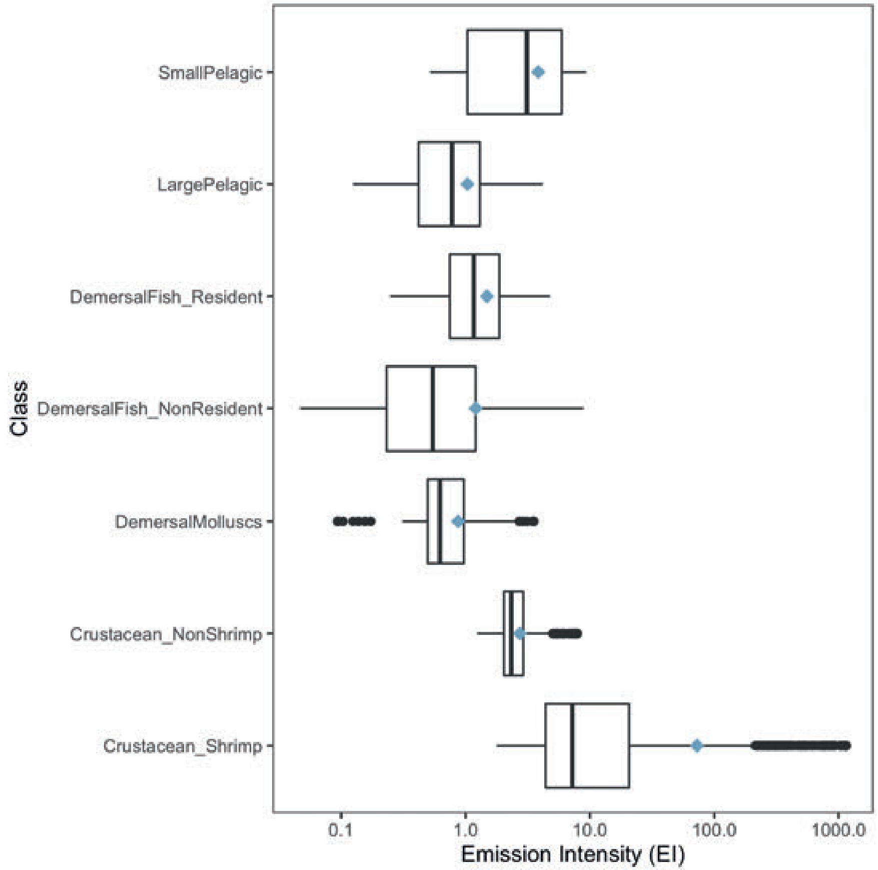
For (8) cephalopods, we assumed that the EI was equal to that of the global estimate reported by Parker et al. (2018) of 2.8 kg CO_2e/kg. For (9) echinoderms and (10) primary producers, providing a best guess estimate was not so straightforward, since very little published data on their footprint exists. What data does exist is not readily applicable to SSF production in Mexico. For example, Purcell et al. (2018) estimate an EI of 3.5 kg CO_2/kg of fresh sea cucumber in Fiji, however, differences in habitat, fisher behavior, use of boats, and fleet size between sea cucumber fishing in Fiji and Mexico are notable. Similarly, we identified a handful of studies estimating the carbon footprint associated with industrially farmed plant products (e.g., Nijdam et al. 2012) and algae farmed for biofuel (Quinn and Davis 2015), which we did not feel were applicable to SSFs in Mexico. Thus, for classes (9) and (10), we supplied the most conservative EI estimate produced by our own data (which, as we report below, is that of demersal molluscs).

Table 2. Lists Emission Intensity (EI) estimates and protein footprint estimates for each class of organism, with 95% confidence intervals listed beneath each estimate; whether or not the EI estimate for that particular type of seafood is better than the global EI estimate generated by Parker et al. (2018), and comparable to vegan protein (Nijdam et al. 2012). Finally, the boxplot shows the distribution of EI estimates, among and within classes, where: the x-axis is log10(EI), the mean is marked by a blue diamond, and individual EI estimates that fell outside of the first and fourth interquantile range appear as individual black points. (Seafood icons courtesy of IAN/UMCES Symbol and Image Libraries, available: ian.umces.edu/imagelibrary/; image authors: Tracey, Saxby, Saxby, Saxby, Saxby, Chenery, Tracey)

(#)		Class sample size / **bootstrap iterations**	Emission Intensity (EI) (kg CO_2e kg^{-1} live wt) / **95% CI (Low, High)**	EI per kg protein (kg CO_2e kg^{-1} protein) / **95% CI (Low, High)**	**Better than global EI estimate?**[1]	**Comprable to vegan protein footprint?**[2]
(1)		**Small pelagics (< 30 cm)**				
		7	**3.84**	**48.05**	no	no
		1000	(1.78, 6.36)	(23.98, 83.55)		
(2)		**Large pelagics (> 30 cm)**				
		521	**1.03**	**12.93**	**yes**	**yes**
		3000	(0.96, 1.12)	(12.01, 13.96)		
(3)		**Resident demersal fish**				
		596	**1.49**	**18.58**	**yes**	no
		3000	(1.41, 1.58)	(17.56, 19.72)		
(4)		**Non-resident demersal fish**				
		348	**1.20**	**15.06**	**yes**	**yes**
		3000	(1.03, 1.43)	(12.76, 17.91)		
(5)		**Demersal Molluscs**				
		187	**0.87**	**10.89**	**yes**	**yes**
		3000	(0.78, 0.99)	(9.63, 12.23)		
(6)		**Crustaceans (non-shrimp)**				
		1290	**2.73**	**34.12**	**yes**	no
		6000	(2.74, 2.96)	(34.24, 36.95)		
(7)		**Shrimp**				
		1985	**72.73**	**909.18**	no	no
		6000	(63.80, 82.42)	(793.6, 1032.1)		

Distribution of EI observations assorted by class

x-axis = log10(EI)



NOTE: EI estimates are not reported for **(8) Cephalods**, **(9) Echinoderms**, or **(10) Primary Producers** due to lack of data. However, these classes of organisms are fished throughout Mexico and accounted for in our subsequent analysis.

[1]EI estimates for the global fleet (including small-scale and industrial vessels) are reported by Parker et al. (2018).

[2]Comprable to the carbon footprint associated with a 100% plant based protein (i.e., legumes, 100% vegetal meat substitutes) reported by Nijdam et al. (2012), that is: 4–17 kg CO_{2e}/kg protein.

We ran our calculation for the total carbon footprint of Mexican SSFs three separate times: (1) using the mean EI estimates supplied by our data and best guesses, as well as the (2) high and (3) low EI estimates predicted by each 95% confidence interval. This allowed us to report the estimate for total carbon footprint in addition to a low–high "range" for that estimate, which we list in parenthetical notation as such: [*main estimate*] (low–high estimate). This low–high estimate was propagated throughout subsequent calculations and reported throughout the text as appropriate.

Estimating Footprint Using GPS Data

As a proxy for carbon emissions, we decided to test the utility of non-fuel data in predicting SSF fuel consumption over individual trips and a 100-member sample of trips (i.e., a small fishing fleet). Using the lme4 package in R, we generated three multiple linear regression models, each one more saturated than the last. In our first model (Y_1), we performed a multiple linear regression where fuel consumption was predicted by (i) the total distance travelled (continuous) and (ii) hours spent on the water (continuous), such that $Y_1 = \beta_i x_i + \beta_{ii} x_{ii} + e_1$. Our second model ($Y_2$) was similar to Y_1 with the additional predictor variable of (iii) class of organism fished (categorical), such that $Y_2 = Y_1 + \beta_{iii} x_{iii} + e_2$. Then, using only fuel records appended with information about the vessel's motor size (which reduced our sample to $n_{motor\ sample} = 915$, excluding $n_{/small\text{-}pelagics} = 1$), we performed a third multiple linear regression (Y_3), including (iv) motor size/horsepower (categorical), such that $Y_3 = Y_2 + \beta_{iv} x_{iv} + e_3$.

We scrutinized the predictive ability of all three models (Y_1, Y_2, and Y_3) when applied to a small fishing fleet using a Monte-Carlo Cross-Validation technique (Xu and Goodacre 2018), which calculated the percent error borne from the difference between predicted and observed fuel consumption over 100 fishing trips, bootstrapped/iterated 1,000 times, such that $n_{trips} = 100$ and $n_{bootstap\_iterations} = 1{,}000$. Twenty-five percent of all available data was used to train the model(s) and generate predicted values, while the remaining 75% of the data points were retained. By iterating this process 1,000 times, we were able to generate the mean of, and range for, percent error borne from each model, providing a coarse picture as to how well each model might perform in the "real world."

RESULTS

EI Estimates for Popular Seafoods in Mexico

EI estimates including 95% confidence intervals for each class of organism are reported in Table 2 and vary between classes and within trips. For example, shrimp—which have long been the target of environmentally hazardous fishing (Cisneros-Mata 2010; Aburto-Oropeza et al. 2017b)—contribute over 83 times as many carbon emissions per kilogram of catch than do demersal molluscs (EI = 72.73 versus 0.87 kg CO_2e/kg). Large-pelagic and non-resident demersal fishes contribute low- to moderate-carbon catches (EI = 1.03 and 1.20 kg CO_2e/kg, respectively), while resident demersal fishes have a slightly higher carbon footprint (EI = 1.49 kg CO_2e/kg).

Closer scrutiny of the data reveals that non-shrimp crustaceans, such as crabs and lobsters, contribute far fewer emissions per kilogram than do shrimp (EI = 2.73 versus 72.73 kg CO_2e/kg), likely explained by gear type used to fish them (see Table 3). For example, crabs and lobsters are landed using stationary traps, which are lightweight and easy to collect relative to other types of gear. In contrast, shrimp are landed using trawls or large gillnets, which carry tremendous mass as they drag across the sea floor. Lending credence to this hypothesis are the results from previous studies (e.g., Kelleher and Mills 2012; Parker et al. 2018), and the observation that, on average, small-scale vessels fitted with "eco-friendly" trawls (*changos*) use 3–26 times less gas per kilogram of unprocessed shrimp than do vessels fitted with traditional trawl nets and large gillnets. Specifically, the EI estimates associated with shrimp landed using eco-friendly trawls is 6.19 kg CO_2e/kg ($n_{records} = 586$) versus 165.28 kg CO_2e/kg for traditional trawls ($n_{records} = 859$) and 21.29 kg CO_2e/kg for large gillnets ($n_{records} = 256$). Point estimates presented here are based on non-winsorized EI values. The decision to winsorize or not changes the point estimates but not the interpretation of our results. Given these discrepancies, we speculate that SSF vessels are particularly fuel-inefficient when it comes to towing heavy equipment (Gulbrandsen 2012).

When we partitioned the data by gear type, we still observed considerable variance across EI estimates for shrimp. A wide range in shrimp EI estimates is driven by high volatility in catch, where some trips were very successful (max = 272.58 kg beheaded), and others were not at all (min < 1 kg beheaded). We observed a similar pattern for the other classes of organisms, where trips with a low catch drove up the average EI, and trips with high catch drove down the average EI. This suggests that one way to lessen emissions associated with seafood is to improve the health of fishery stocks and increase the catch-per-unit effort (Kelleher and Mills 2012).

Certain Seafoods from SSFs Offer Low-Carbon Protein

Some of the seafood landed by SSFs in Mexico offer low-carbon harvests of animal protein (Table 2), consistent with the footprint of a vegetarian or vegan diet, and are potentially climate-friendly (Table 3). Although an exhaustive comparison between proteins is beyond the scope of this paper, previous studies support the following conclusions from our data:

(1) Protein from demersal molluscs, large pelagic fish, and non-resident demersal fish has a low carbon footprint, comparable to protein from vegan meat substitutes (Nijdam et al. 2012; Hilborn et al. 2018; Parker et al. 2018).

(2) Protein from resident demersal fish and non-shrimp crustaceans is about as carbon-intensive as protein from eggs, milk, and poultry (Nijdam et al. 2012; Hilborn et al. 2018; Parker et al. 2018).

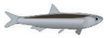
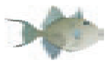
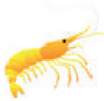
(3) Protein from small pelagic fish landed by SSFs may be carbon-intensive, similar to pork. However, this estimate is highly uncertain due to our small sample size, and is inconsistent with literature surrounding other small pelagic fisheries (Avadí et al. 2014; Hilborn et al. 2018; Parker et al. 2018).

(4) Protein from shrimp is carbon-intensive, on par with protein from ruminant herbivores like cows and sheep (Nijdam et al. 2012; Hilborn et al. 2018; Parker et al. 2018).

The Carbon Footprint of Mexico's Small-Scale Fleet

Using the latest available catch records reported to CONAPESCA (dataMares 2020), in combination with our EI results (Table 2), we estimate that the carbon footprint for Mexico's SSFs was 3.35 million metric tons of CO_2e in 2014 (with a low–high estimate of: 2.96–3.86 million metric tons). Since there exist ~74,000 small–scale motorized vessels in Mexico (Alder et al. 2018), we estimate that the mean

Table 3. Characteristics of each small-scale fishery (SSF) beyond Emission Intensity (EI) estimates, including relevant measures of economic and ecosystem impacts. (Seafood icons courtesy of IAN/UMCES Symbol and Image Libraries [available: ian.umces.edu/imagelibrary/]; image authors: Tracey, Saxby, Saxby, Saxby, Saxby, Chenery, Tracey)

		Emission Intensity (EI)	EI per ex-vessel peso [1]	Ratio of ex-vessel revenue : biomass [2]	Typical trophic level	Commonly-used gear
(#)	**Class**	**(kg CO_2e kg^{-1} live wt)**	**(kg CO_2e $peso^{-1}$)**	***higher- vs. lower-revenue landings?***	***common role in the food web***	***% of trips using gear X***
(1)	 **Small pelagics (< 30 cm)**	3.84	1.082	8.7 : 1 *lower-revenue landings*	**Low** *often primary consumers*	**NA*** **sample too small to generalize: hook & line (n = 4), cast net (n = 3)*
(2)	 **Large pelagics (>30 cm)**	1.03	0.086	11.4 : 1 *lower-revenue landings*	**High** *generally apex predators*	**Gillnets** *82% gillnets; 13% trawls*
(3)	 **Resident demersal fish**	1.49	0.078	21.8 : 1	**Medium - High** *many meso predators*	**Mixed** *35% traps; 26% trawls; 20% gillnet; 18% hook & line*
(4)	 **Non-resident demersal fish**	1.20	0.108	17.7 : 1	**Medium - High** *many meso predators*	**Gillnets** *86% gillnets; 10% hook & line*
(5)	 **Demersal Molluscs**	0.87	0.007	11.0 : 1 *lower-revenue landings*	**Low** *often primary consumers*	**Hookah** *100% hookah*
(6)	 **Crustaceans (non-shrimp)**	2.73	0.072	27.5 : 1	**Low - Medium** *some secondary consumers*	**Traps** *100% traps*
(7)	 **Shrimp**	72.73	0.671	49.5 : 1 *higher-revenue landings*	**Low - Medium** *some secondary consumers*	**Trawls** *79% trawls; 21% gillnets*

[1]Values based on indivial records of fuel consumption and ex-vessel sales from communities in Northwest Mexico (Mascareñas-Osorio et al. 2020).

[2]Ratio of total ex-vessel revenue (pesos) to total landed biomass (kg), based on records from marine SSFs throughout all of Mexico in the year 2014 (dataMares 2020).

annual emissions per vessel is 45.3 metric tons of CO_2e (low–high estimate: 40.0–52.2 metric tons) or ~ 14,597 L gas/year (low–high estimate: 12,909–16,825 L gas/year). Uncertainties associated with this result are discussed in Supplemental Material, however, our estimate appears consistent with findings by Martínez-Cordero and Sanchez-Zazueta (2017), who report median CO_2 reductions in Mexico's SSF fleet resulting from a motor replacement program (not including non-fuel emissions).

Our estimate for fuel use among Mexican SSFs suggests that, relative to other *motorized* SSF fleets, the average SSF vessel in Mexico is "middle of the road" to high in terms of its carbon footprint. For example, compare the average footprint of a small-scale vessel in Mexico (~14,597 L gas/year) to: 1,349 L/male fisher/year for the sea cucumber fishery of Vanua Balavu-Fiji (a sparsely motorized fishery; Purcell et al. 2018); 2,963–15,416 L/vessel/year for the Peruvian Anchoveta *Engraulis ringens* fishery (degrees of motorization; Avadí et al. 2014); and an average 15,000 L/vessel/year among eight SSFs in the European Union (fully motorized; Guyader et al. 2013).

Evidence that Tracking Technologies May Enable Footprint Estimation

We performed three multiple linear regressions (Y_1, Y_2, and Y_3), where fuel was predicted by an increasing number of variables: (i) the total distance travelled (continuous), (ii) hours spent on the water (continuous), (iii) class of organism fished (categorical), and (iv) motor size (categorical).

Our simplest model (Y_1) was significant ($F(2, 4931) = 552.8$, $p <<< 0.05$), but only explained 18% of the variance in our data ($R^2_{adj} = 0.18$); both predictor variables (i) and (ii) were significant ($p <<< 0.05$). Our second regression equation (Y_2) included the third predictor variable (iii) class of organism fished, and was significant ($F(8, 4925) = 859.8$, $p <<< 0.05$), explaining 58% of the variance in our data ($R^2_{adj} = 0.58$); all Y_2 predictor variables were significant ($p <<< 0.05$), except for small-pelagic fishes. Finally, our third multiple linear regression (Y_3), which was applied to a smaller subset of the data containing information about vessel motor size ($n_{motor\ sample} = 915$), was significant ($F(10, 904) = 407.1$, $p <<< 0.05$), and explained 82% of the variance in our data ($R^2_{adj} = 0.82$); and all Y_3 predictor variables (i)–(v) were significant ($p < 0.01$). This makes sense given that Y_3 is more saturated than Y_2, and Y_2 more saturated than Y_1, at the expense of model parsimony.

Using a Monte-Carlo Cross-Validation method (Xu and Goodacre 2018) to test the utility of our regression models in predicting real-world outcomes (where $n_{trips} = 100$ and $n_{bootstap\_iterations} = 1{,}000$), Y_1 predicted the observed fuel footprint of a 100-member fleet with a mean percent error of −0.2% (95% CI: −0.5, 0.1), and a range of −16.4% to 15.3% error. Y_2 had a mean percent error of −0.02% (95% CI: −0.2, 0.2), with a range of −10.6% to 11.0% error. And, Y_3 had a percent error of −0.2% (95% CI: −0.4, 0.0), with a range of −11.5% to 11.5% error. In all cases, percent error is close to normally distributed around zero, and dissipates as n_{trips} increases.

A visual assessment of model output suggests that models Y_1 and Y_2 do not accurately predict individual trips with unusually high fuel consumption (Figure 3A), but perform reasonably well over a small fleet (Figure 3B). Since model Y_3 was applied to a smaller and more "normal" subset of the data, it is unknown how Y_3 would predict fuel consumption for trips or fleets with unusually high values.

Cumulatively, these results suggest that in a real world application of models Y_1 through Y_3, Y_2 would most accurately predict the fuel footprint of a small fleet (Figure 3B), closely rivaled by Y_3, then Y_1. This is interesting in that one might expect Y_3 to have more predictive power than Y_2, given that Y_3 explains a larger amount of variance observed among individual fishing trips. While this may be an artifact of disparate sample size, it still hints at a useful takeaway: while information about motor size is useful, even without it, a large sample size makes it such that Y_2 performs reasonably well at predicting fuel consumption over several trips. Even Y_1, which only contains information about (i) total distance travelled and (ii) hours spent on the water, performs moderately well at predicting fuel consumption over a small fleet, suggesting that footprint estimation may be possible based on GPS data alone.

DISCUSSION

Our results provide a baseline understanding for scientists and fishery managers who seek to incorporate carbon footprint into their calculus surrounding SSFs and carbon management. Additionally, they indicate that SSFs in Mexico contribute substantially to food security (FAO 2003, 2019; Kelleher and Mills 2012) with relatively low carbon impacts. Yet, carbon footprint represents only one dimension of fisheries sustainability to be aware of, and characteristics for each SSF class (summarized in Table 3) lend valuable context to our understanding of what it means for a fishery to be truly climate-friendly. For example, meso and apex predators are known to play an important role in structuring healthy and resilient marine ecosystems (Estes et al. 2011), which, in turn, support carbon sequestration and regulation of Earth's climate (e.g., Atwood et al. 2015). Thus, intense fishing of large pelagic and non-resident demersal fishes may negatively impact carbon reductions overall, despite their apparently low EIs.

To help incentivize climate-friendly fishing, managers might employ various strategies, such as communications campaigns (Merayo et al. 2019), support for cooperative fisheries management (Hilborn 2004; Cota-Nieto et al. 2018), and direct financial transfers to fishers and their communities as they transition away from high-carbon fishing (Cisneros-Montemayor et al. 2016; Merayo et al. 2019). Managers might also consider removing "harmful" subsidies, which artificially decrease the price of fuel, as these tend to encourage unsustainable fishing practices (Sumaila and Pauly 2007; Sumaila et al. 2010; Merayo et al. 2019; Cisneros-Montemayor et al. 2020).

On the supply side of fisheries production, fuel subsidies disincentivize fuel consciousness among existing fishers and lower the barrier to entry for new fishers, contributing to fleet overcapacity (Sumaila et al. 2010; Merayo et al. 2019). While on the demand side, cheap fuel leads to distortions in seafood prices (Sumaila et al. 2010; Merayo et al. 2019), obscuring the costs of harvest and undermining consumers' propensity to select for low-carbon seafood products. Such subsidies give rise to a socially inefficient outcome, where fisheries are more vulnerable to overexploitation (Sumaila et al. 2010; Merayo et al. 2019; Cisneros-Montemayor et al. 2020), and likely increase fishery emissions on net.

At the same time, it is important to understand that these harmful subsidies disproportionately fall to industrial fisheries (Cisneros-Montemayor et al. 2020), and holistic SSF management must account for the various

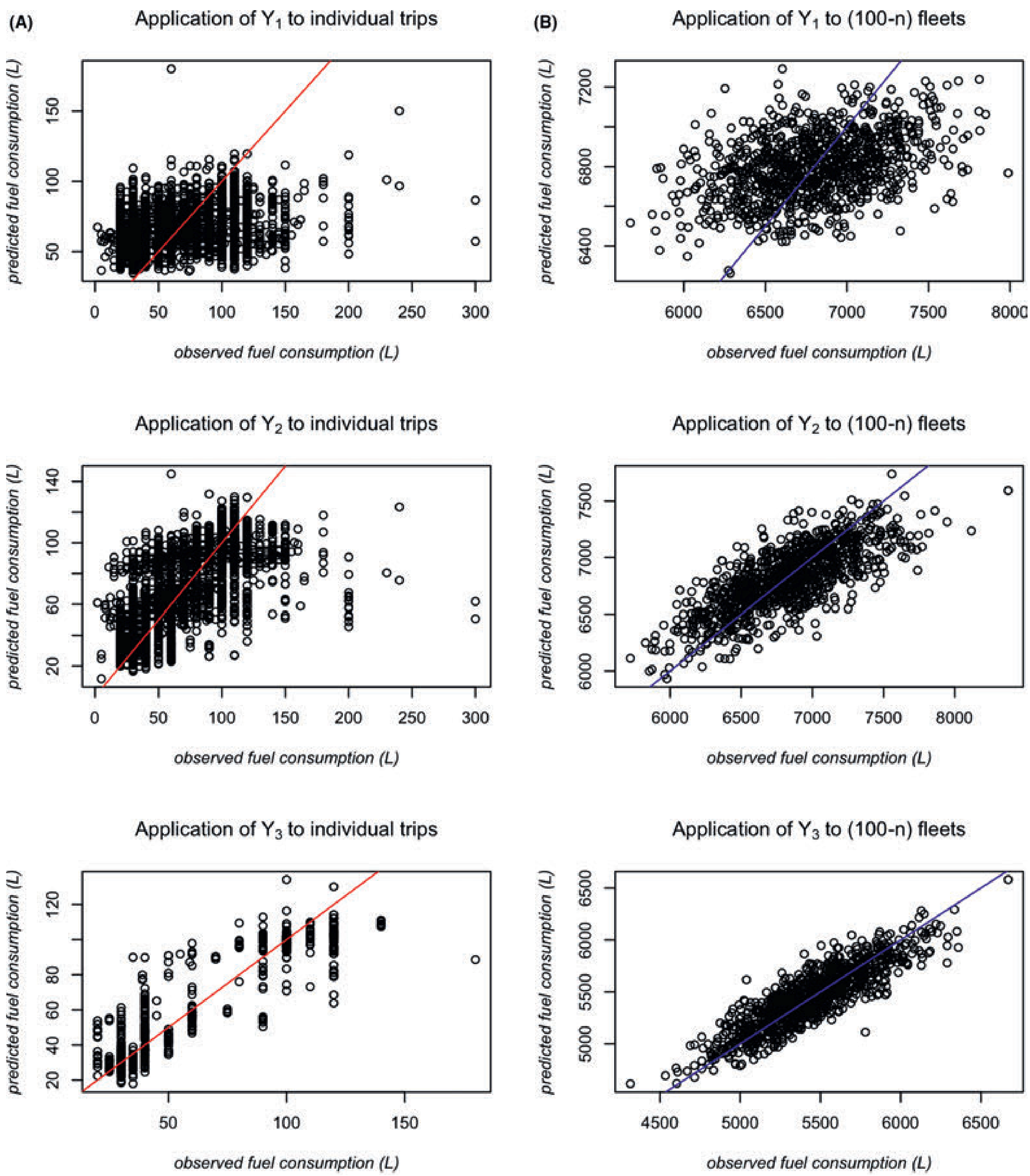


Figure 3. Graphs depicting goodness-of-fit results for multiple linear regression models Y_1, Y_2, and Y_3, when applied to individual trips (A) and small (100-member) fleets (B). Accordingly, in graphs on the left, each point indicates the fuel consumption for an individual fishing trip. In graphs on the right, each point indicates the total fuel consumption for 100-member "fleet," randomly sampled from the wider universe of data (described in "Estimating Footprint Using GPS Data"). Respectively, red and blue lines indicate a perfect 1:1 relationship between the observed and predicted values generated by each multiple regression when applied to individual trips and 100-member fleets, such that points clustered close to the red/blue line indicate a good model fit, and points far from the red/blue line indicate a poor model fit.

socio-economic benefits conferred by a particular subsidy or style of fishing. Our results suggest that shrimp landed by SSFs in Northwestern Mexico, for example, carry a high carbon footprint per kilogram of protein, but a much lower carbon footprint per peso (Table 3). Thus, policies designed to promote climate-friendly fishing need be considered on a case-by-case basis and in the wider context of fisheries "sustainability."

To monitor and address uncertainties between our estimates for fishing emissions and our carbon reality, emergent technologies may provide new and improved information. As evidenced by our results, tracking devices may enable SSF carbon accounting with relatively little adaptation to tracking/monitoring efforts already underway. For example, in an effort to curb illegal, unreported, and underreported fishing, geopositioning technologies such as Automatic Identification Systems and Vessel Monitoring Systems have become commonplace within the world's industrial fishing fleet. These technologies produce massive amounts of automated and semi-automated data, which can be readily utilized by scientists and managers alike through platforms such as the Global Fishing Watch (https://globalfishingwatch.org). We reason that the Global Fishing Watch (and platforms like it) may be able to provide estimates for fishery emissions in nearly real time and at a relatively low cost, based on ground-truthing studies such as ours, plus subsequent modifications to its machine learning algorithms.

Fisheries tracking data has proven valuable for reasons beyond surveillance, in both industrial (Kroodsma et al. 2018) and small-scale settings (e.g., Metcalfe et al. 2016; Cardiec et al. 2020), though fishers' feelings towards tracking technologies are generally mixed. Some are suspicious that tracking data will lead to management decisions that penalize participants who fish honestly, while others benefit from access to geospatial information. Among SSFs, GPS data has been demonstrated to enhance cooperative fisheries management (Metcalfe et al. 2016; Cardiec et al. 2020), observance of Marine Protected Areas (Cardiec et al. 2020), and compensation for area closures (Aburto-Oropeza et al. 2017b).

Fishers' willingness to help with monitoring and management increases when they are included in leadership and decision making (Hilborn 2004; Cota-Nieto et al. 2018; Alder et al. 2018). In our experience, fishers' local ecological knowledge not only provides better context for program design, implementation, and data analysis, fishers are well equipped to identify and communicate issues particular to their community and the resources they fish (e.g., Aburto-Oropeza et al. 2017a, 2017b). Furthermore, establishing trust and equity among stakeholders has been identified as integral to sustainable transformation and restoration of ecosystems, fisheries, and human communities (Bennett et al. 2019; Whyte 2019; Merayo et al. 2019). Therefore, administrators of novel tracking platforms should strive to include fishers as both participants and leaders in program development and implementation.

Our findings demonstrate that there exist several low-carbon SSFs in Northwestern Mexico, and that it may well be possible to monitor and improve upon climate-friendly fishing in the region. The methods described here may prove useful for studies in other countries, in data-limited scenarios, and for monitoring programs already underway. Ideally, this work will serve as stepping stone for novel research in SSF science and contribute to our understanding of sustainable seafood production in a rapidly changing world.

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DATA AVAILABILITY STATEMENT

The primary data sources used herein (Mascareñas-Osorio et al. 2020; dataMares 2020) are available by request at dataMares.org. Individuals who are interested in specific details of the analysis should carefully review the Methods section or contact the corresponding author.

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REFERENCES

Aburto-Oropeza, O., H. M. Leslie, A. Mack-Crane, S. Nagavarapu, S. M. W. Reddy, and L. Sievanen. 2017a. Property rights for fishing cooperatives: how (and how well) do they work? The World Bank Economic Review 31:1–46.

Aburto-Oropeza, O., C. López-Sagástegui, M. Moreno-Báez, I. Mascareñas-Osorio, V. Jiménez-Esquivel, A. F. Johnson, and B. Erisman. 2017b. Endangered species, ecosystem integrity, and human livelihoods. Conservation Letters 11:1–8.

Alder, J., U. Barg, S. Funge-Smith, P. Mannini, M. Taconet, J. Plummer, and M. Barange, editors. 2018. The state of the world fisheries and aquaculture (SOFIA) 2018. FAO (Food and Agriculture Organization of the United Nations) Secretariat, Rome.

Atwood, T. B., R. M. E. Connolly, E. G. Ritchie, C. E. Lovelock, M. R. Heithaus, G. C. Hays, J. W. Fourqurean, and P. I. Macreadie. 2015. Predators protect carbon stocks in blue carbon ecosystems. Nature Climate Change 5:1038–1045.

Avadí, A., I. Vázquez-Rowe, and P. Fréon. 2014. Eco-efficiency assessment of the Peruvian Anchoveta steel and wood fleets using the LCA+DEA framework. Journal of Cleaner Production 70:118–131.

Bennett, N. J., J. Blythe, A. M. Cisneros-Montemayor, G. G. Singh, and U. R. Sumaila. 2019. Just transformations to sustainability. Sustainability 11:3881.

Cardiec, F., S. Bertrand, M. J. Witt, K. Metclafe, B. J. Godley, C. McClellan, R. Vilela, R. J. Parnell, and F. le Loc'h. 2020. "Too big to ignore": a feasibility analysis of detecting fishing events in Gabonese small-scale fisheries. PLoS One 15:e0234091.

Chuenpagdee, R. 2019. Too big to ignore: a transdisciplinary journey. Pages 15–31 *in* R. Chuenpagdee, and S. Jentoft, editors. Transdisciplinarity for small-scale fisheries governance. MARE Publication Series, volume 21. Springer International Publishing, Cham, Switzerland.

Cisneros-Mata, M. A. 2010. The Importance of fisheries in the Gulf of California and ecosystem-based sustainable co-management for conservation. Pages 119–134 *in* R. C. Brusca, editor. The Gulf of California: biodiversity and conservation. University Arizona Press, Tucson.

Cisneros-Montemayor, A. M., Y. Ota, M. Bailey, C. C. Hicks, A. S. Khan, A. Rogers, U. R. Sumaila, J. Virdin, and K. K. He. 2020. Changing the narrative on fisheries subsidies reform: enabling transitions to achieve SDG 14.6 and beyond. Marine Policy 117.

Cisneros-Montemayor, A. M., E. Sanjurjo, G. R. Munro, V. Hernández-Trejo, and U. R. Sumaila. 2016. Strategies and rationale for fishery subsidy reform. Marine Policy 69:229–236.

Cota-Nieto, J. J., B. Erisman, O. Aburto-Oropeza, M. Moreno-Báez, G. Hinojosa-Arango, and A. F. Johnson. 2018. Participatory management

in a small-scale coastal fishery – Punta Abreojos, Pacific coast in Baja California Sur, Mexico. Regional Studies in Marine Science 18:68–29.
dataMares. 2020. National Fisheries Landings and Aquaculture Production, 2006–2014 (Conapesca) [online database]. University of California–San Diego Library Digital Collections. Available: http://bit.ly/38lSTMq.
DEFRA (UK Department of Environment, Food, and Rural Affairs). 2011. Guidelines to Defra/DECC's GHG conversion factors for company reporting: Methodology paper for emission factors. DEFRA, London.
Estes, J. A., J. Terborgh, J. S. Brashares, M. E. Power, J. Berger, W. J. Bond, S. R. Carpenter, T. E. Essington, R. D. Holt, J. B. C. Jackson, R. J. Marquis, L. Oksanen, T. Oksanen, R. T. Paine, E. K. Pikitch, W. J. Ripple, S. A. Sandin, M. Scheffer, T. W. Schoener, J. B. Shurin, A. R. E. Sinclair, M. E. Soulé, R. Virtanen, and D. A. Wardle. 2011. Trophic downgrading of planet earth. Science 333:301–306.
FAO (Food and Agriculture Organization of the United Nations). 2003. Fishery country profile: the United Mexican States years 2003. FAO, Rome. Available: https://bit.ly/3cekq3y (December 2020).
FAO (Food and Agriculture Organization of the United Nations). 2019. Fishery country profile: the United Mexican States years 2019. FAO, Rome. Available: http://bit.ly/3t1dE84 (December 2020).
FAO (Food and Agriculture Organization of the United Nations), IFAD (International Fund for Agricultural Development), UNICEF (United Nations International Children's Emergency Fund), WFP (World Food Program), and WHO (World Health Organization). 2019. Safeguarding against economic slowdowns and downturns. FAO Secretariat, Rome.
Froese, R., D. Pauly, Editors. 2020. FishBase. World Wide Web electronic publication. Available: http://bit.ly/3rnDt1D (December 2020).
Gulbrandsen, O. 2012. Fuel savings for small fishing vessels; a manual. FAO Secretariat, Rome.
Guyader, O., P. Berthou, C. Koutsikopoulos, F. Alban, S. Demanéche, M. B. Gaspar, R. Eschbaum, E. Fahy, O. Tully, L. Reynal, O. Curtil, K. Frangoudes, and F. Maynou. 2013. Small scale fisheries in Europe: a comparative analysis based on a selection of case studies. Fisheries Research 140:1–13.
Hilborn, R. 2004. Ecosystem-based fisheries management: the carrot or the stick? Marine Ecology Progress Series 274:269–303.
Hilborn, R., J. Banobi, S. J. Hall, T. Pucylowski, and T. E. Walsworth. 2018. The environmental cost of animal source foods. Frontiers in Ecology and the Environment 16:329–335.
IPBES (Intergovernmental Panel on Biodiversity and Ecosystem Services). 2019. Summary for policy makers of the global assessment report on biodiversity and ecosystem services. IPBES Secretariat, Bonn, Germany.
IPCC. (Intergovernmental Panel on Climate Change). 2018. Global warming of 1.5°C Special Report. IPCC Secretariat, Geneva, Switzerland.
Kelleher, K., and D. J. Mills. 2012. Hidden harvest report: the global contribution of capture fisheries. Report 66469-GLB. The World Bank, FAO (Food and Agriculture Organization of the United Nations), WorldFish Center, Washington, D.C.
Kroodsma, D. A., J. Mayorga, T. Hochberg, N. A. Miller, K. Boerder, F. Ferretti, A. Wilson, B. Bergman, T. D. White, B. A. Block, P. Woods, B. Sullivan, C. Costello, and B. Worm. 2018. Tracking the global footprint of fisheries. Science 359:904–908.
Martínez-Cordero, F. J., and E. Sanchez-Zazueta. 2017. Emissions of CO_2 from fisheries: analysis of reductions achieved through a national program focused on the artisanal fleet in Mexico. Carbon Management 8:9–17.
Mascareñas-Osorio, I., J. J. Cota-Nieto, V. Jimenez, and C. Lopez-Sagastegui. 2020. Fisheries Monitoring Program: Gulf of California artisanal fisheries data. University of California–San Diego Library Digital Collections. Version 3.
Merayo, E., I. Porras, S. Harper, P. Steele, and E. Mohammed. 2019. Subsidy reform and distributive justice in fisheries. International Institute for Environment and Development Working Paper, London.
Metcalfe, K., T. Collins, K. E. Abernethy, R. Boumba, J. Dengui, R. Miyalou, R. J. Parnell, K. E. Plummer, D. J. F. Russell, G. K. Safou, D. Tilley, R. A. Turner, H. VanLeeuwe, M. J. Witt, and B. J. Godley. 2016. Addressing uncertainty in marine resource management; combining community engagement and tracking technology to characterize human behavior. Conservation Letters 10:460–546.
Natural Resources Canada. 2014. Learn the facts: fuel consumption and CO_2. Available: https://bit.ly/3kWJEYf.
Nijdam, D., T. Rood, and H. Westhoek. 2012. The price of protein: review of land use and carbon footprints from assessments of animal food products and their substitutes. Food Policy 37:760–770.
Parker, R. W. R., J. L. Blanchard, C. Gardner, B. S. Green, K. Hartmann, P. H. Tyedmers, and R. A. Watson. 2018. Fuel use and greenhouse gas emissions of world fisheries. Nature Climate Change 8:333–337.
Purcell, S. W., W. Lalavanua, B. R. Cullis, and N. Cocks. 2018. Small-scale fishing income and fuel consumption: Fiji's artisanal sea cucumber fishery. ICES Journal of Marine Science 75:1758–1767.
Quinn, J. C., and R. Davis. 2015. The potentials and challenges of algae based biofuels: a review of the techno-economic, life cycle, and resource assessment modeling. Bioresource Technology 184: 444–452.
Smith, H., and X. Basurto. 2019. Defining small-scale fisheries and examining the role of science in shaping perceptions of who and what counts: A systematic review. Frontiers in Marine Science 6:1–18.
Sumaila, U. R., A. S. Khan, A. J. Dyck, R. Watson, G. Munro, P. Tydemers, and D. Pauly. 2010. A bottom-up re-estimation of global fisheries subsidies. Journal of Bioeconomics 12:201–225.
Sumaila, U. R., and D. Pauly. 2007. All fishing nations must unite to cut subsidies. Nature 450:945.
TinHan, T., B. Erisman, O. Aburto-Oropeza, A. Weaver, D. Vázquez-Arce, and C. G. Lowe. 2014. Residency and seasonal movements in *Lutjanus argentiventris* and *Mycteroperca rosacea* at Los Islotes Reserve, Gulf of California. Marine Ecology Progress Series 501:191–206.
Vázquez-Rowe, I., A. Hospido, M. T. Moreira, and G. Feijoo. 2012. Best practices in life cycle assessment implementation in fisheries. Improving and broadening environmental assessment for seafood production systems. Trends in Food Science & Technology 28:116–131.
Whyte, K. 2019. Too late for indigenous climate justice: Ecological and relational tipping points. WIREs Climate Change 11:e603.
Xu, Y., and R. Goodacre. 2018. On splitting training and validation set: a comparative study of cross-validation, bootstrap and systematic sampling for estimating the generalization performance of supervised learning. Journal of Analysis and Testing 2:249–262.

SUPPORTING INFORMATION

Additional supplemental material may be found online in the Supporting Information section at the end of the article.

Supplementary Material AFS

FEATURE

Project Review Under Canada's 2012 Fisheries Act: Risky Business for Fisheries Protection

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Whiteshell River, Pine Point Trail, Whiteshell Provincial Park, Manitoba, Canada. Photo credit: Robert Linsdell.

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Canada's *Fisheries Act* provides essential protection for fish and their habitat. To manage thousands of projects a year, Fisheries and Oceans Canada implements a risk-based framework requiring authorization and offsetting for the highest risk projects. Projects considered lower risk proceed via letters of advice. Following changes to the Act in 2012, there were concerns about transparency and cumulative effects of low-risk projects. We used access to information requests to obtain documents and reviewed the department's 2012–2019 risk-based framework. Projects reviewed in Manitoba in 2016 were examined and the amount of permanent alteration and destruction approved without authorization was quantified (23,881 and 6,768 m^2, respectively). The risk-based framework focused reviews and regulatory decisions on project-by-project effects, rather than cumulative risks from multiple projects. Harm from lower risk projects was not tracked or offset. New mechanisms are needed to manage such projects to achieve the conservation purpose of the Act.

INTRODUCTION

The *Fisheries Act* (hereafter, the Act) is one of Canada's oldest environmental laws and the primary legislative tool protecting fish and their habitat. The Act prohibits the carrying on of any work, undertaking, or activity (WUA) that results in harm to fish habitat or death of fish, unless authorized by the Minister of Fisheries, Oceans, and the Canadian Coast Guard. Fisheries and Oceans Canada (DFO) implements this prohibition by developing policy and procedures that interpret the Act and guide application of regulatory and compliance measures, including the review and authorization of proposed projects that may harm fish habitat or cause the death of fish. Authorizations to alter or destroy habitat include legal requirements for proponents (people or entities, such as municipalities, agricultural producers, and forestry companies carrying out projects) to offset harm remaining after avoidance and mitigation efforts. Implementation of the fish habitat protection provisions has faced many challenges; however, the review and authorization of small, "low-risk" projects has been a dominant ongoing problem (Minns 2001; Olszynski 2015; Rice et al. 2015). Such projects number in the thousands annually, are not typically appropriate for application of habitat offsetting tools available under the Act, and become a regulatory burden to DFO and project proponents. However, small projects can destroy important habitat for fish production or lead to cumulative impacts in areas with intensive development pressure.

As written, the Act prohibits *any* alteration or destruction of fish habitat unless authorized by the Minister. In practice, it is not reasonable to apply the authorization and offsetting provisions of the Act with the same level of oversight and enforcement to every activity that affects habitat in marine and freshwater environments. This scenario is common to many environmental regulations and has led to the development of risk-based regulatory and compliance approaches that apply a suite of tools to regulated activities according to some framework for risk assessment (Hood et al. 2001). Ultimately, a risk-based approach requires that regulators be clear about which risks will be managed as lower priorities and be prepared to deal with the consequences, both political and practical, of setting a level of risk tolerance (Baldwin and Black 2008). In the case of the fish and fish habitat protection provisions, this means being clear about which types of habitat impacts will be managed intensively or not, and what the level of risk (habitat alteration and destruction) tolerance will mean for fish and fisheries.

A risk-based approach to project review has been implemented by DFO since 2005 (DFO 2015a). The approach uses surface area of impact and an estimate of habitat quality to classify impacts as high- or low-risk. Projects identified as low-risk based on the criteria proceed without an authorization and without a requirement to offset harm to fish habitat. Instead of an authorization, proponents receive a letter of advice (LOA) that indicates the project may proceed. These LOAs may also include specific recommendations to avoid or mitigate impacts. In 2012, amendments to the Act further reduced regulatory burden on proponents and the department (Galloway 2013) and appeared to weaken protections by changing the language of the Act to a prohibition on "serious harm" to fish and fish habitat (see Hutchings and Post 2013), concurrent with a major reduction in regulatory staff capacity (DFO 2016a). Concerns that the 2012 revisions to the Act weakened protections for fish and fish habitat led to a Parliamentary review and legislative amendments in 2019.

From an ecosystem and fish production perspective, the concept of aquatic systems being resilient to some loss/alteration of habitat or death of fish is well supported (Koops et al. 2013; Rice et al. 2015); however, cumulative effects of multiple projects can exceed resiliency thresholds (Thrush et al. 2008; Koops et al. 2014). If cumulative alteration or loss of habitat is not tracked and cumulative impacts are not assessed for a watershed, lake, or coastal area, then the overall effects on aquatic ecosystems of projects that alter or destroy habitat will remain unquantified and overlooked, as was noted in a 2009 audit of the fish habitat protection program (OAGC 2009). In this context, concerns have been raised that DFO's risk-based approach is potentially facilitating detrimental cumulative effects (Olszynski 2015; Favaro and Olszynski 2017).

Here, we review the 2012–2019 framework for risk-based project review to help inform changes to the regulatory approach currently under development to address amendments made to the Act in 2019. Our objective is to provide recommendations for improvements to the risk-based framework based on: (1) a review of DFO's internal triage and regulatory review processes that detail how decisions were made on whether to issue an LOA or advise proponents to apply for an authorization; (2) an examination of how the framework was applied in practice and the types of projects that proceeded without an authorization using projects reviewed in 2016 in Manitoba as a case study; and (3) an examination of the quantity of alteration and destruction of fish habitat that resulted from these projects.

METHODS

We used a federal Access to Information and Privacy (ATIP) request to acquire a copy of DFO's internal guidance documents for evaluating Requests for Review in March 2018 and received un-redacted copies in July 2018. We also requested all Subsection 35(2) Requests for Review, Applications for a *Species at Risk Act* (SARA) Permit, Applications for Authorization under Paragraph 35(2)(b) of the *Fisheries Act* Regulations and associated documentation for all projects for which a final decision was reached in 2016 across Canada. 2016 was selected, as it was the most recent year for which all decisions would be complete and information available. Given feedback from the ATIP office on the magnitude of this request, it was subsequently reduced to only projects in Manitoba.

Manitoba was selected because it was likely to involve a manageable number of projects in a variety of freshwater and marine habitats with significant inland fishery values (second only to Ontario; DFO 2016b).

We outlined the risk-based decision framework used by DFO for assessing Requests for Review based on internal guidance documents. This framework involved two stages: initial screening (triage), followed by regulatory review. The triage process was summarized based on internal triage guidance (DFO 2013a). The regulatory review process for determining the need for an authorization was summarized based on the Localized Effects Assessment Determination Record Guide (LEADR Guide; DFO 2016c). The overall process and decision points for each review stage were described.

All documents associated with projects in Manitoba for which a final decision was reached in 2016 were reviewed in chronological order. These documents included Requests for Review from proponents, internal records of DFO's assessments at each review stage (triage and, if applicable, regulatory review), and LOAs and authorizations issued to proponents outlining final decisions and recommendations. For each project, the following information was summarized: area of effect (m^2), a brief project description, residual impacts, habitat type (riverine, riparian, lacustrine, marine), and recommended course of action (generic or site-specific LOA, LOA with additional species at risk mitigation, authorization, SARA Permit). In compiling this information, we used the most recent data available in project files. For example, the estimated area of effect or determination of aquatic species at risk presence might have been updated from the initial Request for Review after regulatory review by a DFO biologist, in which case updated information was used.

Projects were categorized by review stage (triaged out or proceeded to regulatory review). For projects that received an LOA, we calculated: range of effect sizes, median, mean, and total habitat destroyed and/or habitat permanently altered, and the number of projects causing death of fish. Finally, three case studies were described to demonstrate the range of project activities and their effects.

RESULTS

Along with the triage and regulatory review guides, the ATIP request yielded 12 different document types used during project

Table 1. Descriptions of document types and number received from the 2018 Access to Information and Privacy Request for all Subsection 35(2) Requests for Review, Applications for a *Species at Risk Act* Permit, Applications for Authorization under Paragraph 35(2)(b) of the *Fisheries Act* regulations, and subsequent documentation for projects in Manitoba for which a final decision was reached in 2016.

Document type	Description	Number received
Request for Review	Proponents submitted a Request for Review outlining their project plans if they determined independently or through Fisheries and Oceans Canada (DFO)'s online self-assessment tool that it was likely their project could cause serious harm to fish and fish habitat (Available: http://bit.ly/3u4NLWh)	36
Request for Review Appendix	Appendices including additional project details were sometimes provided by proponents along with a Request for Review	2
Harm Determination Record (HDR)	A DFO internal review form used prior to March 2016 to assess Requests for Review. HDRs were completed by DFO staff using information provided in the Request for Review to evaluate the potential of a project to cause a "localized effect" (definition below) to fish or their habitat. The recommended course of action was based on assessments in this document	8
Localized Effect Assessment Documentation Record (LEADR)	A DFO internal review form used after March 2016 to assess Requests for Review. This had a similar purpose and structure to the HDR, with some additions. The recommended course of action was based on assessments in this document and guided by the associated LEADR guide	6
Generic Letter of Advice (LOA)	If DFO determined that the project was unlikely to cause localized effects to fish or their habitat after assessing the Request for Review, a generic LOA reiterating the proponent's responsibilities to avoid serious harm was issued. No offsetting was required	20
Site-specific Letter of Advice	Following assessment of the Request for Review, if DFO determined that additional mitigation was required to avoid localized effects, a site-specific LOA containing additional mitigation recommendations was issued. The recommendations were considered advice. No offsetting was required	16
Application for Authorization under Paragraph 35(2)(b) of the *Fisheries Act*	If either the proponent or DFO determined a project would cause unavoidable serious harm that would result in a localized effect to fish habitat in the vicinity of the project, the proponent submitted this form to apply for an authorization	1
Application for a *Species at Risk Act* (SARA) Permit	This application was submitted by the proponent if the project would result in the killing, harm, or harassment of individual aquatic species at risk or destruction of their critical habitat	1
Record of Consideration of Conditions (SARA)	This record was kept on behalf of the Minister to demonstrate how the conditions set out in Section 73 of SARA were considered prior to the issuance or refusal of a SARA Permit	1
Consideration of Factors in Section 6 of *Fisheries Act*	This record was kept on behalf of the Minister to demonstrate how the factors set out in Section 6 of the Act were considered prior to issuance or refusal of an authorization	1
Authorization	This document authorized proponents to proceed with a project causing a localized effect to fish and/or fish habitat, with requirements to offset unavoidable impacts	1
SARA Permit	This permitted proponents to engage in activities that killed, harmed, harassed, or captured individuals of threatened or endangered species or destroyed their critical habitat, provided the harm was incidental or would benefit the species, and that project implementation would satisfy conditions in Section 73 of SARA	1

reviews in Manitoba in 2016. Table 1 provides descriptions of each document and the number of each received (94 total).

Project review began by proponents evaluating whether serious harm (language of the Act from 2012 to 2019) may result from the project (Figure 1). When uncertain, proponents submitted a Request for Review directly or determined the need for review using DFO's online self-assessment process. If proponents were certain that the nature of impacts would require an authorization or *Species at Risk Act* Permit, they would apply directly for them rather than submit a Request for Review.

Triage

Requests for Review were processed by DFO Fisheries Protection Program (FPP) triage staff using a screening process (Figure 2). A Triage Tracking Guidance Form (DFO 2013a) was used to evaluate projects and decide whether regulatory review was required. First, projects were screened out of regulatory review if habitat present at the project location was considered low priority based on a Low Priority Waterbody List included in the guidance. Examples of low-priority habitats included non-fish-bearing waterbodies and industrial or man-made ponds or irrigation channels.

Second, projects were screened for impact types considered higher risk: those that should be prioritized for review based on past authorizations, existing guidelines, scientific advice, and staff expertise. Triage staff referred to a High Priority Impact Table that included advice and past decisions on whether to recommend regulatory review for common activities such as infilling, deposition of non-deleterious substances in water, changes in flows/water levels, dredging/excavating, watercourse alteration, and fish mortality. For example, it was advised that previously authorized dredging projects in 2011–2012 (the most recent fiscal year prior to development of the guide) ranged in area from 4,000 m^2 to over 2 million m^2, and that dredging and infilling proposals >250 m^2 should undergo regulatory review.

Finally, habitats and species for which regulatory review should be undertaken irrespective of impact type or size were identified based on region-specific guidelines (the High Priority Species and Habitat List). These included projects proposed in rare or limiting habitat, in ecologically sensitive areas, or that could affect aquatic species at risk and their residences or critical habitat. If projects did not meet any criteria for regulatory review, proponents were sent a generic or, in some cases, site-specific LOA, indicating the project could proceed without an authorization. However, FPP triage staff could still recommend regulatory review, despite a project not meeting the criteria, if specific justification was provided. For example, a project proposal not on the Low Priority Waterbody List and falling below thresholds for a high-priority impact (an infill <250 m^2) could be sent for further regulatory review if the risk

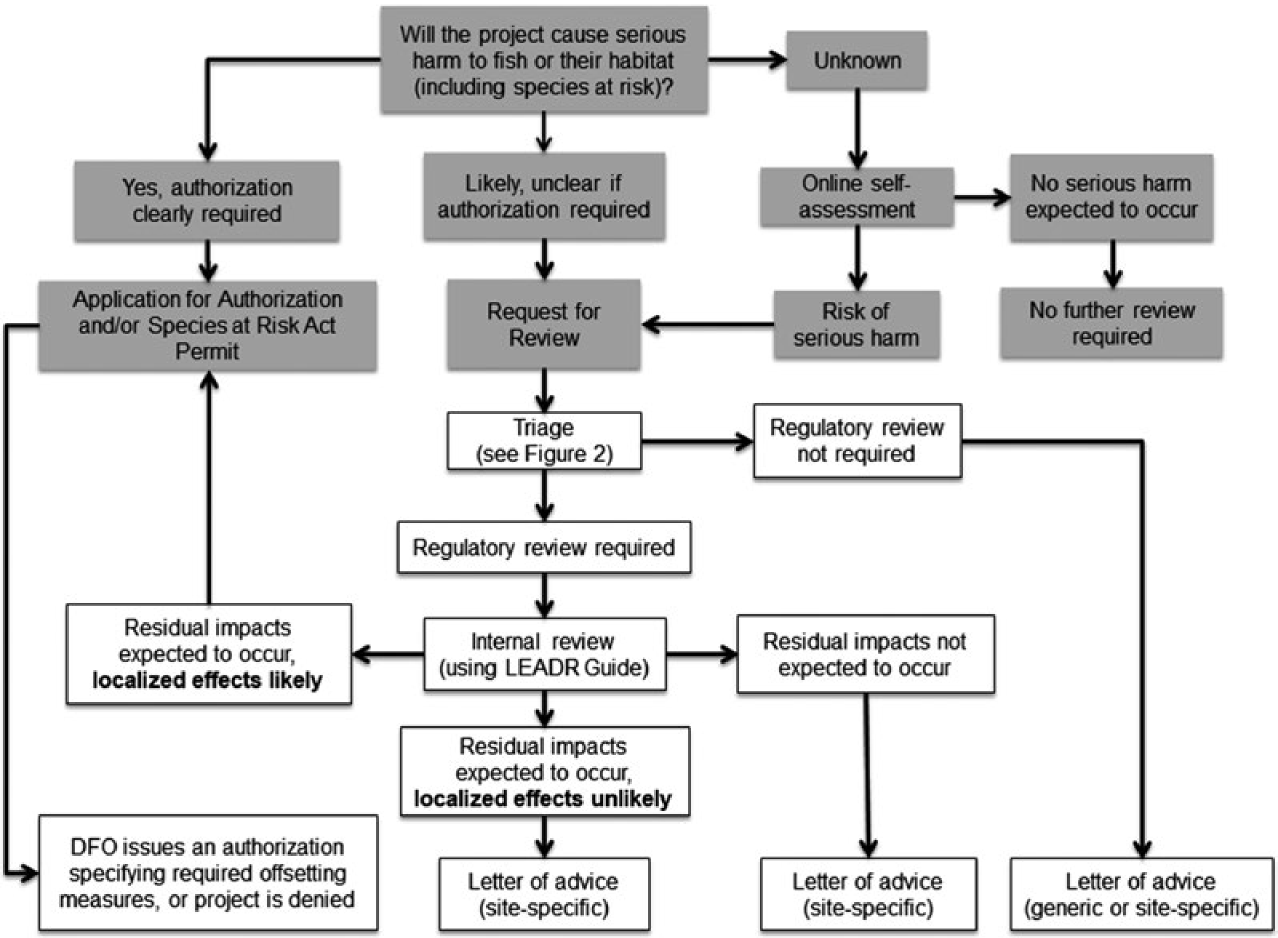

Figure 1. Sequence of actions and decisions made by proponents (shaded) and Fisheries and Oceans Canada (DFO; white) when determining whether a project is likely to have a localized effect and therefore require an authorization. LEADR Guide = Localized Effects Assessment Determination Record Guide

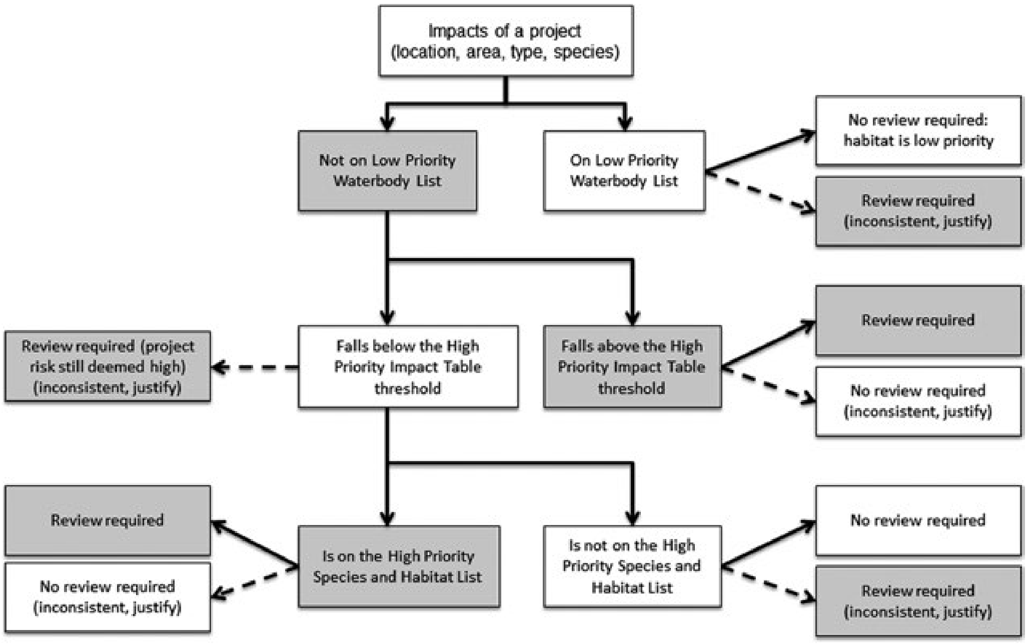

Figure 2. Sequence of criteria assessed by Fisheries and Oceans Canada triage staff when deciding whether a project should require regulatory review. Criteria and decisions leading to regulatory review are represented as shaded boxes. Dashed arrows represent decisions that are inconsistent with the Triage Tracking Guidance Form recommendations and require justification from triage staff (Figure adapted from DFO 2013a).

associated with the impact size or activity type was deemed high (e.g., infill size relative to waterbody size).

Regulatory Review

Projects requiring regulatory review were forwarded to FPP regulatory review biologists who used internal guidance documents to assess projects and determine if an authorization was required. The guidance documentation changed part way through the time period of our analysis of project reviews in Manitoba. From January to March 2016, a regulatory review document called the Harm Determination Record (HDR) was used. In March 2016, this was replaced by a document called the Localized Effect Assessment Documentation Record (LEADR) Guide (DFO 2016c), and the associated LEADR Form. Reviewers filled out LEADR Forms based on information provided by proponents in a Request for Review, an application for an authorization or SARA Permit, or a provincial application from an area where a DFO-provincial agreement was in place. We did not receive a guide for HDR Forms; however, based on the similarity between HDR and LEADR Forms (the LEADR Form added options to recommend species at risk mitigation within an LOA or SARA conditions within an authorization) we understood that they served the same purpose.

The purpose of the LEADR Guide was to aid regulatory review biologists in deciding whether to issue an LOA or recommend that proponents apply for an authorization. The basis of this decision was whether residual impacts (unavoidable serious harm after measures to avoid and mitigate) would result in a "localized effect…of a spatial scale, duration or intensity that cause the death of fish that may negatively affect the population of fish in the vicinity of the project, or that diminish or eliminate the ability of fish to use habitats within the vicinity of the project to carry out one or more of their life processes" (DFO 2016c). The vicinity of the project was defined as the area in which impacts were likely to occur directly or indirectly and its size could vary depending on the magnitude of project impacts and habitat type (rarity, quality).

Figure 3. Habitat decision matrix included in the Localized Effects Assessment Determination Record Guide used when determining the course of regulatory action for a proposed project (light = letter of advice, shaded = recommend applying for authorization) based on habitat quality and size of impact (DFO 2016c).

Regulatory review biologists recorded the following information in the LEADR Form as the basis for their decision: project description, fish species present, habitat description, presence of species at risk and their habitat, measures taken to avoid and mitigate, residual impacts, and whether these residual impacts were significant enough that a localized effect was likely. The LEADR Guide provided a list of recommended considerations for the likelihood of fish mortality to result in a localized effect: life-history characteristics, spawning success, generation time, population status, and natural or other major sources of mortality. The LEADR Guide also provided a decision matrix based on size of impact and quality of affected habitat (Figure 3). This matrix provided regulatory review staff with thresholds beyond which permanent alteration or destruction caused by the project were expected to result in a localized effect and require an authorization. Habitat quality could range from low to exceptional. Exceptional habitats were described as those that were rare or limiting, exceptionally productive, or residences/critical habitat for aquatic species at risk. Low-quality habitats were described as not meaningfully contributing to the productivity of fisheries, ubiquitous and not limiting in any way, or historically altered by human activities. Projects whose size of impact and quality of affected habitat fell below the thresholds in the decision matrix were issued an LOA.

Table 2. Summary of Requests for Review in Manitoba in 2016 that were triaged out of requiring regulatory review. For each project the following information was extracted and summarized: area of effect (m^2), brief project description, residual impacts (permanent alteration, destruction, death of fish, *Species at Risk Act*, not applicable [NA], or unknown), habitat type (riparian, lacustrine, riverine, marine), and resulting action (generic or site-specific letter of advice [LOA]).

Project #	Area of effect (m^2)	Description	Residual impacts	Habitat type	Course of action
2	0	Directional drilling under a river	NA	Riparian	LOA (generic)
4	0	Replacing a gravel boat launch with a concrete one	NA	Lacustrine	LOA (generic)
5	0	Replacement of a trestle with a bridge	NA	Riparian	LOA (site-specific)
7	50	Reinforcement of a float-plane launch ramp	NA	Riparian	LOA (generic)
8	500	Trenchless installation of a watermain	NA	Riparian	LOA (site-specific)
11	700	Infrastructure and river-walk upgrades	NA	Riparian	LOA (generic)
12	27.1	Culvert widening, bridge replacement	Permanent alteration, destruction	Riverine	LOA (generic)
13	27.1	Bridge replacement	Permanent alteration, destruction	Riverine	LOA (generic)
14	27.1	Bridge replacement	Permanent alteration, destruction	Riverine	LOA (generic)
17	60	Remediation of a failed riverbank	Permanent alteration, destruction	Riverine	LOA (generic)
18	100	Bridge replacement	Permanent alteration	Riverine	LOA (generic)
20	120	Bridge repairs, rip rap placement	Permanent alteration, destruction	Riverine	LOA (generic)
22	108	Emergency culvert replacement	NA	Riparian	LOA (generic)
23	60	Shoreline stabilization	NA	Riparian	LOA (generic)
24	74	Shoreline stabilization, riprap placement	Permanent alteration, destruction of habitat	Riverine	LOA (generic)
25	1	Geotechnical investigation for a sewer pipe	Destruction of habitat	Riverine	LOA (site-specific)
26	32	Culvert installation	Permanent alteration, destruction	Riverine	LOA (generic)
29	12	Dredging silt in a creek cut-out	NA	Riverine	LOA (generic)
30	160	Boat launch, ramp replacement	NA	Riparian and riverine	LOA (generic)
32	150	Shoreline stabilization, riprap placement	Permanent alteration, destruction	Riparian and riverine	LOA (generic)
35	15	Boat launch	NA	Riverine	LOA (generic)
36	929	Canal cleanout	Unknown	Lacustrine	LOA (generic)
37	625	Removal of rocks from tidal flats	NA	Marine	LOA (generic)

Project Summaries

A total of 37 projects containing 41 WUAs and their corresponding documents were evaluated. The type of habitat affected across all projects was: 58% riverine, 27% riparian, 8% lacustrine, 5% both riparian and riverine, and 2% marine. Of these projects, 23 were triaged out (Table 2) and 14 underwent regulatory review (Table 3). The majority of projects (36) received an LOA and one project received an authorization.

Of the 23 projects (23 WUAs) that were triaged out of regulatory review, 10 resulted in permanent alteration or destruction of habitat ranging from 27.1 to 150 m^2 with a median and average impact size of 46 and 62 m^2, respectively, 12 projects had no impact on fish or fish habitat, and 1 project, a clean out of a canal, had an unknown impact. The total amount of habitat permanently altered or destroyed by these projects was 618.3 m^2 (517.3 m^2 unspecified permanent alteration/destruction, 1 m^2 destroyed, and 100 m^2 permanently altered). None of the projects triaged out listed death of fish as a potential harm. These estimates of area of impact are from information provided by the proponent in Requests for Review and were not adjusted by DFO biologists during their review.

Of the 14 projects that underwent regulatory review, 1 project proposing realignment of 515 m of a creek resulting in the destruction of 5,496 m^2 of riverine habitat required and received an authorization on the condition that the newly constructed streambed incorporate fish habitat features to offset the loss. Of the 13 projects (17 WUAs) that received an LOA following regulatory review, 11 resulted in permanent alteration or destruction of habitat (13 WUAs), with impact sizes ranging from 27 to 12,950 m^2, with a median and average impact size of 737 and 2,777 m^2, respectively. The total amount of habitat permanently altered or destroyed by these projects was 30,548 m^2 (23,781 m^2 altered, 6,767 m^2 destroyed). Two projects listed death of fish as a residual impact, however it was noted that the actual number of fish killed was unknown/difficult to predict. No evidence was provided of projects being cancelled by proponents prior to implementation; therefore, we assume that all reported impacts to fish habitat occurred. The total area of habitat altered or destroyed by all 36 projects that received LOAs was 31,166 m^2 (6,768 m^2 destroyed, 23,881 m^2 altered, and 517 m^2 unspecified as either destroyed or altered). The following projects provide examples of the range of activities that received a letter of advice.

Replacement of a trestle with a bridge

The project involved installing a pedestrian footbridge where a former trestle was using the existing structures. The project was planned for late summer, after spawning periods, when flow was expected to be minimal or non-existent. There were no species at risk or their habitats present, and the project planned to implement strategies for erosion and sediment control and shoreline revegetation. The project was triaged out, no regulatory review was undertaken, and a site-specific LOA was issued for this project.

Table 3. Summary of projects in Manitoba in 2016 that underwent regulatory review. For each project the following information was extracted and summarized: area of effect (m^2), brief project description, residual impacts (permanent alteration, destruction, death of fish, *Species at Risk Act* [SARA], not applicable [NA], or unknown), habitat type (riparian, lacustrine, riverine, marine), and resulting action (site-specific letter of advice [LOA] or authorization). For projects 1, 9, 15 and 28, which each contained two different undertakings, area of effect and residual impacts for each undertaking are separated by a /. Project 28 listed residual effects of riprap placement as NA, however we included this impact size as permanent alterations to maintain consistency with decisions made for similar projects in our analysis.

Project #	Area of effect (m^2)	Description	Residual impacts	Habitat type	Course of action
1	5,000/500	Shoreline stabilization/riprap placement	Destruction/permanent alteration	Riparian	LOA (site-specific)
3	67	Install of sheet pile wall in a harbour	Destruction	Lacustrine	LOA (site-specific)
6	350	Bridge replacement	Permanent alteration	Riverine	LOA (site-specific)
9	400/1,600	Riprap to protect a pipeline/ Mapleleaf mussel *Quadrula quadrula* salvage	Permanent alteration/SARA	Riverine	LOA (site-specific) with SARA Permit
10	5,496	Emergency watercourse realignment	Destruction	Riverine	Authorization
12	318.75	Lock & dam armor and riprap maintenance	Permanent alteration	Riverine	LOA (site-specific)
15	27.3/+2,000	Creek lengthening/excavating a new stream	Death of fish, permanent alteration/habitat creation	Riverine	LOA (site-specific)
16	104,000	Two 2-hour shutdowns of 9.5 km of the Assiniboine River	Death of fish	Riverine	LOA (site-specific)
19	18	Directional drilling for water intake pipes	NA	Riverine	LOA (site-specific)
21	1,700	Infilling to protect road erosion	Destruction	Riverine	LOA (site-specific)
27	737.1	Culvert replacement	Permanent alteration	Riverine	LOA (site-specific)
28	2,500/2,500	Shoreline grading/riprap placement	Permanent alteration/ permanent alteration	Riparian	LOA (site-specific)
31	2,343/1,155	Shoreline stabilization/riprap placement	Permanent alteration/ permanent alteration	Riverine	LOA (site-specific)
34	12,950	Canal dredging	Permanent alteration	Riparian	LOA (site-specific)

Shoreline Protection in an Inlet

The project involved shoreline protection using 10,000 m^3 of riprap along ~755 m of an eroding shore. This resulted in infilling 5,500 m^2 of fish habitat (below the high-water mark) with quarried angular granite rock, where 5,000 m^2 of habitat would be destroyed and 500 m^2 would be permanently altered. Impacts to riparian habitat above the high-water level were not included in estimates of harm. Work was planned for early spring, during the egg incubation period for Lake Whitefish *Coregonus clupeaformis*, which were known to spawn in the area, and outside the spawning period for other fish. No species at risk or their habitat were present in the vicinity of the project. Following regulatory review, a site-specific LOA was issued.

Dewatering 9.5 km of the Assiniboine River to Inspect a Water-Control Structure

This project proposed to stop the flows to the lower Assiniboine River, temporarily affecting 104,000 m^2 of habitat. Species at risk and their critical habitat were present. Fewer than 100 fish were expected to be killed in favorable conditions, otherwise mortality could reach thousands. The Request for Review was submitted May 5, 2016, with a plan to commence work between August 15 and October 31, 2016. The LEADR Form was completed September 14, and a site-specific LOA was sent on October 14, 2016. Generally, DFO recommends at least 5 months for review in case an authorization is required. In this LOA, DFO noted that the time allowed to review this activity was insufficient for consideration of an authorization should one have been required, affecting the advice that DFO provided.

DISCUSSION

The risk-based project review process as applied in Manitoba in 2016 was successful at reducing the regulatory burden on DFO and proponents and focusing the department's resources on projects with the largest individual impacts. Internal departmental guidance focused on clarifying which types of habitat impacts would not be prioritized for authorization and identifying areas of uncertainty such as whether riparian alteration should require regulatory review. This chosen level of risk tolerance meant some impacts received more regulatory oversight than others. Guidance documents did not elaborate on how to consider long-term consequences of reduced oversight, nor were processes put in place to track and quantify effects of projects screened out of requiring an authorization. The Manitoba case study indicates that DFO's risk-based approach would likely come at a cost to fish and fish habitat when considered at a national scale across the thousands of projects that receive an LOA. Of the projects issued an LOA in 2016 in Manitoba, 58% resulted in alteration or destruction of habitat. Nationally, DFO reviewed 3,121 projects in 2016–2017 that did not result in issuing an authorization (DFO 2017). Based on our findings in Manitoba, this would potentially correspond to over 2 million square meters of habitat altered or destroyed without offsetting and without a public record.

Applying a risk-based regulatory regime to activities that result in harm and that may accumulate over time is particularly challenging and subject to the regulator obscuring risks by focusing on individual sites rather than the frequency or prevalence of specific activities in an area (Black and Baldwin 2012). For harm that accumulates, risk-management frameworks should address the total risk posed by the suite of projects or impacts, rather than focusing narrowly on the risks posed by individual projects. Aquatic ecosystems can be resilient to some disturbances, such as changes in daily flow that do not destroy critical habitats or alter ecosystem function beyond thresholds (DFO 2013b; Rice et al. 2015), as well as occurrences of mortality where there is consideration for factors like density dependence (Mace 1994), life-history strategy (Musick et al. 2000), and current population status/fishing pressure (Rice 2009; Randall et al. 2013). However, cumulative changes of a sufficient scale or intensity may cause aquatic systems to cross ecological thresholds beyond which they may degrade or shift to alternative states (Davies-Colley and Smith 2001; Schröder et al. 2005; Finley 2011). Application of a risk-based approach to fish-habitat protection, particularly in areas with many projects occurring over time, is more likely to avoid cumulative impacts from multiple low- and high-risk projects when guided by: knowledge of the current status of ecosystem characteristic affected by the suite of projects (Capon et al. 2015); relevant ecosystem-level thresholds that cannot be exceeded (Hunter et al. 2009); and an assessment of the risk that projects will push this ecosystem characteristic closer to or over its threshold (Link 2005; Martin et al. 2009). For example, invasive species, a history of disturbance, and projects occurring simultaneously could all potentially reduce a riparian habitat's ability to be rehabilitated through replanting (Richardson et al. 2007). Treating projects on a site-by-site basis with limited reference to broader ecosystem characteristics and status was deeply entrenched within the triage and regulatory review process developed by DFO. Central to this was development of the concept of "localized effects," which became the basis for classifying risks from a project as sufficient to require authorization or not. While there was some direction and guidance around the consideration of cumulative effects, the guidance documents and forms focused the reviewer on determining if an individual project was likely to have a localized effect in its immediate vicinity. The LEADR Guide recommends that reviewers consider broader ecosystem characteristics, but does not reference guidance on how they be considered or require that they be estimated or included in evaluations. Based on the documentation for project reviews in Manitoba, it was clear that consideration of these factors was left to the knowledge and experience of regulatory review biologists who varied in their field of expertise and had limited resources to understand the location and impact type in the context of the broader ecosystem. With no tracking of accumulated harm by area or activity type, no reporting on the status of the ecosystem being impacted, and no public registry of projects that proceeded with an LOA, the regulatory framework was likely to obscure the level of risk allowed to occur.

Another limitation of the risk-based regulatory approach noted in our review of projects in Manitoba was the limited use of evidence to support decision criteria within the triage and LEADR guides and the completed review forms. Four references were cited in the LEADR guide: two for describing/assessing habitat (DFO 2004; Randall et al. 2014), one to support development of area thresholds in the matrix (DFO 2015b, although this study acknowledges its limited usefulness), and one to define ongoing fisheries productivity (DFO 2014). Reviewers were encouraged to seek out relevant resources where available, such as DFO's pathways of effects guidance, the FPP Fish and Fish Habitat database, and Integrated Fisheries Management Plans. For other critical elements of the decision framework, no evidence or resources were provided to guide reviewers' interpretation. This included concepts such as project vicinity, ecosystem context, and resilience. Reviewers were not asked to document evidence or rationale for their decisions, and ultimately decisions reviewed here seemed to be based primarily on the habitat decision matrix (Figure 3) using a subjective assessment of habitat quality to guide the decision.

There was also a lack of transparency in the development and implementation of the risk-based regulatory process. The triage and LEADR processes were not established in consultation with affected communities and the multiple stakeholders involved, including Indigenous groups, fisheries resource users, NGO's, and common project proponents such as municipalities and natural resource companies. The review process was not made public and remained basically unknown to proponents and other stakeholders and rightsholders. The decision framework focused on concepts not described in the Act or clearly defined in policy (localized effects, the habitat decision matrix; DFO 2013c). If broad consultation and engagement with stakeholders and the regulated community on development of the risk-based review process had been undertaken, it may have helped DFO identify and address gaps in the decision framework as well as helped build consensus around the acceptable level of risk tolerance for habitat impacts and fish mortality.

Fisheries and Oceans Canada has limited resources to focus on a broad suite of high- to low-risk activities. Risk-based regulation can be problematic when applied to legislation that did not contemplate risk-based decision making or when confronted with societal norms that view the costs and benefits of a chosen level of risk tolerance differently (Rothstein et al. 2006). The issuing of LOAs for projects that caused harmful alteration, disruption, or destruction of fish habitat or death of fish was potentially outside the powers of the Act (Kwasniak 2004; Olszynski 2015) and led to criticism that DFO was not exercising sufficient oversight on projects that proceeded without an authorization. Following best practices in building a risk-based regulatory regime can ensure an efficient, effective, and transparent risk management framework that avoids accumulation of harm. An essential first step is to determine what distribution of resources best manages the hazards projects pose to policy objectives, across all levels of risk, and from this, develop a transparent and justifiable system (Black and Baldwin 2012). This framework should be dynamic and respond accordingly to changes in risk (SNIFFER 2010). Many tools can be applied to manage the lower risks in this framework, such as: self-regulation with third-party monitoring, themed or random audits and inspections, engagement and incentives, encouraging stakeholder or industry-led solutions, and exemptions that require notification, registration, or a permit (Black and Baldwin 2012). Both the frequency and intensity of auditing and inspection activities and the level of enforcement and intervention actions can be tailored according to levels of risk and a proponent's history of cooperation and ability to comply (Baldwin and Black 2008). The 2019 *Fisheries Act* provides DFO with several new regulatory mechanisms to manage projects causing harm. The use of a suite of regulatory tools that are applied according to the risk level of the activity, ensure that impacts to fish habitat are tracked and offset, and enable auditing and enforcement should replace the use of LOAs for projects that cause harm to fish or fish habitat. Finally, improved transparency in development of the review process and consultation with affected stakeholders and rights-holders would help ensure a revised regulatory approach and risk-based framework are successful at protecting and conserving fish and fish habitat. Together, these options and approaches could form the basis for a more robust regulatory approach that ensures a healthy future for Canadian fisheries.

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REFERENCES

Baldwin, R., and J. Black. 2008. Really responsive regulation. The Modern Law Review 71:59–94.

Black, J., and R. Baldwin. 2012. When risk-based regulation aims low: approaches and challenges. Regulation and Governance 6:2–22.

Capon, S. J., A. J. J. Lynch, N. Bond, B. C. Chessman, J. Davis, N. Davidson, M. Finlayson, P. A. Gell, D. Hohnberg, C. Humphrey, and R. T. Kingsford. 2015. Regime shifts, thresholds and multiple stable states in freshwater ecosystems; a critical appraisal of the evidence. Science of the Total Environment 534:22–130.

Davies-Colley, R. J., and D. G. Smith. 2001. Turbidity, suspended sediment, and water clarity: a review. Journal of the American Water Resources Association 37:1085–1101.

DFO (Fisheries and Oceans Canada). 2004. Identification of ecologically and biologically significant areas. Department of Fisheries and Oceans, Canadian Science Advisory Secretariat, Science Advisory Report 2004/006, Ottawa.

DFO (Fisheries and Oceans Canada). 2013a. Fisheries Protection Program Triage Tracking Guidance. Department of Fisheries and Oceans, Ottawa.

DFO (Fisheries and Oceans Canada). 2013b. Framework for assessing the ecological flow requirements to support fisheries in Canada. Department of Fisheries and Oceans, Canadian Science Advisory Secretariat, Science Advisory Report 2012/17, Ottawa.

DFO (Fisheries and Oceans Canada). 2013c. Fisheries Protection Policy Statement. Available: https://bit.ly/37pouMP. (July 2020).

DFO (Fisheries and Oceans Canada). 2014. A science-based framework for assessing changes in productivity, within the context of the amended Fisheries Act. Department of Fisheries and Oceans, Canadian Science Advisory Secretariat, Science Advisory Report 2013/071, Ottawa.

DFO (Fisheries and Oceans Canada). 2015a. Public report on the Fisheries Protection Program monitoring efforts. Available: http://bit.ly/2ORL0Yb. (July 2020).

DFO (Fisheries and Oceans Canada). 2015b. Science guidance for Fisheries Protection Policy: advice on equivalent adult calculation. Department of Fisheries and Oceans, Canadian Science Advisory Secretariat, Science Advisory Report 2015/011, Ottawa.

DFO (Fisheries and Oceans Canada). 2016a. Evaluation of the Fisheries Protection Program and its aquatic invasive species component. Department of Fisheries and Oceans, Ottawa.

DFO (Fisheries and Oceans Canada). 2016b. Freshwater landings. Department of Fisheries and Oceans, Ottawa. Available: http://bit.ly/3pBaRQK. (November 2020).

DFO (Fisheries and Oceans Canada). 2016c. Fisheries Protection Program Localized Effect Assessment Guide. Department of Fisheries and Oceans, Ottawa.

DFO (Fisheries and Oceans Canada). 2017. Annual report to Parliament on the administration and enforcement of the Fisheries Protection and Pollution Prevention Provisions of the *Fisheries Act* – April 1, 2016 to March 31, 2017. Department of Fisheries and Oceans, Ottawa.

Favaro, B., and M. Olszynski. 2017. Authorized net losses of fish habitat demonstrate need for improved habitat protection in Canada. Canadian Journal of Fisheries and Aquatic Sciences 74:285–291.

Finley, C. 2011. All the fish in the sea: maximum sustainable yield and the failure of fisheries management. University of Chicago Press, Chicago.
Galloway, G. 2013. Controversial changes to Fisheries Act guided by industry demands. The Globe and Mail (August 5). Available: http://tgam.ca/3s6vh5P. (July 2020).
Hood, C., H. Rothstein, and R. Baldwin. 2001. The government of risk: understanding risk regulation regimes. Oxford University Press, Oxford.
Hunter, M. L., M. J. Bean, D. B. Lindenmayer, and D. S. Wilcove. 2009. Thresholds and the mismatch between environmental laws and ecosystems. Conservation Biology 23:1053–1055.
Hutchings, J. A., and J. R. Post. 2013. Gutting Canada's *Fisheries Act*: no fishery, no fish habitat protection. Fisheries 38:497–501.
Koops, M. A., M. Koen-Alonso, K. E. Smokorowski, and J. C. Rice. 2013. A science-based interpretation and framework for considering the contribution of the relevant fish to the ongoing productivity of commercial, recreational or Aboriginal fisheries. Department of Fisheries and Oceans, Canadian Science Advisory Secretariat, Research Document 2012/141, Ottawa.
Koops, M. A., R. G. Randall, K. D. Clarke, E. C. Enders, K. E. Smokorowski, S. E. Doka, D. A. Watkinson, and M. J. Bradford. 2014. A review of scientific evidence supporting generic productivity-state response curves. Department of Fisheries and Oceans, Canadian Science Advisory Secretariat, Research Document 2014, Ottawa.
Kwasniak, A. 2004. Slow on the trigger: the Department of Fisheries and Oceans, the *Fisheries Act* and the *Canadian Environmental Assessment Act*. Dalhousie Law Journal 27:347–378.
Link, J. S. 2005. Translating ecosystem indicators into decision criteria. ICES Journal of Marine Science 62:569–576.
Mace, P. M. 1994. Relationships between common biological reference points used as thresholds and targets of fisheries management strategies. Canadian Journal of Fisheries and Aquatic Sciences 51:110–122.
Martin, J., M. C. Runge, J. D. Nichols, B. C. Lubow, and W. L. Kendall. 2009. Structured decision making as a conceptual framework to identify thresholds for conservation and management. Ecological Applications 19:1079–1090.
Minns, C. K. 2001. Science for freshwater fish habitat management in Canada: current status and future prospects. Aquatic Ecosystem Health & Management 4:423–436.
Musick, J. A., M. M. Harbin, S. A. Berkeley, G. H. Burgess, A. M. Eklund, L. Findley, R. G. Gilmore, J. T. Golden, D. S. Ha, G. R. Huntsman, and J. C. McGovern. 2000. Marine, estuarine, and diadromous fish stocks at risk of extinction in North America (exclusive of Pacific salmonids). Fisheries 25(11):6–30.
OAGC (Office of the Auditor General of Canada). 2009. 2009 Spring report of the Commissioner of the Environment and Sustainable Development. Minister of Public Works and Government Services Canada, Ontario. Available: http://bit.ly/3udkNDq. (July 2020).
Olszynski, M. 2015. From 'badly wrong' to worse: an empirical analysis of Canada's new approach to fish habitat protection laws. Journal of Environmental Law & Practice 28. Available http://bit.ly/37syPaD. (July 2020).
Randall, R. G., C. M. Boston, S. E. Doka, E. L. Gertzen, and J. Mossman. 2014. Assessing marine criteria for ecologically and biologically significant areas (EBSA): are the criteria interpretable and measurable in Lake Ontario? Department of Fisheries and Oceans, Canadian Science Advisory Secretariat, Research Document 2014/044, Ottawa.
Randall, R. G., M. J. Bradford, K. D. Clarke, and J. C. Rice. 2013. A science-based interpretation of ongoing productivity of commercial, recreational or Aboriginal fisheries. Department of Fisheries and Oceans, Canadian Science Advisory Secretariat, Research Document 2012/112, Ottawa.
Rice, J. C. 2009. A generalization of the three-stage model for advice using the precautionary approach to fisheries, to apply broadly to ecosystem properties and pressures. ICES Journal of Marine Science 66:433–444.
Rice, J. C., M. J. Bradford, K. D. Clarke, M. A. Koops, R. G. Randall, and R. Wysocki. 2015. The science framework for implementing the fisheries protection provisions of Canada's *Fisheries Act*. Fisheries 40:268–275.
Richardson, D. M., P. M. Holmes, K. J. Esler, S. M. Galatowitsch, J. C. Stromberg, S. P. Kirkman, P. Pyšek, and R. J. Hobbs. 2007. Riparian vegetation: degradation, alien plant invasions, and restoration prospects. Diversity and Distributions 13:126–139.
Rothstein, H., P. Irving, T. Walden, and R. Yearsley. 2006. The risks of risk-based regulation: insights from the environmental policy domain. Environment International 32:1056–1065.
Schröder, A., L. Persson, and A. M. De Roos. 2005. Direct experimental evidence for alternative stable states: a review. Oikos 110:3–19.
SNIFFER (Scotland and Northern Ireland Forum for Environmental Research). 2010. Assessing the effectiveness of regulatory activities at 'low risk' sites and proposed good practice framework. Phase 1 Report, Project ER13, Edinburgh, UK.
Thrush, S. F., J. Halliday, J. E. Hewitt, and A. M. Lohrer. 2008. The effects of habitat loss, fragmentation, and community homogenization on resilience in estuaries. Ecological Applications 18:12–21.

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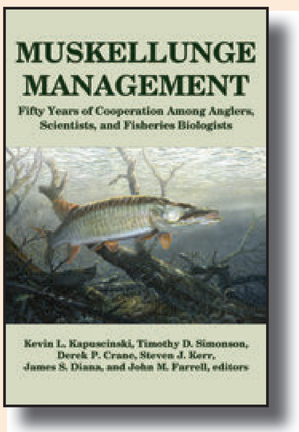

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ESSAY

Stizostedion Rafinesque, 1820 (Percidae) is the Valid Generic Name for Walleye, Sauger, and Eurasian Pikeperch

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Theodore Nicholas Gill's misconception of Lorenz Okenfuss's use of the Latvian vernacular name Sander for Cuvier's French vernacular name Les Sandres, as a properly coined Latin name, led to Gill's and subsequent authors' incorrect acceptance of *Sander* as the senior synonym for *Stizostedion*. However, some authors, aware Sander is a common name and never proposed as a valid generic name, have continued using the correct generic name *Stizostedion*. American Fisheries Society guidelines for publication in their journals and the Canadian Journal of Fisheries and Aquatic Sciences requires authors to use the current edition of *Common and Scientific Names of Fishes from the United States, Canada, and Mexico*, which has incorrectly used Sander in the last two editions. Thus, fishery biologists have been forced to use an incorrect generic name for one of the most important freshwater fisheries of North America.

> Stability of zoological nomenclature will never be attained as long as authors exercise indiscriminately their privilege of introducing into the literature any name that suits their fancy or convenience. Few users of scientific terminology have the means, the time, or the inclination to verify the validity of each name they use. They are prone to accept, and thus tend to promote the perpetuation of, names as they find them in secondary bibliographic references. The practice of overturning valid, well established names in favor of others derived from unacceptable or questionable sources has degenerated from a nuisance to a calamity and reflects discredit on the work of systematists.
>
> Hershkovitz (1949).

Bloch (1785) listed the common names *Sandat* and Sander for *Perca lucioperca* in Liefland (now modern day Latvia and Estonia). Fischer (1791) also listed the Latvian and Estonian common names in his description of *Perca lucioperca* as *Sandat* and Sander. Vitins et al. (2001) confirmed that Fischer (1791) used Latvian names in his 48 descriptions of fish species. The first correct use of a valid generic name for the percids Walleye, Sauger, and the Eurasian pikeperch was by Constantine Samuel Rafinesque (1820). Rafinesque (1820) erected the subgeneric name *Stizostedion* for *Perca salmonea* Rafinesque, 1818, synonym of *Stizostedion vitreum* (Mitchill, 1818), stating that:

> The *Perca Salmonea* may also form a peculiar subgenus, or section distinguished by the cylindrical shape of the body, long head and jaws, large teeth, and a second spine outside of the opercule over the base of the pectoral fins. It may be called *Stizostedion*, which means pungent throat. I could have made peculiar genera of each of them, under the proposed names; but as they otherwise agree with the reduced genus *Perca*, I have preferred delaying this innovation until more species are found possessing the same distinctions, in which case my two perches may then be called *Stizostedion salmoneum*, and *Lepibema chrysops*.

Rafinesque's *Stizostedion* thus was the first correctly described generic or subgeneric name.

Jordan and Gilbert (1877) accepted *Stizostedion* Rafinesque, 1820, as the type genus for *Perca salmonea* Rafinesque, 1818. Because *Perca vitrea* Mitchill, 1818 (published by Mitchill in March 1818) is a senior synonym *Perca salmonea* Rafinesque, 1818 (published in September), the type species for *Stizostedion* is *Stizostedion vitreum*.

Theodore Nicholas Gill (1894) concluded *Stizostedion* was the correct generic name for Walleye, Sauger, and Pikeperch. In that paper, he did not cite the works of Bloch (1785) and Fischer (1791) and may have been unaware of them. However, Gill (1894) cited Bosc (1819) to report that "Bosc defined the names *Sandat* and *Sandre* in the following words, neither being used as a scientific or Latin designation of an accepted genus." The following papers agree with Gill's (1894) placement of Walleye, Sauger, and European pikeperch in *Stizostedion*: Billington et al. (1991), Faber and Stepien (1997, 1998), Stepien and Faber, (1998), Bruner (2011), Haponski and Stepien (2013, the only paper to include all five living species).

Jordan and Evermann (1896) recognized two genera, *Stizostedion* for Walleye and Sauger, and *Lucioperca* for Eurasian pikeperch. They divided *Stizostedion* into two subgenera, subgenus *Stizostedion* for *Stizostedion vitreum*, and subgenus *Cynoperca* for *Stizostedion canadense* (Smith, 1834).

The names began to be confused after Joel Asaphi Allen (1902), a curator of mammals at the American Museum of Natural History, published a paper in which the names of Lorenz Okenfuss (who published under the name Lorenz Oken) were brought to the attention of biologists. Allen discussed 11 terms from Oken's (1816) *Lehrbuch der Naturgeschichte*, among which were nine mammal names that he decided were available as valid genera (Allen 1902). The

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German systematist Matschie (1904) published the first objection to Allen's acceptance of Oken's mammal names, writing:

Die in Oken's *Lehrbuch der Naturgeschicht* verwendeten Bezeichnungen dürfen deshalb nicht gebraucht werden, weil die Grundsatze der binaren Nomenklatur is diesem Buche nicht befolgt sind. [The designations employed in Oken's Textbook of Natural History therefore must not be used, because the principles of binary nomenclature in this book are not followed.]

Hershkovitz (1949) later wrote, "None of the above names credited to Oken, 1816, has the status of a generic name in the 'Lehrbuch.' Oken's system of nomenclature is neither Linnaean nor scientific. Most names proposed by Oken for his categories are expressed in vernacular or pseudo-scientific terminology." Hemming (1956) published Opinion 417 of the International Commission on Zoological Nomenclature, which made the names in Oken's 1816 publication unavailable.

However, Allen's 1902 paper attracted Theodore Nicholas Gill's attention (professor at George Washington University, and a long-time research associate at the Smithsonian Institution of Natural History), who then went through Oken's publications for fish names and discovered another paper published by Oken (1817). Gill (1903), not aware that Sander was a Latvian common name, wrote "I [Gill 1894] was unable to find a latinized generic name for the Pike-perches earlier than 1820, when Rafinesque published the name *Stizostedion.* The name Sander, published in the year 1817 [by Oken] as Cuvier's, must now be received and take its place."

The International Code of Zoological Nomenclature, (2000), 4th Edition ('the Code'), Chapter 4: Criteria of availability, Article 11, states in Recommendation 11A:

> Use of vernacular names. An unmodified vernacular word should not be used as a scientific name. Appropriate latinization is the preferred means of formation of names from vernacular words." Although there are Latin nouns that end in "-er", e.g. *frater*, *mater*, *magister*, according to Article 11.8. "Genus-group names. A genus-group name (see also Article 10.3) must be a word of two or more letters and must be, or be treated as, a noun in the nominative singular." This is why Stark (1828) used the "-us" ending when he coined the name *Sandrus*. It is also why Jordan (1929) used the properly formed *Sandrus* for the Eurasian Pikeperch. Gill's (1903) error in thinking Sander was a Latin name was the beginning of chain of publications that has perpetuated this nomenclature error to this day.

For example, David Starr Jordan (1917), not realizing that Gill had mistaken a common name for a scientific name, wrote in his *Genera of Fishes*, "Professor Oken gives Latin equivalents to all the French names in the first edition of the *Règne Animal* of Cuvier."… "Sander (Cuvier) Oken, 294, ("Les Sandres" Cuvier), Sander Oken, 1182, type *Perca lucioperca* L." However, American authors were not inclined to adopt Sander as the genus name, continuing to use *Stizostedion* for Walleye and Sauger (e.g., Forbes and Richardson 1920; Hubbs 1926; Simon 1946; Hubbs and Lagler 1947; Harlan and Speaker 1956; Trautman 1957; Smith and Bailey 1961).

Even Jordan (1929) continued using *Stizostedion* Rafinesque for the Walleye and Blue Pike, and elevated the subgenus *Cynoperca* Gill and Jordan, 1877 to generic status for the Sauger, but then used *Sandrus* Oken (*Lucioperca* Cuvier) for the Eurasian pikeperch. The genus *Sandrus* was attributed to Stark (1828) by Jordan and Evermann (1896), not to Oken (1817). In this same footnote, Jordan and Evermann used the genus *Lucioperca* for the Eurasian pikeperch and ascribed it to Fleming (1822).

Collette (1963) rejected giving credit to Fleming for coining the genus *Lucioperca*, saying,

> The first available use of *Lucioperca* is that of Schinz (1822: 475, type species *Perca lucioperca* Linnaeus by monotypy). In the same year, Fleming (1822: 394) listed *Lucioperca* (*L. vulgaris*) as a subgenus of *Perca*. Although Fleming's usage was accepted by Jordan and Evermann (1896:1020), I [Collette] am forced to reject his subgenus *Lucioperca* as unavailable because there is no description and the only species name (*vulgaris*) has not been used for a pikeperch.

Collette (1963), also rejected the availability of Sander. He wrote,

> Gill (1903), Chevey (1925), and Cărăusu (1952) considered that the first available name was Sander, originating in Oken (1817). Sander is listed in the column entitled 'Cuvier's System' on page 1182 (misprinted 1782) of Oken but the closest approach to it in the columns labeled 'Oken's System' is on the succeeding page where, under Barsche, is listed 'Perca, etc.' Therefore, it does not seem to me [Collette] that in this case Oken was either proposing or accepting a generic name. Oken gave no indication of doing more than referring to the *Règne Animal* when he used Sander, the Austrian vernacular version of Les Sandres. Furthermore, Oken's system is apparently modified from his *Lehrbuch der Naturgeschichte* (Oken, 1816) where he placed *fluviatilis*, *cernua*, *lucioperca*, *zingel*, and *aspera* all in *Perca* without mention of Sander. …. and the valid name for the genus therefore is *Stizostedion* Rafinesque, 1820.

I agree with Collette that Oken was not erecting a new genus for *Perca lucioperca.* Oken (1817) lists in a column under Cuvier's System, under the heading Zingel, and indented to the right, "*Perca, Apogon, Terapon, Sander, Enoplosus, Centropomus*." This is the reverse order of the headings of paragraphs found on pages 292–295 in Cuvier (1816), "Les Centropomes, Les Enoploses, Les Sandres, Les Esclaves (Terapon), Les Apogons, Les Perches." Oken is merely listing the Eastern European common name Sander for Cuvier's French common name Les Sandres. He is not erecting a new genus. He did not designate a type species. He did not illustrate Sander, and he never provided a description. Sander cannot be considered the senior synonym for Walleye, Sauger, and Eurasian pikeperch. Collette and Bănărescu (1977) later confirmed the validity of the generic name *Stizostedion*.

Eschmeyer and Bailey (1990) in their *Genera of Fishes* wrote,

> *Sander* Oken (ex Cuvier) 1817:1182 [ref. 3303]. Masc. *Perca lucioperca* of Bloch (= *Perca lucioperca* Linneaus 1758:289). Type by subsequent monotypy. Technical addition of species after Latinization not investigated. Based on "Les Sandres" of Cuvier 1816:294 [ref. 993] (see Gill

> 1903:966 [ref. 5768]). Synonym of *Stizostedion* Rafinesque 1820. Percidae." Eschmeyer and Bailey (p. 597) added to the literature cited for Oken, L. 1817 [ref. 3303], [See Gill 1903:965-967 [ref. 5768] for discussion of pagination and Cuvier's French "generic" names Latinized by Oken.]

Eschmeyer and Bailey thus cited Gill (1903), who made the mistake of thinking Sander was a Latin name, and were misled by Gill's error into giving the Latvian common name Sander as a senior synonym of *Stizostedion* Rafinesque. Eschmeyer (1998) repeated the same error word for word in his *Catalog of Fishes*.

Maurice G. Kottelat (1997) reviewed the systematics and nomenclature of the European freshwater fishes. Kottelat (1997) wrote of his checklist, "I certainly do not consider it as a systematic revision but more as a working document on which to base further researches." Kottelat singled out as noteworthy two changes: present name *Sander lucioperca* earlier name *Stizostedion lucioperca*, and present name *Sander volgensis* earlier name *Stizostedion volgense*. Kottelat stated that Sander Oken, 1817, is the senior synonym of *Stizostedion*. He quoted Gill (1903) and Eschmeyer (1990) (*sic*) as confirmation. However, as we have seen above, Gill was wrong about Sander being a Latin name and both Eschmeyer and Bailey (1990) were misled by Gill's (1903) paper. Kottelat admitted that he did not review any literature from the former Soviet Union. As a result, he missed the important paper by Fischer (1791), not in Kottelat's literature cited, on the 48 fishes of Latvia, and would not have seen Fischer's listing Sandat and Sander as Latvian vernacular names for *Stizostedion lucioperca*. However, there is no equivalent reason for his missing Bloch's (1785) Berlin paper, also not in Kottelat's literature cited, in which Sandat and Sander are listed as the common names of *Stizostedion lucioperca* in Latvia. Kottelat (1997) wrote, "Synonyms based on North American material have usually been omitted." Although Kottelat did cite Rafinesque (1820) and Collette and Bănărescu (1977), he did not cite Collette's (1963) revision of Percidae, in which he would have read Collette's argument against Sander being a valid name. Kottelat wrote with respect to his choice of names, "I have tended to choose unconventional alternatives, not for the pleasure of being provocative …but partly because unconventional problems will attract more attention and hopefully generate the much needed detailed studies." This is exactly what Hershkovitz (1949) warned us against.

Nelson et al. (2003) then followed Kottelat (1997) writing,

> Gill (1903) concluded that Sander was a valid and properly formed generic name and had priority over *Stizostedion.* … Although the International Commission of Zoological Nomenclature could have been petitioned to conserve *Stizostedion*, other references to *Sander* in the European literature suggest to us that it is now too late to petition and we thus employ the generic name *Sander*.

Nelson et al. (2003) did not corroborate whether or not Gill was correct and so sank *Stizostedion*, a name correctly in use for 183 years. They also were misled by Gill's mistake that Sander is a Latin name. Nelson et al. (2004) perpetuated this mistake writing, "Reasons for changing the generic name from *Stizostedion* to *Sander* are given in Nelson et al. (2003)."

In contrast, Miller and Robison (2004) in *Fishes of Oklahoma* wrote,

> We continue to use the generic name *Stizostedion* despite the fact that some workers are using Sander for the pikeperch. In our view, the latter was a buried name and probably intended as a common name by the author, Oken 1817. The international rules of zoological nomenclature do not favor use of such a name, so we believe *Stizostedion* is the valid name for the pikeperch.

Bruner (2011) also recently recognized the generic name as *Stizostedion*. Bruner pointed out that Fischer (1791) had listed Sander as a common name for *Perca lucioperca* (= *Stizostedion lucioperca*). Furthermore, the species Oken referred to of Cuvier (1816) was an illegal trinomial *Perca lucio perca* Bl., and the correct authorship of *Stizostedion lucioperca* (Linnaeus 1758) is Linneaus (1758), not Marc Eleiser Bloch (1785).

Page et al. (2013) further perpetuated the error of Nelson et al. (2003, 2004) by accepting the Latvian common name for pikeperch as a generic name. According to the guide for authors, in writing for American Fisheries Society journals and the *Canadian Journal of Fisheries and Aquatic Sciences*, authors are expected to follow certain style conventions pertaining to capitalization, spelling, punctuation, mathematical expressions, technical terms, and so forth. "The standard resource for the common and scientific names of North American fish species is the current edition of *Common and Scientific Names of Fishes from the United States, Canada, and Mexico* (American Fisheries Society, Bethesda, Maryland)." Unfortunately, AFS authors who follow the seventh edition will be forced to use the wrong generic name for Walleye, Sauger, and Eurasian pikeperch until a future edition of *Common and Scientific Names* corrects the error.

Perpetuation of Gill's (1903) error about the origin of the word Sander by Jordan (1917, 1923), Chevey (1925), Cărăusu (1952), Eschmeyer and Bailey (1990), Kottelat (1997), Eschmeyer (1998), Nelson et al. (2003, 2004), Nelson (2006), and Page et al. (2013) has led to the misconception that Sander is a Latin name and is the senior synonym for Walleye, Sauger and Eurasian pikeperch. This mistake has also misled fisheries biologists into using the wrong scientific term for Walleye fisheries that are worth billions. Because the rules of the International Code of Zoological Nomenclature were not followed initially for the establishment of the genus *Sander*, and the first use of an available generic name for Walleye was *Stizostedion* Rafinesque, 1820, the latter rightly remains the correct generic name for Walleye, Sauger, and Eurasian pikeperch. In addition to the authors listed above who recognized *Stizostedion* as the valid name in 1961 and earlier, the following are among those who have correctly used *Stizostedion* more recently: Collette (1963), Nelson (1976, 1984, 1994), Collette and Bănărescu (1977), Coad (1995), Faber and Stepien (1997, 1998), Stepien and Faber (1998), Miller and Robison (2004), Bruner (2011), Nelson et al. (2016), and Robison and Buchanan (2020).

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REFERENCES

Allen, J. A. 1902. Mammal names proposed by Oken in his 'Lehrbuch der zoologie'. Bulletin of the American Museum of Natural History 16(27):373–379.

Billington, N., R. G. Danzmann, P. D. N. Herbert, and R. D. Ward. 1991. Phylogenetic relationships among four members of the genus *Stizostedion* determined by mitochondrial DNA and allozyme analyses. Journal of Fish Biology 39(Supplement A):251–258.

Bloch, M. E. 1785. Naturgeschichte der ausländischen Fische. Berlin, Vol. 1:1–136, Pls. 109–144.

Bosc, L. A. G. 1819. [Pisces accounts.] Pages 126, 129 *in*: Nouveau Dictionnaire d'Histoire Naturelle, Nouv. Ed. Paris. 30: Pages 126, 129.

Bruner, J. C. 2011. A phylogenetic analysis of Percidae using osteology. Pages 5–84 *in* B. A. Barton editor. Biology, management, and culture of Walleye and Sauger. American Fisheries Society. Bethesda, Maryland.

Cărăusu, S. I. 1952. Tratat de ichtiologie. Academiei Republicii Populare, Bucharest, Romania.

Chevey, P. 1925. Recherches sur la perche et le bar, étude embryogénique, systematique et biogéographique des percidés Européens. Biological Bulletin 59(2):145–292.

Coad, B. W. 1995. Encyclopedia of Canadian fishes. Canadian Museum of Nature and Canadian Sport Fishing, Ottawa.

Collette, B. B. 1963. The subfamilies, tribes, and genera of the family Percidae (Teleostei). Copeia 1963(4):615–623.

Collette, B. B., and P. Bănărescu. 1977. Systematics and zoogeography of the fishes of the family Percidae. Journal of the Fisheries Research Board of Canada 34(10):1450–463.

Cuvier, G. 1816. Le Régne Animal distrihué d'après son organization, pour servir de base è l'histoire naturelle des animaux et d' introduction à l' anatomie comparée. Les reptiles, les poissons. Les mollusques et les annelids. Edition 1. Chez Déterville, Paris.

Eschmeyer, W. N. (editor). 1998. Catalog of fishes. Special Publication No. 1 of the Center for Biodiversity Research and Information. 3 Volumes. California Academy of Sciences. San Francisco.

Eschmeyer, W. N., and R. M. Bailey. 1990. Part 1. Genera of fishes. Pages 7–433 *in* W. N. Eschmeyer editor. Catalog of the genera of recent fishes. California Academy of Sciences, San Francisco.

Faber, J. E., and C. A. Stepien. 1997. The utility of mitochondrial DNA control region sequences for analyzing phylogenetic relationships among populations, species, and genera of the Percidae. Pages 129–143 *in* T. D. Kocher, and C. A. Stepien editors. Molecular systematics of fishes. Academic Press, San Diego, California.

Faber, J. E., and C. A. Stepien. 1998. Tandemly repeated sequences in the mitochondrial DNA control region and phylogeography of the pike-perches *Stizostedion*. Molecular Phylogenetics and Evolution 10(3):310–322.

Fischer, J. B. 1791. Vesuch einer Naturgeschichte von Livland 2, Aufl. 24 Fridrich Nicolovins, Königsberg.

Fleming, J. 1822. The philosophy of zoology, volume 2. Archibald Constable and Co., Edinburgh, Scotland.

Forbes, S. A., and R. E. Richardson. 1920. The Fishes of Illinois, 2nd edition. Illinois Natural History Survey, Springfield.

Gill, T. N. 1894. On the relations and nomenclature of *Stizostedion* or *Lucioperca*. Proceedings of the U. S. National Museum 17(993):123–128.

Gill, T. N. 1903. On some fish genera of the first edition of Cuvier's Règne Animal and Oken's names. Proceedings of the United States National Museum 26(1346), 965–967.

Gill, T. N., and D. S. Jordan. 1877. Cynoperca. Pages 44–45 *in* D. S. Jordan, editor. Contributions to North American ichthyology based primarily on the collections of the United States National Museum. II. A. Notes on Cottidae, Etheostomatidae, Percidae, Centrarchidae, Aphododeridae, Dorysomatidae, and Cyprinidae with revisions of the genera and descriptions of new or little known species. Bulletin of the U.S. National Museum 10:5–68.

Haponski, A. E., and C. A. Stepien. 2013. Phylogenetic and biogeograhical relationships of the *Sander* pikeperch (Percidae: Perciformes): patterns across North America and Eurasia. Biological Journal of the Linnean Society 110:156–179.

Harlan, J. R., and E. B. Speaker. 1956. Iowa Fish and Fishing, 3rd edition. Iowa State Conservation Commission, Des Moines.

Hemming, F. 1956. Opinion 417. Rejection for nomenclatorial purposes of volume 3 (Zoologie) of the work by Lorenz Oken entitled *Okens Lehrbuch der Naturgeschichte* published in 1815–1816. Opinions and declarations rendered by the International Commission on Zoological Nomenclature 14(Part 1):1–42.

Hershkovitz, P. 1949. Status of names credited to Oken, 1816. Journal of Mammalogy 30(3):289–301.

Hubbs, C. L. 1926. A check-list of the fishes of the Great Lakes and tributary waters, with nomenclatural notes and analytical keys. University of Michigan Museum of Zoology Miscellaneous Publications 15:1–77 + IV plates.

Hubbs, C., and K. F. Lagler. 1947. Fishes of the Great Lakes region. Cranbrook Institute of Science Bulletin 26:1–186.

International Code of Zoological Nomenclature. 2000. Fourth Edition ('the Code'). Available: http://www.iczn.org/code

Jordan, D. S. 1917. The Genera or fishes part I. From Linneaeus to Cuvier, 1758–1833 seventy-five years with the accepted type of each. A contribution to the stability of scientific nomenclature. Leland Stanford Junior University Publications, Stanford, California University Series 27:1–161.

Jordan, D. S. 1923. A classification of fishes including families and genera as far as known. Stanford University Publications, University Series, Biological Sciences 3(2):77–243.

Jordan, D. S. 1929. Manual of the vertebrate animals of the northeastern United States inclusive of marine species13th edition. World Book Company, Yonkers-on-Hudson, New York.

Jordan, D. S., and B. W. Evermann. 1896. The fishes of North and Middle America. Bulletin of the U. S. National Museum 47(part:1):1–1240.

Jordan, D. S., and C. H. Gilbert. 1877. On the genera of North American fresh-water fishes. Proceedings of the Academy of Natural Sciences of Philadelphia 29:83–104.

Kottelat, M. 1997. European freshwater fishes. An heuristic checklist of the freshwater fishes of Europe (exclusive of former USSR), with an introduction for non-systematists and comments on nomenclature and conservation. Biologia, Section. Zoology 52(Supplement 5):1–271.

Linnaeus, C. 1758. Systema Naturae, 10th edition. (Systema naturae per regna tria naturae, secundum classes, ordines, genera, species, cum characteribus, differentiis, synonymis, locis. Tomus I. Editio decima, reformata.). Holmiae 1:1–824.

Matschie, P. 1904. Einige Bemerkungen über die Schimpansen. Sitzungs-Bericht der Gesellschaft naturforschender Freunde zu Berlin 4:55–69.

Miller, R. J., and H. W. Robison. 2004. Fishes of Oklahoma. University of Oklahoma Press, Norman.

Mitchill, S. L. 1818. Memoir on ichthyology. The fishes of New York, described and arranged. In a supplement to the Memoir… American Monthly Magazine and Critical Review 2(4):241–248.

Nelson, J. S. 1976. Fishes of the world. John Wiley and Sons, New York.

Nelson, J. S. 1984. Fishes of the world, 2nd edition. John Wiley and Sons, New York.

Nelson, J. S. 1994. Fishes of the world, 3rd edition. John Wiley and Sons, New York.

Nelson, J. S. 2006. Fishes of the world, 4th edition. John Wiley and Sons, New York.

Nelson, J. S., E. J. Crossman, H. Espinosa-Pérez, L. T. Findley, C. R. Gilbert, R. N. Lea, and J. D. Williams. 2003. The "Names of Fishes" list, including recommended changes in fish names: Chinook salmon for chinook salmon, and *Sander* to replace *Stizostedion* for the Sauger and Walleye. Fisheries 28(7):38–39.

Nelson, J. S., E. J. Crossman, H. Espinosa-Pérez, L. T. Findley, C. R. Gilbert, R. N. Lea, and J. D. Williams. 2004. Common and scientific names of fishes from the United States, Canada, and Mexico, 6th edition. American Fisheries Society, Special Publication 29, Bethesda, Maryland.

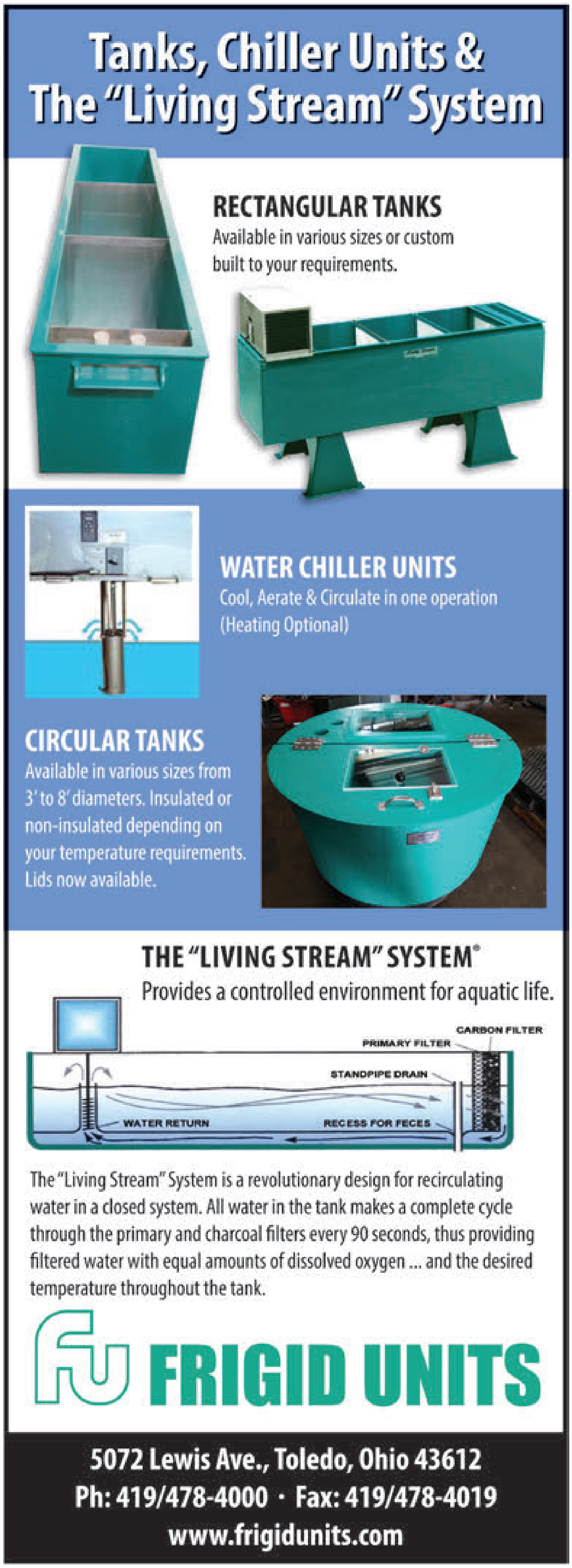
Nelson, J. S., T. C. Grande, and M. V. H. Wilson. 2016. Fishes of the world, 5th edition. John Wiley and Sons, Hoboken, New Jersey.

Oken, L. 1816. Lehrbuch der Naturgeschichte. Zweite Abtheilung. Fleischthiere. August Schmidt und Company, Donzdorf, Germany.

Oken, L. 1817. Cuvier's und Oken's zoologien naben einande gestellt. Isis, Encyclopädische Zeitung 8(148):1779–1782.

Page, L. M., H. Espinosa-Pérez, L. T. Findley, C. R. Gilbert, R. N. Lea, N. E. Mandrak, R. L. Mayden, and J. S. Nelson. 2013. Common and scientific names of Fishes from the United States, Canada, and Mexico, 7th edition. American Fisheries Society, Special Publication 34, Bethesda, Maryland.

Rafinesque, C. S. 1818. Discoveries in natural history, made during a journey through the western region of the United States. American Monthly Magazine and Critical Review 3(5):354–356.
Rafinesque, C. S. 1820. Ichthyologia Ohiensis, or natural history of the fishes inhabiting the river Ohio and its tributary streams, preceded by a physical description of the Ohio and its branches. Lexington, Kentucky.
Robison, H. W., and T. M. Buchanan. 2020. Fishes of Arkansas, second edition. The University of Arkansas Press, Fayetteville.
Schinz, H. R. 1822. Das Thierreich II. Fische, Stuttgart, Germany.
Simon, J. R. 1946. Wyoming Fishes. Wyoming Game and Fish Department. Cheyenne. Bulletin No. 4:1–129.
Smith, C. L., and R. M. Bailey. 1961. Evolution of the dorsal-fin supports of percoid fishes. Papers of the Michigan Academy of Science, Arts, and Letters 46:345–63.
Stark, J. 1828. Elements of natural history, adapted to the present state of the science, containing the generic characters of nearly the whole animal kingdom, and the descriptions of the principal species, volume 1. Vertebrata, Edinburgh, Scotland and London.
Stepien, C. A., and J. E. Faber. 1998. Population genetic structure, phylogeography and spawning philopatry in Walleye (*Stizostedion vitreum*) from mitochondrial DNA control region sequences. Molecular Ecology 7:1757–1769.
Trautman, M. B. 1957. The fishes of Ohio with illustrated keys. The Ohio State University Press, Baltimore, Maryland.
Vitins, M., R. Gaumiga, and A. Mitäns. 2001. History of Latvian fisheries research. Proceedings of the Estonian Academy of Sciences Biology and Ecology. 50(2):85–109. AFS



MAGAZINE

World Fisheries Congress 2021 – Registration Now Open

Jane Ham | SARDI. E-mail:Jane.Ham@sa.gov.au

Registration to attend the World Fisheries Congress 2021, September 20–24, is now open (available: https://wfc2021.com.au/).

Normally held every 4 years, the eighth World Fisheries Congress 2021 (WFC2021) is one of the largest gatherings of the research, industry, and management sectors to discuss the latest advances in fisheries worldwide.

The 5-day program will be delivered under the overarching theme of "Sharing our oceans and rivers—a vision for the world's fisheries." With an overwhelming response of over 1,400 abstracts submitted, WFC2021 promises a dynamic, engaging, and comprehensive program.

The event's opening address will be given by Peter Thomson, the United Nations Secretary–General's Special Envoy for the Ocean, who is responsible for driving global support for U.N. Sustainable Development Goal 14, to conserve and sustainably use the ocean's resources.

The Fijian diplomat is a founding co-chair of the Friends of Ocean Action and is a supporting member of the High-Level Panel for Sustainable Ocean Economy.

Reflecting on the importance of the congress for the future, Gavin Begg, Chair of the World Fisheries Congress, said this year's event would provide an opportunity for the global fisheries community to focus on the issues of sustainability, conservation and fisheries management:

> With increasing pressures from fishing and non-fishing activities the Congress will provide the key forum for identifying the critical developments needed over the coming decades to ensure the world's oceans, estuaries, lakes and rivers are managed sustainably for the benefit of current and future generations.

WFC2021 PLENARY SPEAKERS

Peter Thomson is the United Nations Secretary–General's Special Envoy for the Ocean, in which role he drives global support for the UN Sustainable Development Goal 14, to conserve and sustainably use the ocean's resources.

Katsumi Tsukamoto, winner of the International Fisheries Science Prize and from the University of Tokyo, is a world leader in the biology, ecology, and conservation of freshwater eels. Katsumi's research will be presented by Toyoji Kaneko, University of Tokyo, on his behalf. Kaneko is an expert in fish osmoregulation and is currently engaged in research on the application of osmoregulation to the fisheries industry, especially to land-based aquaculture of marine fish.

Manuel Barange is the Director of the Fisheries and Aquaculture Policy and Resources Division at the Food and Agriculture Organization in Rome. He has expertise in physical/biological interactions, climate and anthropogenic impacts on marine ecosystems, fish ecology, behaviour, and trophodynamics, and fisheries assessment and management.

Meryl Williams is an eminent Australian agricultural research leader and was Director–General of the WorldFish Centre, chaired the Commission for International Agricultural Research, founder and current Chair of the Gender in Aquaculture and Fisheries Section of the Asian Fisheries Society.

Beth Fulton, Principal Research Scientist with CSIRO Oceans and Atmosphere, focuses on sustainably managing potentially competing users of marine environments and adaptation to global change, including effective means of conserving and monitoring marine and coastal ecosystems. Fulton has been awarded the Science Minister's Prize for Life Scientist of the Year as a part of the Prime Ministers Science Prizes, and is a global leader in her field.

Nicholas Mandrak, Director of a professional Master's program in Conservation and Biodiversity at the University of Toronto, will be presenting joint research on behalf of Olaf Weyl, who was the Chair and Chief Scientist at the South African Institute for Aquatic Biodiversity.

Ratana Chuenpagdee, Memorial University of Newfoundland, St. John's, Canada, is leading a major global research partnership, "Too Big To Ignore," which aims to elevate the profile of small-scale fisheries and rectify their marginalization in national and international policies.

Kerstin Forsberg is the Founder and Director of Planeta Océano, a Peruvian non-profit organization empowering coastal communities in marine conservation through research, education, policy and sustainable development efforts. Her work includes research and legal protection for Giant Manta Rays *Mobula birostris* and critically endangered sawfish (Pristidae), and the consolidation of a Marine Educator's Network in Peru.

Martin Exel, of Austral Fisheries, is also the Managing Director of SeaBOS, a collaborative venture between 10 of the world's largest seafood businesses, and the Stockholm Resilience Centre in Sweden, with an aim to transform wild capture and aquaculture fisheries to sustainable seafood production and promote a healthy ocean, globally.

Matthew Osborne is a Kaurna and Narungga man and has extensive experience in Indigenous fisheries. He is the program

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leader, Aquaculture and Regional Development in Northern Territory Fisheries overseeing a range of Aboriginal and industry development programs including supporting small scale fishing and aquaculture operations in remote Aboriginal communities.

More information about this year's plenary speakers available: https://bit.ly/3wO4AG6

In Person and Virtual Registrations

Delegates will be invited to participate in person or online through a hybrid program. This ensures the Congress continues to connect the global community to discuss the sustainable development of the world's oceans, lakes, estuaries and rivers.

Virtual registration (available: https://bit.ly/2Qm05SI) will include access to all presentations, including plenary speakers for up to 6 months post congress, participation in Q&A sessions, and access to sponsors and exhibitors materials and a range of networking opportunities.

A complete program will be available by mid-2021.

Sponsorship Opportunities for WFC2021

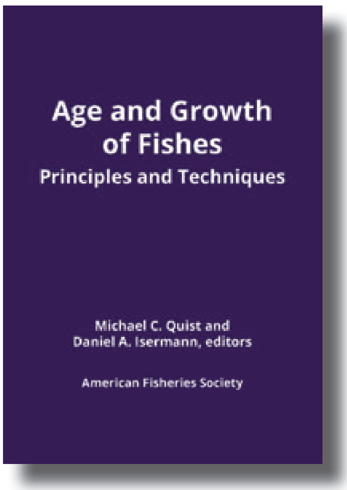
WFC2021 will bring together more than 1,500 stakeholders—including the best researchers, key industry sectors, and the world's largest and most influential marine science agencies.

The Congress offers you the opportunity to connect with and showcase your business to this large and diverse international audience.

A range of virtual sponsorship benefits have been added to the Sponsorship Prospectus (available: https://bit.ly/3d84IIK), to maximise exposure and engagement with congress participants before, during, and after the event. This includes the option of a completely virtual sponsorship package for those who are unable to travel.

For more information available: https://bit.ly/2PZBfIa AFS

Age and Growth of Fishes: Principles and Techniques



Michael C. Quist and Daniel A. Isermann, editors

359 pages, hardcover
List price: $79.00
AFS Member price: $55.30
Item Number: 550.78C
Available November 2017

Estimating age structure of fish populations and growth of individuals is fundamental to evaluating fish population demographics and dynamics. This text provides a comprehensive overview of concepts and techniques associated with estimating age and growth of fishes. Although the material presented in the book is applicable to systems around the world, the primary focus is on postlarval fish in North American freshwater systems.

The book is organized into four sections. Chapters in the first section (Chapters 1–2) provide an overview of the history and importance of age and growth information, as well as an introduction to how calcified structures grow. The second section (Chapters 3–5) focuses on validation and verification of structures, choice of structures, and sampling considerations. The third section (Chapters 6–9) provides a discussion of the most common structures used to estimate the age of fish. The last section (Chapters 10–12) details methods for data summarization and analysis.

This book is intended for practicing fisheries managers, researchers, and graduate and advanced undergraduate students.

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CALENDAR

To submit upcoming events for inclusion on the AFS website calendar, send event name, dates, city, state/province, web address, and contact information to bbeard@fisheries.org. (If space is available, events will also be printed in *Fisheries magazine.*) More events listed at www.fisheries.org

July 5–8, 2021
Fisheries Society of the British Isles 2021 Symposium | Virtual |
http://bit.ly/2JMIeRT

July 12–14, 2021
Ecological and Evolutionary Ethology of Fishers Virtual Conference | Virtual |
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July 20–23, 2021
ICAST | Orlando, FL | https://icastfishing.org/

July 25–30, 2021
12th Symposium on European Freshwater Sciences | Virtual |
https://www.sefs12.com/

July 27–29, 2021
27th Annual Aquaculture Drug Approval Coordination Workshop | Virtual |
http://bit.ly/3qzTekN

August 11–14, 2021
Aquaculture America | San Antonio, TX |
https://www.was.org/meeting

September 3–11, 2021
IUCN World Conservation Congress | Marseille, France |
https://bit.ly/3dZnJMV

September 6–10, 2021
ICES Annual Science Conference | Copenhagen, Denmark |
https://bit.ly/3bTD2nk

September 20–24, 2021
8th World Fisheries Congress | Adelaide, Australia |
https://wfc2021.com.au/

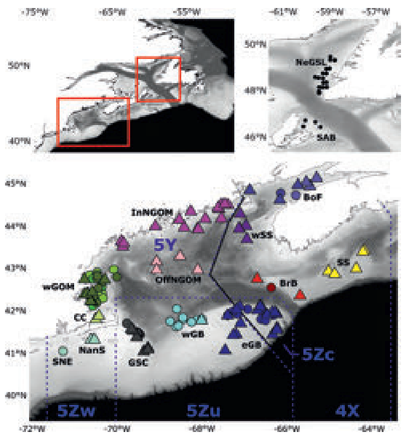
September 26, 2021
World Rivers Day | Worldwide |
http://worldriversday.com/ AFS

JOURNAL HIGHLIGHTS

Transborder Gene Flow Between Canada and the USA and Fine-Scale Population Structure of Atlantic Cod in the Broader Gulf of Maine Region

Gregory Neils Puncher, Yanjun Wang, Ryan Martin, Gregory DeCelles, Steven X. Cadrin, Douglas Zemeckis, Sherrylynn Rowe, Nathalie M. Leblanc, Genevieve J. Parent, and Scott A. Pavey

Transactions of the American Fisheries Society



- A southwesterly decrease in the proportion of Atlantic Cod *Gadus morhua* super gene haplotypes may indicate gene flow from areas north of 45°N.
- Atlantic Cod from both the northern Gulf of Maine and Bay of Fundy were genetically distinct from all other cod in the Gulf of Maine region, suggesting that local spawning groups may still be active.
- Genetic similarities between Atlantic Cod from Browns Bank and eastern Georges Bank indicate that gene flow across the U.S. and Canada border is ongoing.
- Our results will help to better define the stocks in order to guide the implementation of management strategies in the USA and Canada, which should consider rebuilding exhausted and genetically isolated populations.

[Image credit: Authors]

DOI: https://doi.org/10.1002/tafs.10305

Ingestion of PIT Tags by Hatchery-Reared Juvenile Steelhead and Subsequent Detection at Main-Stem Dams in the Columbia River Basin

Douglas P. Peterson and Rod O. Engle

North American Journal of Fisheries Management

- PIT tags are used to tag millions of Pacific salmon *Oncorhynchus* spp. in the Columbia River basin and monitor their movement and survival through the river system and the hydroelectric dams that comprise the Federal Columbia River Power System.
- An important assumption about the analysis of the tagging data is that tags are not lost. Loss or "shedding" of PIT tags by juvenile salmon can complicate the analysis. Tag shedding rates are often assumed to be very low, but this is not always the case.
- To study the fate of shed tags during hatchery rearing of salmon, we simulated tag shedding by releasing loose PIT tags into raceways and tanks containing summer steelhead *Oncorhynchus mykiss*.
- We found that juvenile steelhead consumed PIT tags, and between 20–52% of the loose tags were present in smolts at the time of their release. Tags remained within fish during some of their seaward migration, but it appears that some fish also excreted tags as they migrated.

[Image credit: USFWS Pacific Southwest Region/Dan Cox]

DOI: https://doi.org/10.1002/nafm.10610

Age, Growth, and Mortality of Atlantic Tripletail in the North-Central Gulf of Mexico

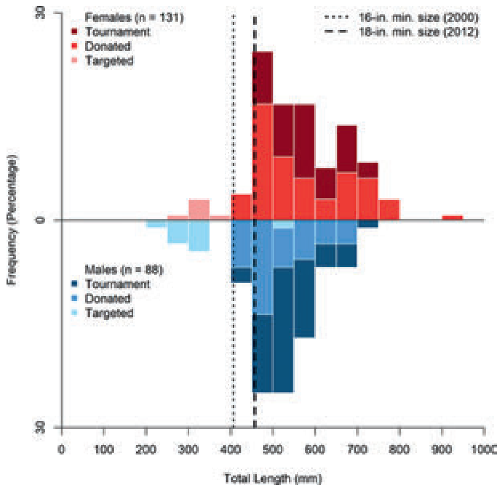
Amanda E. Jefferson, Matthew B. Jargowsky, Meagan N. Schrandt, Pearce T. Cooper, Sean P. Powers, John J. Dindo, and J. Marcus Drymon

Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science

- In the southeastern USA and Gulf of Mexico, Atlantic Tripletail *Lobotes surinamensis* are increasingly targeted by recreational anglers, indicating that stock status should be assessed.
- From 2012–2019, Atlantic Tripletail (N = 230, including a near record-size specimen) were collected from the north-central Gulf of Mexico via hook-and-line and aged using otoliths and first dorsal spines.
- Otoliths produced higher percent agreement and lower average percent error between readers compared to spines. For both otolith- and spine-based sex-specific data, the best-fitting version of the von Bertalanffy growth function permitted L_∞ to vary by sex.
- Empirical, life history-based mortality estimates suggested low levels of exploitation.

[Image credit: Authors]

DOI: https://doi.org/10.1002/mcf2.10146



Reproductive Strategy of a Continental Shelf Lane Snapper Population from the Southern Gulf of Mexico

Jorge Trejo-Martínez, Thierry Brulé, Natalia Morales-López, Teresa Colás-Marrufo, and Manuel Sánchez-Crespo

Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science

- The Lane Snapper *Lutjanus synagris* reproductive strategy remains unclear, since studies on the reproduction of this species have been primarily focused on populations associated with islands.
- As expected, the Lane Snapper from the Yucatan Peninsula (southern Gulf of Mexico) exhibited a reproductive seasonality and sexual maturity characteristic of lutjanid populations associated with continental margins, and with shallow habitats.
- This species exhibits asynchronous oocyte recruitment and spawns by batches. Preliminary results on batch fecundity, relative batch fecundity, spawning fraction and interval and the duration of the individual spawning season are also presented.
- Results were compared with data available from both island and continental Lane Snapper populations. It was observed that Lane Snapper populations do not always conform to the pattern of reproductive seasonality and/or size at sexual maturity with regard to habitat type.

[Image credit: SEFSC Pascagoula Laboratory; Collection of Brandi Noble, NOAA/NMFS/SEFSC.]

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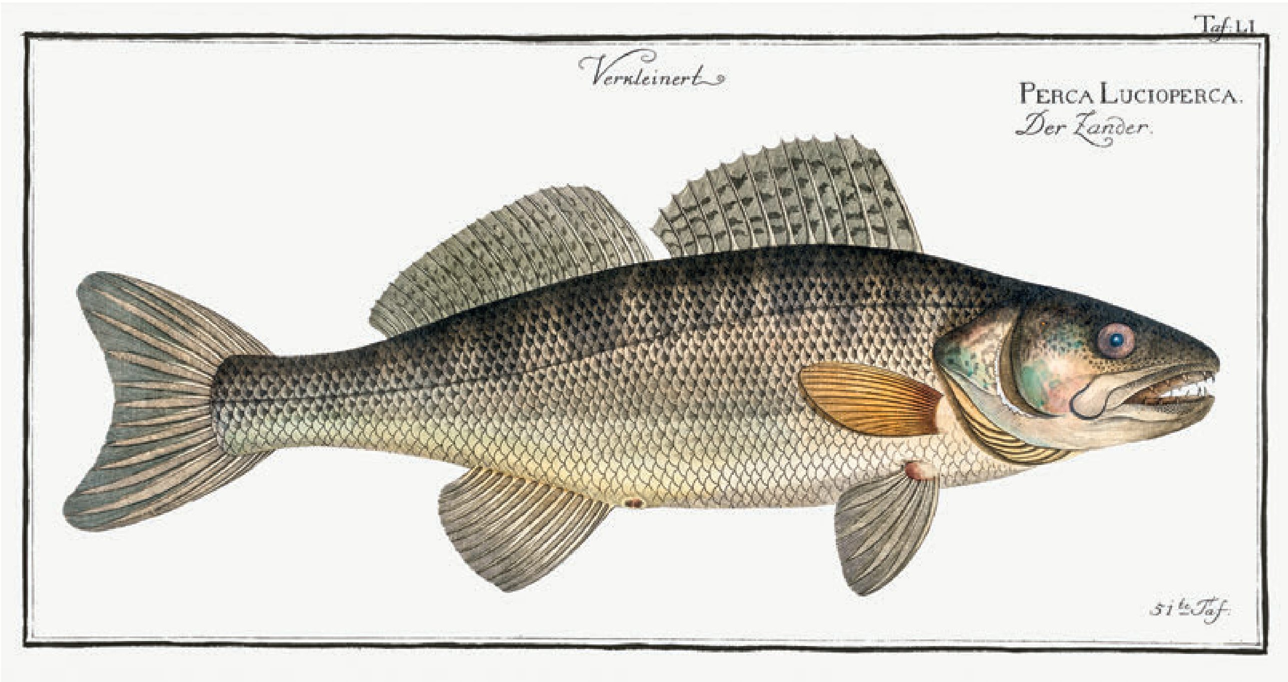
BACKPAGE

Picke-Perch



Picke-Perch (*sic*) *Perca Lucioperca* from *Ichtylogie, ou Histoire naturelle: génerale et particuliére des poissons* (1785–1797) by Marcus Elieser Bloch. Pikeperch, which are currently identified by the scientific name *Sander lucioperca*, is also known as zander or sander, are native to western Europe, and belong to the same genus as the Walleye *S. vitreus* in North America. Both species are popular game fish and are the topic of contention discussed by Bruner (this issue).

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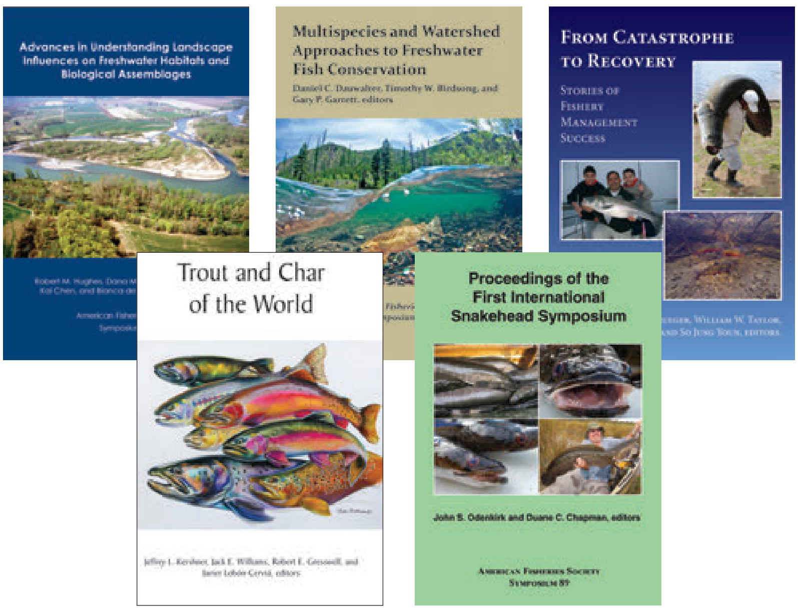

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