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Using the telecoupling framework to improve Great Lakes fisheries sustainability

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Fisheries are coupled human and natural systems across space and time, involving movements of fish, money, and information in a globalized world. However, these social-ecological interactions over local to global scales are largely absent from the fisheries literature, as fisheries research to date has often been discipline- and location-specific. We analyzed this knowledge gap by using an emerging coupled human and natural systems research paradigm – the telecoupling framework – to investigate social-ecological interactions over distances (i.e. telecouplings) in the Great Lakes salmonine (i.e. Coho Salmon Oncorhynchus kisutch*, Chinook Salmon* O. tshawytscha*) fishery. Since the 1960s, this fishery has involved telecoupled movements of fish, money, and information over relatively long distances facilitated by numerous individual and organizational agents. These telecouplings have been characterized by diverse social-ecological causes (e.g. decline of commercial fisheries, rising incomes and greater leisure time for recreational fishing) and effects (e.g. salmonine stocking, creation of angling- and tourism-based economies). Telecouplings are critical for fisheries professionals to consider because they promote holistic understanding of fisheries management while occasionally confounding conservation efforts (e.g. salmonine stocking spreads diseases and parasites and changes fish community structure and genetic integrity). Hence, fisheries professionals will benefit from using the telecoupling framework to optimize favorable and reduce unfavorable telecouplings and thereby enhance fisheries management programs. Overall, the telecoupling framework advances fisheries science by enabling fisheries professionals to systematically understand the causes and consequences of complex social-ecological fisheries interactions and develop informed strategies for sustainable fisheries management and governance throughout the Great Lakes and the world.*

Keywords: Chinook Salmon, Coho Salmon, fisheries management

Introduction

In a globalized world, the exchange of goods, services, capital, and information is accelerating through advancements in trade, transportation, and technology (Liu et al., 2007a). Although globalization affects society and the environment both locally and globally, human systems and ecosystems have traditionally been studied separately (Liu et al., 2015). However, humans and the environment are not independent entities but rather tightly linked in coupled human and natural systems (Liu et al., 2007a, 2007b), a concept that has implicitly – if not always explicitly – undergirded

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the work of historic scientists like Dr. Henry A. Regier. Dr. Regier is a decorated fisheries scientist whose prolific research and teaching career extended throughout the Great Lakes basin and the world. Although Henry is well-known for championing ecosystem-based management in the Great Lakes, he is recognized worldwide for his contributions to the Food and Agriculture Organization of the United Nations, International Biological Program, and numerous other global initiatives. Henry's tireless efforts to merge the ecological and human dimensions of fisheries science provide a critical backdrop for the present study.

One method for operationalizing coupled human and natural systems research is the telecoupling framework (Liu et al., 2013), an approach for studying social-ecological interactions between human and natural systems over distances (i.e. telecouplings; Liu et al., 2013). The telecoupling framework deconstructs telecouplings into five components: systems, flows, agents, causes, and effects (Figure 1). Flows are movements of fish, money, and information that connect systems, defined as sending systems (those that send flows), receiving systems (those that receive flows), and spillover systems (those that influence or are affected by flows between sending and receiving systems; Liu et al., 2013). Flows are facilitated by agents (e.g. individuals, agencies, governments) with underlying causes and resultant effects that can be environmental, economic, political, social, or cultural in nature (Figure 1). The telecoupling framework's systematic structure can help reveal leverage points (i.e. areas for effective management/policy intervention) to enhance governance of coupled human and natural systems for the benefit of society and the environment. For instance, the telecoupling framework promotes holistic, flow-centered management of Kirtland's Warbler *Setophaga kirtlandii*, a species of conservation concern, by allowing biologists and policy makers to manage telecouplings (e.g. intercontinental warbler migration, monetary exchange) as opposed to individual sites or localized issues (Hulina et al., 2017).

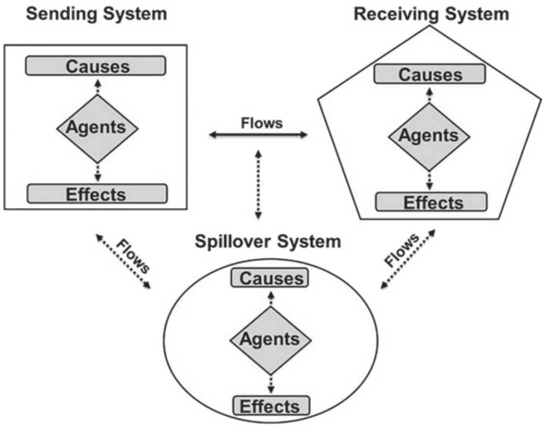

Figure 1. Conceptual diagram of telecoupling (human-nature interactions between two or more distant coupled systems; modified from Liu et al. 2013). The diagram depicts five major components and interrelationships: systems (sending, receiving, and spillover), flows, agents, causes, and effects.

To date, the telecoupling framework has been used to improve management and governance of terrestrial coupled human and natural systems by illustrating social-ecological linkages associated with land-based issues such as land-use/land cover change, species invasion and migration, urbanization, tourism, and trade (Liu, 2014; Fang and Ren, 2017; López-Hoffman et al., 2017; Silva et al., 2017; Sun et al., 2017). Although the telecoupling framework is increasingly being applied to aquatic systems such as fisheries (Carlson et al., 2017a, 2018a) and urban water systems (Deines et al., 2016; Liu et al., 2016), there are many opportunities to further investigate aquatic telecouplings and thereby enhance the management and governance of aquatic coupled human and natural systems. For instance, establishment of a recreational fishery for Coho Salmon *Oncorhynchus kisutch* and Chinook Salmon *O. tshawytscha* in the Laurentian Great Lakes in the 1960s caused complex, telecoupled social-ecological interactions involving fish, money, information, and people. Telecouplings in this fishery (hereafter "salmonine fishery") are important to study because they fundamentally changed Great Lakes ecosystems (e.g. predator-prey interactions, trophodynamics) and economies (e.g. angling, tourism) with far-reaching social-ecological effects (Crawford, 2001; Taylor et al., 2011). However, the Great Lakes have not been investigated using the telecoupling framework, meaning the salmonine fishery is managed without crucial information regarding telecoupled social-ecological interactions (e.g. fish movement, monetary exchange, knowledge transfer).

The goal of this paper was to use the telecoupling framework to investigate social-ecological interactions in the Great Lakes salmonine fishery and thereby promote the holistic, sustainable fishery management and governance that conservation leaders like Henry Regier have long envisioned. We focused on the Great Lakes salmonine fishery from its inception in the 1960s to the present day because it is major contributor to the identity and social-ecological importance of the Great Lakes (Crawford, 2001; Taylor et al., 2011). Our aim was to deconstruct telecouplings in the Great Lakes salmonine fishery, particularly their systems, flows, agents, causes, and effects, and integrate this information using the telecoupling framework to enhance fishery sustainability. Overall, we sought to demonstrate how the telecoupling framework is a useful tool for understanding the presence and magnitude of social-ecological linkages in the Great Lakes salmonine fishery and thereby promote telecoupled fisheries governance – that which explicitly accounts for and manages telecouplings over space and time to enhance fisheries sustainability. The telecoupling framework is a natural extension of the ecosystem-based, socially-informed fisheries management that Henry Regier advanced throughout his illustrious career; we are honored to explore fisheries telecouplings as a tribute to his lasting influence on the fisheries profession.

Telecouplings in the Great Lakes Salmonine fishery

Introductions of salmonine fishes into the Great Lakes date back to the 1870s, when native Lake Trout *Salvelinus namaycush*, Brook Trout *S. fontinalis*, and Atlantic Salmon *Salmo salar* (native to Lake Ontario) declined due to pollution, damming, and overharvest (Crawford, 2001). In response, managers introduced species such as Brown Trout *Salmo trutta*, Arctic Charr *Salvelinus alpinus*, and Pacific salmonines such as Coho Salmon, Chinook Salmon, Kokanee Salmon *Oncorhynchus nerka*, and Rainbow Trout *O. mykiss*. Commercial fishing for Lake Trout and Lake Whitefish *Coregonus clupeaformis* predominated in the Great Lakes prior to the 1960s but then declined due to overharvest and habitat degradation, providing an opportunity for fisheries managers to establish a recreational salmonine fishery. Below we describe how this fishery has historically involved – and continues to involve – diverse telecouplings that influence salmonine management, governance, and the sustainability of fishery ecosystems and human systems.

Systems

Beginning in 1964, Coho Salmon and Chinook Salmon eggs were sent to Michigan (i.e. receiving system) from hatcheries in sending systems such as Oregon and Washington (Crawford, 2001; Table 1, Figure 2). After eggs were reared to fry, Michigan hatcheries functioned as sending systems, delivering salmon smolts to lakes Michigan and Superior and eventually the other Great Lakes (Crawford, 2001). Stocking involved spillover systems, including the lakes, economies, fisheries management agencies, and people that were affected by salmonine introductions in lakes Michigan and Superior. For instance, adult Coho Salmon originally stocked in Lake Michigan moved into lakes Huron and Erie (i.e. spillover systems) and were caught by recreational fishers as early as 1967, much to the surprise and delight of anglers and businesses such as bait and tackle shops, hotels, and marinas (Crawford, 2001; Table 1). "Salmon fever" spread quickly to other spillover systems, including fisheries agencies in Wisconsin, Ohio, Pennsylvania, New York, and Ontario that welcomed Coho Salmon eggs from Michigan and instituted stocking programs in 1967 to establish recreational fisheries (Tanner and Tody, 2002).

Financial telecouplings in the Great Lakes salmonine fishery involve sending systems such as state legislatures, the federal government, and private conservation organizations and their respective funding sources, including state game and fish funds and the federal Dingell-Johnson Sport Fish Restoration Program (Scott, 2015; United States Fish and Wildlife Service (USFWS), 2016a). Fishery finances – allocated for stocking, habitat rehabilitation, research, and related fisheries conservation activities – flow from sending systems to receiving systems such as fisheries management agencies, universities, and regulatory bodies, including state Departments of Natural Resources, the United States Geological Survey (USGS), and the Great Lakes Fishery Commission (GLFC; Table 1, Figure 2). Spillover systems are those that affect, or are affected by, flows of fishery finances. For

Table 1. Summary of systems, flows, agents, causes, and effects associated with telecouplings in the Great Lakes salmonine fishery (i.e. long-distance movements of fish, money, and information).

Components of the telecoupling framework		Examples
Systems (units in which humans and nature interact)	Sending (origins/ sources/donors)	Oregon, Washington (fish); Michigan state legislature, Federal agencies, private conservation organizations (money); fisheries agencies and regulatory bodies (information); states within and beyond Great Lakes basin (people); Crawford (2001), Scott (2015), USFWS (2016a)
	Receiving (destinations/ recipients)	Michigan fisheries agencies (fish, money, information, people); individuals and organizations that obtain fisheries information (e.g. public citizens, policy makers, non-governmental organizations); Crawford (2001), Scott (2015), USFWS (2016a)
	Spillover (systems that affect/are affected by sending-receiving system interactions)	Lake basins and economies in the Great Lakes (fish); fisheries agencies outside Michigan (money, information); people outside Michigan (e.g. anglers, fisheries professionals) (information); states such as Illinois, Minnesota, Wisconsin, etc. (people); Crawford (2001), Knuth et al. (2002)
Flows (movements of material, information, people, etc., between systems)		Fish (e.g. Coho Salmon, Chinook Salmon); money; information and knowledge (e.g. fisheries management approaches, salmonine rearing and stocking data) sent via letters, phone calls, newspapers, etc.; people (e.g. anglers, tourists, fisheries professionals, policy makers); Parsons (1973), MacCrimmon (1977), Ford (1997), Kocik and Jones (1999), Crawford (2001), Tanner and Tody (2002), ASA (2013), USFWS (2016b)
Agents (autonomous decision-making entites that directly or indirectly facilitate or hinder telecouplings)		Fisheries professionals and management agencies (e.g. Michigan, Ontario, Oregon, Washington); anglers, tourists, policy makers, public citizens; Michigan state legislature, Federal agencies, private conservation organizations; news media outlets, academic journals, book publishers, website developers, etc.; businesses (e.g. restaurants, hotels, sporting goods); Crawford (2001), Tanner and Tody (2002), ASA (2013), Scott (2015)
Causes (factors that influence emergence or dynamics of telecouplings)	Environmental	Aquatic habitats suitable for salmonine establishment in the Great Lakes, large salmonine populations in West Coast sending systems and thus abundant eggs for shipment to the Great Lakes, Great Lakes Alewife in need of predatory control; Crawford (2001), Goddard (2002), Tanner and Tody (2002)

(*Continued on next page*)

Table 1. Summary of systems, flows, agents, causes, and effects associated with telecouplings in the Great Lakes salmonine fishery i.e. long-distance movements of fish, money, and information. (*Continued*)

Components of the telecoupling framework		Examples
	Socioeconomic	Availability of fisheries agency funds for establishing the salmonine fishery and associated infrastructure, citizens' expendable incomes for angling; Tanner and Tody (2002)
	Political	Decline of commercial fishing in the Great Lakes; Crawford (2001), Tanner and Tody (2002)
	Technological	Improved fishing technologies (e.g. boats, downriggers, radar, lures); Tanner and Tody (2002)
	Cultural/humanitarian	Public desire for recreational fishing opportunities, increased leisure time in the 1960s relative to previous years, professional and social networks for rapid information dissemination regarding the salmonine fishery; Crawford (2001), Tanner and Tody (2002)
Effects (impacts or consequences of telecouplings)	Environmental	Increased salmonine abundance and decreased forage fish abundance, salmonine movement and migration to lakes where they were not stocked; Crawford (2001), Tanner and Tody (2002), GLFC (2015)
	Socioeconomic	Increased angler catch and harvest, heightened public enthusiasm for salmonine fishes and angling, public support for continued salmonine stocking, development of angling-based and tourism-based Great Lakes economies, improved fishing technologies, increased recreational boating and tourism (e.g. birdwatching, beach use, park visitation); Tanner and Tody (2002), Austin et al. (2007), Austin et al. (2008), Krantzberg and deBoer (2008), USACE (2008), ASA (2013), Allan et al. (2015)

example, fisheries management agencies and anglers in smaller states, or those with fewer license holders, may experience spillover effects resulting from a greater proportion of Dingell-Johnson funds being allocated to larger states and those with more anglers.

In information exchange telecouplings, sending systems include fisheries management agencies, universities, and regulatory bodies that generate fisheries information (e.g. fish abundance, growth, management approaches; Table 1, Figure 2). Receiving systems encompass public citizens, policy makers, non-governmental organizations (NGOs), and other stakeholders that obtain fisheries information and communicate or act on it via phone calls, legislation, peer-reviewed manuscripts, popular articles, social media, etc. For instance, after a state Department of Natural Resources publishes a report describing high Chinook Salmon abundance and catch rates in Lake Michigan, anglers within (and beyond) the Great Lakes basin may receive this information and respond by booking salmon charter fishing trips, hotels, etc. Spillover systems are the places in which individuals and organizations are not the intended targets of fisheries information but nonetheless use it to learn about the Great Lakes salmonine fishery (Table 1). For

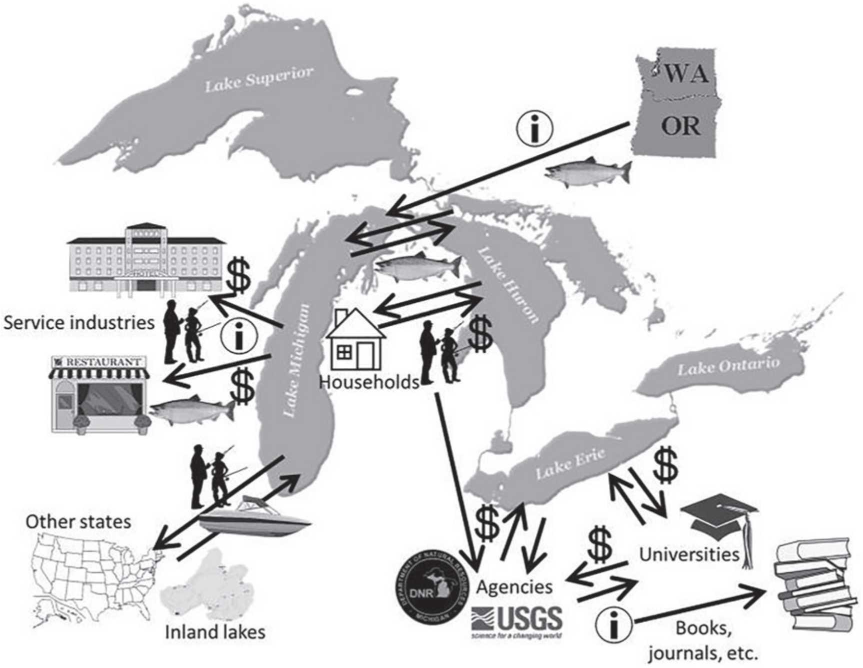

Figure 2. Application of the telecoupling framework to the Great Lakes salmonine fishery with arrows illustrating telecouplings related to fish stock enhancement, fishery finances, and information exchange (denoted by the "i" symbol). The fisherman and fisherwoman symbols represent anglers and other fisheries stakeholders (e.g. tourists, fisheries professionals) that exhibit telecoupled movements within and beyond the Great Lakes basin.

example, Michigan anglers may tell their friends from Wisconsin and Minnesota (i.e. spillover systems) about high Chinook Salmon catch rates in Lake Michigan, causing non-resident anglers to travel to Michigan and fish.

Flows

Flows are telecoupled movements of fish, money, and fisheries information among coupled human and natural systems. The major flow associated with stocking telecouplings is the movement of salmonine fishes from sending to receiving systems (Table 1, Figure 2). For instance, one million Coho Salmon eggs were shipped from Oregon to Michigan in December 1964 and January 1965 (Crawford, 2001). In the spring of 1966, Michigan fisheries professionals stocked 822 000 Coho Salmon smolts into tributaries of lakes Michigan and Superior, followed by more than 800 000 Chinook Salmon smolts in 1967 (Parsons, 1973; MacCrimmon, 1977). Since then, hundreds of millions of Coho Salmon and Chinook Salmon have been stocked by fisheries management agencies and, more recently, Great Lakes angling groups (Crawford, 2001).

Money is the principal flow in financial telecouplings (Table 1), moving among human components of the salmonine fishery, including anglers, fishery management agencies, universities, charter fishing companies, bait and tackle shops, restaurants, and hotels (Figure 2). For example, in fiscal year 2015-2016, funding from the Michigan state legislature for Great Lakes fishery management (including but not limited to salmonines) totaled \$20.1 million, with an additional \$2.2 million from the General Fund/ General Purpose funding (Scott, 2015) and \$11.4 million from the Dingell-Johnson Sport Fish Restoration Program (USFWS, 2016b).

In information exchange telecouplings, the principle flow is the movement of information via word of mouth, phone calls, letters, articles, social media, television programs, scientific meetings, etc. (Table 1, Figure 2). In the early 1960's, fisheries managers in Michigan exchanged letters and phone calls with hatchery personnel in Oregon, promoting information flow that culminated in salmon egg shipments to Michigan (Tanner and Tody, 2002). After smolts were introduced in 1966, newspaper reports spread information about the stockings to thousands of readers, rousing excitement about angling among anglers and fisheries professionals. In 1967, interest in salmonine stocking programs was so large that the Michigan Department of Natural Resources (MDNR) sent Coho Salmon to fisheries management agencies in Wisconsin (N = 300 000 eggs), Ohio (N = 200 000), Pennsylvania (N = 300 000), New York (N = 100 000), and Ontario (N = 200 000) (Crawford, 2001; Tanner and Tody, 2002).

Agents

Agents are the individuals, organizations, governments, and other entities that influence flows between sending and receiving systems. For instance, agents of stocking telecouplings in the 1960s were the people and organizations (e.g. fisheries management agencies) that made stocking possible in sending and receiving systems (Crawford, 2001; Table 1, Figure 2). Agents in spillover systems were the fisheries management agencies and people located in Wisconsin, New York, Ontario, and other states/provinces outside sending and receiving systems who influenced or were affected by salmonine stockings (Table 1). Today, agents of stocking telecouplings include fisheries management and extension professionals in states and provinces throughout the Great Lakes basin, as well as the anglers, tourists, and public citizens who are affected directly or indirectly by the salmonine fishery.

In financial telecouplings, the Michigan state legislature, federal agencies such as the U.S. Fish and Wildlife Service, and private conservation organizations (e.g. angling groups) are the agents in sending systems that provide money to agents in receiving systems, including the MDNR and other state and provincial fisheries agencies that manage the Great Lakes salmonine fishery (Table 1, Figure 2; Scott, 2015). Agents in spillover systems are the fisheries management agencies and stakeholders – including fisheries professionals, anglers, tourists, and the general public – who affect, or are affected by, telecouplings connecting sending and receiving systems.

In information exchange telecouplings, agents in sending systems are the people and organizations that produce information on the Great Lakes salmonine fishery, including scientists, managers, biologists, policy makers, and their respective employers (Table 1, Figure 2; Crawford, 2001; Tanner and Tody, 2002). Agents in receiving systems include news media outlets, academic journals, book publishers, and website developers that obtain fisheries information and disseminate it scientific and lay audiences such as fisheries professionals, policy makers, conservationists, anglers, and public citizens (Figure 2). These audiences are often located in spillover systems outside of the systems that send and initially receive fisheries information (Table 1).

Causes

Causes are the reasons (e.g. environmental, socioeconomic, political, cultural) why telecouplings occur. For example, millions of people lived within driving distance of the Great Lakes in the early 1960s and had expendable incomes and more leisure time than their predecessors, fostering demand for recreational fishing opportunities (Tanner and Tody, 2002; Table 1). As commercial fishing became an obsolete, politically weak enterprise due to overharvest and habitat degradation, fisheries management agencies focused on fisheries conservation and public service by creating Coho Salmon and Chinook Salmon stocking programs (Table 1, Figure 2). Moreover, by the early 1960s, Great Lakes fish communities and commercial fisheries had been severely impacted by parasitic Sea Lamprey *Petromyzon marinus* (Goddard, 2002). As a result of lamprey-induced mortality and overharvest, native Lake Trout became extinct in lakes Michigan, Ontario, and Erie and significantly reduced in lakes Huron and Superior (Tanner and Tody, 2002). In the absence of predation by Lake Trout, non-native Alewife became highly abundant in lakes Michigan, Huron, and Ontario. However, poor growing conditions resulting from high densities coupled with spawning stress and rapidly fluctuating water temperatures caused massive Alewife die-offs wherein dead fish plugged municipal and industrial water intakes and littered beaches along the Great Lakes coast, causing significant aesthetic and economic costs (i.e. > $100 million;

Greenwood, 1970). Overall, socioeconomic, political, and ecological causes made the 1960s an opportune time for Great Lakes fisheries managers to introduce salmonine fishes that could harness public enthusiasm for recreational fishing and also help contain Alewife population in need of predatory control (Table 1). Today, causes of salmonine stocking in the Great Lakes reflect fisheries agencies' emphasis on maximizing angling opportunities, maintaining broodstock, optimizing hatchery logistics (e.g. truck capacity, fuel costs), and promoting natural reproduction where possible (MDNR, 2016).

Ecological, socioeconomic, and political conditions also influence financial telecouplings in the Great Lakes salmonine fishery. For instance, in the 1960s, monetary flows for salmonine introduction were caused by lamprey-induced mortality of native fishes, over-abundant Alewife populations, and public excitement about salmonine angling opportunities (Table 1; Crawford, 2001; Goddard, 2002; Tanner and Tody, 2002). Moreover, monetary telecouplings that helped establish the salmonine fishery were caused by the decline of commercial fishing in the Great Lakes, political momentum for salmonine stocking, and the availability of salmonine eggs from West Coast states (Table 1; Crawford, 2001; Tanner and Tody, 2002). These conditions were conducive for monetary flows into Great Lakes salmonine stocking programs, fishery infrastructure (e.g. hatcheries), and angling- and tourism-related industries (e.g. charter boats, marinas, fishing equipment, restaurants, hotels; Tanner and Tody, 2002; Figure 2). Today, monetary telecouplings are driven by the diverse social, psychological, aesthetic, ecological, and educational values associated with the Great Lakes salmonine fishery. For instance, the fishery supports local economies via angling- and tourism-driven revenue as well as coastal community development, family cohesion, and stress reduction resulting from angling and tourism activities (Knuth et al., 2002) – all of which promote continued monetary investment in the fishery.

A number of factors have caused information exchange telecouplings in the Great Lakes salmonine fishery. Historically, the public's desire to participate in recreational fishing stimulated support for fishery establishment (Table 1), which involved communication among anglers and public citizens as well as reporting by the news media (Crawford, 2001; Tanner and Tody, 2002). In addition, the initial success of Coho Salmon stockings by the MDNR caused flows of information to fisheries management agencies in other states that culminated in salmonine introductions into lakes Huron, Erie, and Ontario (Table 1, Figure 2). Moreover, as the Great Lakes salmonine fishery developed, scientists, managers, and biologists caused information flows by communicating fisheries data to scientific and lay audiences via journal articles, books, newspaper articles, reports, scientific conferences, and public meetings (Crawford, 2001; Tanner and Tody, 2002; Figure 2).

Effects

Effects are the socioeconomic and environmental impacts of telecouplings. In stocking telecouplings, historical stocking efforts bolstered the abundance of Coho Salmon and Chinook Salmon in lakes Michigan and Superior, causing angler catch rates to increase and public enthusiasm for recreational fishing to soar (Tanner and Tody, 2002; Table 1). The initial success of the salmonine fishery, both ecologically and socioeconomically, fostered subsequent stocking by fisheries management agencies and increased the fishery's public popularity (Table 1, Figure 2). However, with continual stocking, salmonine populations have at times become too large for their prey base, causing managers to reduce stocking in recent years (i.e. 1999, 2006, 2013) to reduce predation pressure on Alewife, which also suffered from reduced food availability due to plankton declines caused by Zebra Mussels *Dreissena polymorpha* (GLFC, 2017). Another effect of stocking is the movement of salmonine fishes within and among Great Lakes basins to areas where they were not stocked (Table 1, Figure 2), which can complicate fishery management efforts by, for example, increasing fish abundance, competition, predation, and genetic introgression (Crawford, 2001).

The principal effect of financial telecouplings was the establishment of a vibrant recreational salmonine fishery in the Great Lakes, which has stimulated continued monetary flows within and beyond the fishery. Fishery investments represent a foundation for angling- and tourism-based economies and indeed the cultural importance of Great Lakes salmonine fishing (Table 1). For instance, the salmonine fishery provides $7.2 billion in annual economic benefit to the Great Lakes basin, driven by flows of money from anglers, boaters, and tourists to service industries such as restaurants, hotels, marinas, zoos, and aquaria (Tanner and Tody, 2002; American Sportfishing Association, 2013). Moreover, annual angling ($3 billion) and boating ($3.8 billion) expenditures in the Great Lakes basin provide jobs for 60 000 people (United States Army Corps of Engineers, 2008).

Since the 1960s, information exchange telecouplings have culminated in today's internationally recognized, socioeconomically important Great Lakes salmonine fishery (Table 1). For instance, scientific and news media reports about salmonine stocking and written/oral communications involving fisheries agencies and extension organizations have greatly increased the fishery's visibility. As a result, conservation organizations have provided hundreds of millions of dollars for research to protect and restore Great Lakes fish populations and their habitats, including salmonines (Great Lakes Fishery Trust, 2019). A principal effect of these information (and associated financial) telecouplings has been to advance understanding of the Great Lakes salmonine fishery, leading to informed management and policy programs. Policies such as the Joint Strategic Plan for Management of Great Lakes Fisheries (originally written in 1981) are a foundation for sustainable fisheries management and are continually updated to address changing social-ecological conditions (GLFC, 2007).

Implications for Great Lakes fisheries management and governance

The telecoupling framework contributes to Great Lakes fisheries science, management, and governance in multiple ways. First, the telecoupling framework is conducive for systematically evaluating the systems, flows, agents, causes, and effects that connect humans and ecosystems in Great Lakes fisheries. Providing an organized, logical approach for evaluating the causes and consequences of social-ecological conditions and their interactions in Great Lakes fisheries, the telecoupling framework offers a roadmap for understanding and managing these fisheries as coupled human and natural systems. This is especially important in the fisheries field, wherein causes and effects of events (e.g. population booms, stock collapses, invasive species introductions) are often ambiguously connected (Fulton et al., 2011); the telecoupling framework helps fill this knowledge gap by facilitating rigorous causality assessments (Carlson et al. 2018b). Second, the telecoupling framework offers a useful approach for conceptualizing Great Lakes fisheries spillover systems, which are not well-understood but exhibit telecouplings that have important effects on fisheries management and governance outcomes. For instance, salmonine fishes stocked into one of the Great Lakes (e.g. Huron) can move into new basins (e.g. Michigan), affecting fish communities and allied human systems (e.g. recreational fisheries) by increasing fish densities, angling catch rates, intraspecific and interspecific competition, predation, and genetic introgression. On the other hand, spillover systems that acquire telecoupled fisheries information (e.g. population assessment techniques, harvest strategies) may benefit from increasingly effective fisheries management approaches through, for instance, interagency collaborations and public engagement activities (Carlson et al., 2017b).

A third contribution of the telecoupling framework for Great Lakes fisheries sustainability is the identification of complex fisheries dynamics. For example, the growth of the Great Lakes salmonine fishery from a relatively small operation to its current status as a globally important, telecoupled human and natural system (Crawford, 2001; Tanner and Tody, 2002; Allan et al., 2015) would have been difficult to predict in the 1960s, making it a "surprise" in the telecoupling lexicon (Liu et al. 2013, 2015). Identifying surprises, feedbacks, multiscalarity, and other complex fisheries dynamics is challenging, if not impossible, using conventional (i.e. non-telecoupling) fisheries investigations that do not account for social-ecological interactions between human and natural systems over space and time. Fourth, when applied to Great Lakes fisheries, the telecoupling framework has notable flexibility (i.e. delineating social-ecological conditions in different fisheries) and applicability (i.e. transforming scientific results into management and governance programs). For example, Great Lakes fisheries professionals can use the telecoupling framework to develop a decision-support tool to assist anglers who pursue salmonids, percids, centrarchids, and other fishes in choosing fishing locations based on ecological (e.g. fish abundance, size) and cultural (e.g. restaurants, hotels, museums) information. Such a platform could expand on the online, map-based Trout Trails program operated by the MDNR (MDNR, 2019) by coupling information on ecosystems and human systems over distances (i.e. telecouplings) for a variety of fishes. Altogether, these diverse contributions enable the telecoupling framework to advance beyond monothematic approaches historically used in fisheries science that emphasize either ecological or socioeconomic outcomes, rather than their interactions. Ultimately, the telecoupling framework yields integrative, adaptive approaches for Great Lakes fisheries management and governance that are rooted in knowledge of local and distant social-ecological conditions, an important contribution to fisheries science and practice amid increasing globalization (Crona et al., 2015; Tapia-Lewin et al., 2017).

The telecoupling framework can be used to understand leverage points that establish a roadmap for improving Great Lakes fisheries management and governance. Leverage points are places in a system's structure where small shifts in one social-ecological factor produce large changes across the system, providing insights about social-ecological challenges if not specific entry points for management or governance intervention. Climate change and invasive species are leverage points for Great Lakes fisheries management because they are inherently large-scale, telecoupled processes whereby human decisions in one location can exert disproportionately large effects on societies and ecosystems in distant locations. For example, invasive Zebra Mussels and Quagga Mussels *Dreissena bugensis* represent a leverage point because their proliferation has reduced Alewife abundance and caused the MDNR to decrease stocking rates of Chinook Salmon (i.e. Alewife predators) to regain predator-prey balance (Clark Jr. et al., 2017), much to the concern of anglers, business owners, and other fisheries stakeholders. Because invasive species and climate change greatly influence social-ecological conditions in the Great Lakes basin (McKenna Jr., 2019), using the telecoupling framework to characterize the context-specific conditions for effectively managing and adapting to these stressors (e.g. when, where, how) offers a roadmap for Great Lakes fisheries conservation.

Whereas climate change and invasive species are leverage points that the telecoupling framework helps researchers address (rather than identify), other leverage points would be difficult or impossible to ascertain without using the framework. For instance, by providing a systematic, scientific approach to connect ecosystems and human systems across local, lake, and Great Lakes basin scales, the telecoupling framework establishes a leverage point (i.e. social-ecological multiscalarity) that has heretofore been absent from Great Lakes fisheries management. Indeed, identifying small to large-scale linkages and feedbacks among societal decisions and biological/physicochemical dynamics is a "grand challenge" in Great Lakes research (Sterner et al., 2017) that the telecoupling framework directly addresses by coupling human and natural systems across scales. Through its multiscalar structure, the telecoupling framework reveals how humans and the environment interact locally, regionally, and globally, helping navigate another leverage point for Great Lakes fisheries management: conceptualizing fisheries stakeholders (e.g. anglers, charter boat captains, tourists, hotel and restaurant managers) as telecoupling agents. By using the telecoupling framework's to illuminate the diverse – although not always straightforward – ways in which Great Lakes fisheries benefit humans (e.g. food, nutrition, clean water, indicator species of environmental degradation), fisheries professionals can construct a roadmap for optimizing public engagement activities (e.g. newsletters, websites, seminars, volunteer opportunities) to best serve fisheries stakeholders throughout the basin. After all, people who are knowledgeable about the many ways fisheries improve their lives via telecouplings are more likely to recognize, support, and be engaged in fisheries management than those who lack this understanding.

The telecoupling framework also helps elucidate and manage leverage points related to fisheries valuation, spillover systems, and social-ecological causality. For instance, studying monetary telecouplings in Great Lakes fisheries (e.g.

where money for fisheries management comes from, where it goes, why it flows) can yield multiscalar insights for revolutionizing fisheries management funding streams to ensure fisheries sustainability. As traditional funding modes (e.g. angling license sales and excise taxes) become less consistent and sustainable, particularly for fisheries habitat management (Sass et al., 2017), there is a need for dedicated, long-term financial support for fisheries conservation. By providing insights on the social-ecological linkages underlying traditional funding streams as compared to alternatives (e.g. partnerships with the business community, use of existing federal royalties on energy and mineral development; AFWA, 2016), the telecoupling framework provides a roadmap for sustainable Great Lakes fisheries management funding. Likewise, the telecoupling framework can be used as a tool to measure the non-monetary values and benefits of Great Lakes fisheries (e.g. ecological, social, psychological, aesthetic, cultural, nutritional; Knuth et al., 2002; Cooke et al., 2017), a leverage point for truly holistic fisheries management wherein economics is just one of many variables considered when policies are crafted. Spillover systems are another relatively unexplored leverage point for Great Lakes fisheries management. For instance, how does a recent expression of climate change – a rapid rise in "blow days" (days on which charter boat captains elect not to launch due to high winds, large waves, etc.; D. Grinold, Fish'N Grin Charter Service, Grand Haven, MI, pers. comm.) – affect local economies in the Great Lakes basin (i.e. spillover systems)? Ultimately, expanding research on spillover systems in the Great Lakes through the use of tools such as flow diagrams, agent-based models, and social network analyses (Bodin and Prell, 2011; Liu et al., 2013) will generate a roadmap for more socioeconomically, ecologically informed and effective fisheries management. For example, flow-based management that emphasizes telecoupled relationships among places (e.g. changes in Chinook Salmon movements between lakes Huron and Michigan due to Alewife declines; Clark Jr. et al., 2017) offers a holistic, multiscalar perspective that can improve the efficacy of Great Lakes fisheries conservation at local, lake, and basinwide scales. Likewise, because the social-ecological causality of fisheries events is often complex and poorly understood, causality is a leverage point that the telecoupling framework helps address via systematic conceptualization of fisheries systems, flows, agents, causes, and effects (Carlson et al., 2018b).

Conclusions

In conclusion, the telecoupling framework is a useful tool for understanding the causes and consequences of social-ecological interactions in the Great Lakes salmonine fishery. The telecoupling framework advances fisheries science by allowing users to systematically evaluate systems, flows, agents, causes, and effects; conceptualize spillover systems; and understand complex fisheries dynamics. As a paradigm applicable in wide-ranging fisheries systems, the telecoupling framework furnishes insights for sustainable fisheries management and governance in a globalized world. In so doing, the telecoupling framework operationalizes the ideas of visionary fisheries scientists like Henry Regier who had the insight and courage to imagine a fisheries profession that is truly holistic, socially and ecologically.

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