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The History and Role of Research in Managing Minnesota's Fisheries Resources

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INTRODUCTION

Research has been an integral part of fisheries management in Minnesota since the inception of the State of Minnesota's Department of Conservation (MN DOC), the forerunner to today's Department of Natural Resources (MN DNR). Early attempts to stock various species across the state were often evaluated and the results shared staff. These efforts were most often recorded in letters and ledgers and were used to inform what culture techniques worked and which species were successfully introduced. As the science of fisheries and wildlife management advanced, so too did the research efforts of the MN DOC. In 1938 the first Investigational Reports appeared detailing the significant contributions of research to fisheries management in Minnesota. Research remains a fundamentally important tool in managing the fisheries resources in Minnesota. Innovative research has improved the efficiency of management and evaluated long-standing programs to ensure they meet the changing demands of managers and anglers. Research has provided insight into the ecological interactions in our waters as well as alternatives for managers who face the need to adapt to changes in climate, landscapes, and the presence of invasive species.

Previously, Davis (1985) and Jacobson and Davis (1991) summarized the role the Fisheries Research Unit (FRU) has played within the MN DNR Section of Fisheries (hereafter Section). Those reports categorized the types of research that has been conducted by researchers and summarized and enumerated the number of research reports by topic. They also provide brief summaries of what at the time was recent research. We encourage Section staff to read both reports to gain a fuller understanding of what has been accomplished by the FRU. In this report, we summarize research completed after the Jacobson and Davis report (1992 to present) and have summarized efforts that include internal reports (Fish Management and Investigational Reports) as well as peer-reviewed publications. Climate change, landscape-level changes, invasive species introductions, the increased mobility and use of novel technologies by anglers have all added to the complexity of fisheries management and by association fisheries research. In response, the FRU has responded in part by being more collaborative with universities, federal agencies, and other scientific entities that were not traditionally within the realm of fisheries management. In addition, FRU staff have worked closely and collaboratively with MN DNR fisheries management staff on a diversity of projects covering wider geographic areas within the State. These efforts are also included within this report. MN DNR fisheries management staff also conduct research projects (e.g., Study 4 projects); although these projects are important to Minnesota fisheries management, most of those projects are not included here.

While not a comprehensive review of all research efforts, this report is designed to provide an overview of work that has been done by the FRU in the last 35 years. The report also includes a reference section that will guide staff to completed works. This document should be considered not only a reflection of the past but also a guide to future research needs.

SALMONIDS

Lake Superior and tributaries

Research has played an important role during the last 30 years in helping guide fisheries management and improve fisheries assessment in Lake Superior and its tributaries. Naturalized (wild) anadromous Rainbow Trout *Oncorhychus mykiss* (steelhead) have become an important component of the tributary fisheries since being introduced into Lake Superior from the west coast in 1985 and consequently steelhead have been the focus of stocking efforts and several research projects to evaluate and improve stocking strategies. During the early 2000's, work by Negus (2000, 2003) helped maximize the smolting of stocked yearling steelhead in the French and Knife rivers by evaluating the timing of stocking and the conditions at the French River Hatchery. The author estimated steelhead gill sodium-potassium-activated adenosine triphosphatase (ATPase) activity level and related it to fish size, determining that stocking occurred at sizes larger than smolt size. It was recommended controlling the sizes attained by steelhead in the hatchery may maximize in-stream smolting and future homing to desired locations. Additional research conducted by Ward et al. (2013) during the early 2000's further improved the yearling steelhead stocking program by finding that fish stocked at the river mouths had greater returns than fish stocked at upstream locations. Despite these efforts, the yearling Steelhead stocking program was ultimately discontinued during 2007 because of high costs, poor returns, and genetic concerns (Negus et al. 2012). Following the discontinuation of yearling steelhead stocking, attention switched to improving the efficiency of fry or fryling stocking. A study by Carofinno et al. (2008) showed that stocking fry from local steelhead sources could enhance short-term abundance of depleted populations but that fish with no hatchery ancestry were a better source for supplemental stocking. Minnesota DNR initiated fryling steelhead stocking in 2008 hoping they would survive better than fry, and the evaluation of these efforts is still ongoing (Negus et al. 2013; Goldsworthy et al. 2017). Strain evaluation research (Close and Hassinger 1981) also informed the decision to initiate a program for raising and stocking Kamloops strain Rainbow Trout which provided a harvest opportunity for anglers after a catch-and-release regulation was implemented for wild steelhead in 1997. Negus et al. (2012) found that stocking Kamloops in the summer at a larger size increased return rate compared to those stocked in spring at a smaller size. Despite the good intentions of the Kamloops stocking program, there were concerns about potential genetic consequences, and several research projects addressed these concerns. Initially Close (1999) found that Kamloops and wild steelhead can successfully produce hybrid offspring in the wild and Negus (1999) showed that survival of eggs to fry and wariness traits were higher for steelhead than Kamloops, and that hybrid survival and wariness traits were intermediate. Research efforts later found higher reproductive success (Miller et al. 2014) and better survival of offspring (Miller et al. 2004) from naturalized steelhead compared to hatchery origin Kamloops. Page et al. (2011) simulated effects of annual Kamloops stocking on the sustainability and recovery of wild steelhead populations and the results showed an increased risk of extinction of wild steelhead through non-introgressive hybridization. Additionally, Miller et al. (2020) showed that Kamloops ancestry was found in many Minnesota streams and Wisconsin's Bois Brule. Most recently, Steelhead scale samples collected by volunteer anglers were used to determine the extent of genetic variation of North Shore steelhead populations and delineate the genetic variation and sample sizes of spawning adults required for maintaining genetic variation equivalents to wild populations in the newly established Steelhead broodstock at Crystal Springs Hatchery (MN DNR, unpublished data). These research efforts ultimately helped inform the decision to transition away from the Kamloops strain Rainbow Trout stocking program to a wild Lake Superior strain steelhead program in 2017.

Research has also helped informed management and assessment of other Lake Superior and tributary fisheries with research projects not focused on stocking. Bioenergetics modeling of predator demand in combination with hydroacoustic assessments of prey biomass has become an important component of managing Lake Superior fisheries (Negus et al. 2007, 2008). Negus (1992) estimated that prey consumption by predators was substantially greater than estimated prey biomass resulting in the recommendation that additional stocking of predator species be considered with caution (Negus 1995). A second bioenergetics modeling effort suggested that the western arm of Lake Superior was at or near carrying capacity for predators, driven primarily by increased Lake Trout *Salvelinus namaycush* abundance (Negus et al. 2007, 2008). Minnesota DNR partnered with external collaborators around Lake Superior to establish a lake wide hydroacoustic survey program to assess forage fish abundance (Mason et al. 2005). Hrabik et al. (2006) created a hydroacoustic survey design that aided in developing sustainable harvest targets for the commercial Cisco *Coregous artedi* fishery, and an in-house standard operating procedure (SOP) for hydroacoustic was developed collaboratively by Lake Superior area fisheries staff and fisheries research staff (Holbrook 2022). The FRU built statistical-catch-at-age models for Lake Trout *Salvelinus namaycush* in Minnesota waters of Lake Superior that are used to estimate mortality rates, help determine harvestable surplus levels, and measure progress towards rehabilitation goals (Schreiner et al. 2006; Goldsworthy et al. 2017). Some relatively recent research by Miller et al. (2016) focused on "Coaster" Brook Trout *Salvelinus fontinalis*. The researchers found that a 20-inch minimum length limit implemented in 1997 appears to have improved the size and age structure of Brook Trout sampled from the lower portions (below barriers) of tributary streams. They also found that most Brook Trout longer than 13-inches (below barriers) were of wild Minnesota Ancestry rather than of hatchery or admixed ancestry. The FRU is currently collaborating with Lake Superior Area Fisheries staff and external partners on additional Brook Trout genetics projects, including one that is focused on determining whether wild fish are mostly produced in upstream or downstream reaches of tributary streams (i.e., above or below barriers).

Streams

Stream-resident Brown Trout *Salmo trutta* populations continued to be a focus of research efforts over the past 30 years in large part because their management often included considerable controversy. Much of the research continued to focus on habitat improvement methods, such as wood cover (Thorn and Anderson 2001) and identification of important habitat requirements, especially for large brown trout, to aid instream habitat improvement designs (Thorn and Anderson 1993; Dieterman et al. 2006, 2018a). Additional management efforts to increase abundance of large Brown Trout were identified in MN DNR (2000) which led to research examining bioenergetic and food web factors influencing growth rates (Dieterman et al. 2004; French et al. 2014, 2016, 2017). These studies suggested that large Brown Trout were a function of flow, specific cover types (wood debris, instream rock, 90cm depth, overhead bank cover) and individual growth (not average population growth). More and varied restrictive angling regulations were implemented and expanded to many streams, which necessitated their evaluation from biological (Thorn et al. 2000; Dieterman et al. 2020) and sociological (Snook and Dieterman 2006, 2015; Dieterman and Snook 2015) perspectives. The ever-expanding knowledge base regarding Brown Trout ecology in the Driftless Area and around the world prompted comprehensive reviews to organize management efforts (Thorn et al. 1997; Dieterman et al. 2012). Yet, these reviews also identified important areas of uncertainty that were subsequently studied including seasonal, spatial and ontogenetic changes in Brown Trout survival, movement, growth and reproductive traits (Dieterman and Hoxmeier 2011; Dieterman et al. 2012, 2016). Survival, growth, movement, and abundance of young Brown Trout is dictated by seasonal and annual changes in abiotic and biotic factors whereas larger adults are affected more so by instream physical habitat. Various methods to better assess stream resources or fish populations were examined, such as a stream classification system to simplify management efforts (Thorn and Anderson 1999), a rapid assessment method to classify stream habitat quality (Thorn and Anderson 2001) and evaluation of PIT tag retention in salmonids (Dieterman and Hoxmeier 2009).

Research on Brook Trout began when Thorn and Ebbers (1997) summarized existing data from internal surveys and documents. They found Brook Trout were present in 54% of Southeast Minnesota streams, but concluded that remnant Brook Trout populations were unlikely given stocking histories. More comprehensive research was subsequently initiated to better understand available Brook Trout resources and ecological aspects surrounding populations in the Driftless Area. Hoxmeier et al. (2015) found Brook Trout in 68% of Southeast Minnesota streams and 21% of streams had remnant populations. This resulted in the development of a new Heritage hatchery strain and increased management efforts towards Brook Trout. Subsequent studies evaluated competition between Heritage Brook Trout and Brown Trout and found that Brown Trout excluded Brook Trout and lowered their growth (Hoxmeier and Dieterman 2013; Hoxmeier and Dieterman 2016). However, Brook Trout can out compete Brown Trout when environmental conditions are favorable (Hoxmeier and Dieterman 2019).

NORTHERN PIKE

Other than Walleye *Sander vitreus*, no other species of fish has been studied more by FRU staff than Northern Pike *Esox lucius*. Following FRU's focus on broader fish community effects of intensive Northern Pike stocking during the during the 1980's largely the result of the winter rescue program (Anderson and Schupp 1986), the emphasis shifted to address the growing frustration from managers and anglers dealing with populations of small, overabundant Northern Pike. The decline in quality and large Northern Pike was noted in the "Fuller Tackle Study", (Olson and Cunningham 1989). As a result, Jacobson (1993) examined the factors affecting Northern Pike growth and found growth of large Northern Pike to be greatest in deep, cool lakes that contained populations of Cisco. Furthermore, he found shallow, fertile lakes were best for young Northern Pike growth, but that high population densities and summer water temperatures resulted in generally poor size structure. This work was also among the first research efforts to incorporate bioenergetics modeling.

The FRU first began investigating population dynamics of Northern Pike in the late 1980's. Goeman et al. (1993) examined the use of liberalized bag limits and intensive removal for improving the size structure of 'hammer-handle' dominated populations. They concluded that unless anglers harvested more small Northern Pike, liberalized bag limits were ineffective as a management tool. Size-selective harvest of large individuals (>500 mm) and overall high mortality rates were identified by Pierce et al. (1995). Furthermore, removal of large Northern Pike by anglers was found to be detrimental to the overall size structure of a population. These findings led to an expanded use of special harvest regulations, mainly in the form of various minimum length limits and protected slot limits aimed at improving the size structure of Northern Pike populations . Pierce (2010) summarized the first evaluations of these efforts and reported that populations under maximum size limits ranging from 20 to 24 inches had increases in Northern Pike greater than 24 and 30 inches in length. He also found slot length limits had variable results but generally improved size structure. Ultimately, special regulations were condensed into a manager's toolbox that was available in 2003. Pierce's review of Minnesota's experimental regulation history suggests that protection of larger Northern Pike with length limits has more conservation potential than liberalized bag limits. A second evaluation of these regulations was completed in 2019 (Bethke et al. 2021). Finally, FRU efforts have led to recommendations that longer implementation and evaluation periods of special regulations are need to fully evaluate the effectiveness of regulations (Pierce 2010; Bethke et al. 2021).

During the efforts to identify methods to produce higher quality Northern Pike populations, research staff were also able to assess standard survey gears (Pierce and Tomcko 1994; Pierce 1997), angler compliance with special regulations (Pierce and Tomcko 1997), catchability (Pierce 1997; Pierce et al. 2010), tag loss and handling mortality (Pierce and Tomcko 1993), and habitat effects on Northern Pike density and biomass (Pierce and Tomcko 2003). Research staff also undertook novel efforts to identify important spawning and nursery habitats of Northern Pike. Pierce et al. (2007) first used oviduct implanted radio transmitters to identify the preferred spawning habitats of both Northern Pike and Muskellunge *Esox masquinongy*. Similarly, to characterize larval habitat needs and juvenile habitat use, FRU staff implemented the use of Quatrefoil light traps to identify important nursery areas in complex habitats (Pierce et al. 2007; Timm and Pierce 2015).

WALLEYE

While most of the research regarding Walleye has focused on the effectiveness of stocking, the FRU has undertaken several projects examining the population dynamics and community ecology of Walleye. The dynamics of two stocked populations in Southern Minnesota were studied by Bandow et al. (1993). They noted high yield and natural mortality, poor natural recruitment, and minimal contribution to the fishery of stocked fingerlings led to a collapse of one of the populations, demonstrating the boom-and-bust cycle common to the southern portion of the State. They recommended further assessing the use of fry and the protection of spawning habitat in similar systems to mitigate some of the effects of poor recruitment. Conversely, lower total annual mortality, high rates of release by anglers, and better growth at large size made sustaining a trophy fishery for Walleye possible in a Northcentral Minnesota lake (Jacobson 1994).

Understanding the ecological roles of Walleye, either stocked or naturally produced, as well as their response to system change have been a large focus of the FRU. A two-part study that first examined the discontinuation of Walleye stocking followed by a resumption of fry stocking on the lake fish community found responses by Yellow Perch *Perca flavescens* to be most pronounced (Pierce and Tomcko 1998, 2003). Numbers of small Yellow Perch increased at the cessation of Walleye stocking then decreased as stocking resumed. The number of large Yellow Perch also declined during the 17 years of the study. Like the findings from research into using Walleye to suppress minnow populations in wetland basins (Herwig et al. 2004); they also found controlling abundant, small Yellow Perch through a top-down approach with stocked Walleye fry to be successful. Recent introductions of non-native invasive species such as zebra mussels *Dreissena polymorpha* and spiny waterflea *Bythotrephes cederstroemi* has led to research into how Walleye populations might be affected. Walleye in the largest of Minnesota's lakes were found to grow more slowly through age-1 in the presence of either invader and were 12 to 14% smaller at the end of the first growing season when zebra mussels or water fleas were present (Hansen et al. 2020).

Walleye is the most sought-after species by anglers in Minnesota, so research related to angling and the effects of angling on Walleye fisheries has been conducted by MN DNR. Reeves and Bruesewitz (2007) estimated post-release Walleye mortality rates ranged from 0% in May to just over 12% in July. Mortality increased with water temperature and was also influenced by bleeding, fish length, hook location, and fish floating upon release. Post-release mortality was also affected by hook type, with mortality being lower for jigs compared to plain hooks, but barbless hooks did not reduce mortality (Reeves and Staples 2011). Talmage and Staples (2011) expanded on Walleye post-release mortality research by evaluating the effects of capture depth and found mortality increases with depth. Meerbeek and Hoxmeier (2011) evaluated post-release mortality of Sauger *Sander canadensis* for a popular winter fishery on the Mississippi River, and they also found that winter post-release mortality increased with depth of capture.

Walleye sampling methods have been evaluated for multiple gears. Gill net selectivity of walleye was evaluated by Anderson (1998), Grant et al (2004), Myers et al. (2014), and Radomski et al. (2019). Anderson (1998) used multiple data sets to describe the size selectivity of multifilament gill nets for Walleye and partition selectivity into encounter, contact, and retention components. This work has been incorporated into standard MN DNR assessments that seek to estimate Walleye abundance from survey gill net catches. Seasonality in gill net catch rates was noted by Grant et al. (2004) and they recommended that nets be set during the same time of year within a lake. Myers et al. (2014) estimated Walleye capture and harvest selectivity for angling and harvest selectivity for tribal spearing. The authors found that the length specific angling catchability was higher for female than male Walleyes at all lengths. However, spearing catchability was greater for male than female Walleyes. The differential angling selectivity has been incorporated into age-structure stock assessment models for Mille Lacs. Radomski et al. (2019) estimated selectivity for Walleye in Minnesota's standard gill net and determined the degree to which Walleye density was related to gill-net CPE. The work resulted in a statistical assessment model (SAM) that can provide an estimate of Walleye abundance by length group from gill net CPE, like Anderson (1998). Such estimates may be useful in determining the appropriate sample size for a well-designed mark-recapture experiment. Schmalz and Staples (2011) conducted a study to help optimize sampling of Walleyes with short-term gill nets, The authors suggested that it may be better to extend the sampling period (i.e., across higher water temperatures) and reduce soak times to maximize catch while keeping mortality low. Thousands of electrofishing surveys for juvenile Walleyes have been conducted on hundreds of lakes in Minnesota and are often used to index Walleye recruitment or evaluate if contingency stocking is required. Borkholder and Parsons (2001) compared fall age-0 Walleye catch rates in 18 lakes sampled multiple times over a wide range of water temperatures. Although no clear single pattern was observed between catch rate and water temperature for all lakes, in general, catch rates were highest at intermediate temperatures and declined when water temperatures fell below 10 C. Shroyer et al. (2019) evaluated factors influencing juvenile Walleye electrofishing catch rates and determined the relationship between electrofishing catch rates and subsequent gill net catch rates Age-0 Walleye catch rates increased with increased water temperature. The amount of time electrofishing was positively related to the probability of detecting age-0 Walleyes with the probability of detection of 0.90 at 1.5 hours.

Walleye stocking evaluations have been conducted by the FRU since the 1940's. Recent evaluations have focused on the contributions to overall year class strength in populations where natural reproduction occurs and evaluating different life stages of Walleye for stocking. Parsons et al. (1994) found neither normal- nor high- density stocking rates of fingerlings contributed significantly to the Walleye populations or angler yield of any of three study lakes. Additionally, they found the cost of stocked fish harvested by anglers ranged from $4.02 to $16.35. However, fry stocking did contribute to year-class strength in the lakes within the study (Parsons and Pereira 2001). Additionally, the same study revealed that stocked fingerling dispersal was influenced by basin morphometry and in some cases, it took several years for fish to distribute themselves throughout the lake (Parsons and Pereira 1997). Statewide evaluations, via meta-analysis, of Walleye stocking largely replaced experimental evaluations beginning with cooperative work between the University of Minnesota and FRU staff. This included work by Li et al. (1996a, 1996b) who found fingerling stocking could suppress strength of year classes immediately preceding and after fingerling stocking. They also found that stocking fingerlings in lakes without natural reproduction could increase Walleye abundance but stocking in lakes with natural reproduction had no overall effect on Walleye abundance. Additionally, stocking on top of a naturally reproducing population negatively affected weights of Walleye. Examining over 1,500 population assessments of Walleye from 1986 through 2004, Jacobson and Anderson (2007) found that the response of Walleye to stocking was asymptotic, and that peak abundance occurred at a stocking density greater than 0.65 lb/littoral acre. To maintain population levels and remain cost-effective, they recommended a stocking level of 0.50 lb/littoral acre.

Evaluating stocking of different life stages, i.e., (fry, small fingerling, and large fingerlings) has also been a focus of the FRU. Parsons et al. (2015) examined the contributions of fry, small fingerlings, and large fingerlings in 50 lakes across the state. Their results were highly variable, and largely confounded by varying levels of natural reproduction within the study lakes. Outcomes of the study suggest that managers looking to experiment with stocking differing life stages should consider the status of natural reproduction in their lakes, the fish community present, and use age-3 gill net CPUE to guide their stocking decisions. In a related study, Reed and Staples (2017) found the stocking of small fingerlings in certain circumstances contributed up to 72% of age-3 gill net catches and recommended a stocking rate of 30 small Walleye/ littoral acre.

FRU staff have also evaluated Walleye fry stocking as a tool in re-establishing a collapsed fishery (Logsdon 2006; Logsdon et al. 2016) as well as the effects of 'put back' stocking on populations from which Walleye eggs are taken on an annual basis (Logsdon and Anderson 2018). Three large fry-stocking events, following a total moratorium on harvest, led to a rapid recovery of the Red Lakes Walleye population. In respect to put-back stocking the researchers found that fry densities stocked into egg-source lakes were considerably higher than needed and recommended put-back levels be moderate such that recruitment, growth, and changes to forage abundance could be accounted for. These and other efforts have allowed the Section of Fisheries to continually ‘fine tune’ stocking rates, thereby reducing costs, and optimizing returns.

Other areas of research related to Walleye production that have been completed by FRU staff include the use of Oxytetracycline to mark large quantities of Walleye fry (Logsdon et al. 2004, 2009), calcein marking of juvenile walleye (Logsdon and Pittman 2012), methods to reduce hauling stress and improve survival of stocked fingerlings (Parsons and Reed 2001; Barton et al. 2003), body condition and overwinter survival (Bandow and Anderson 1993), factors influencing pond production (Jacobson 2004), and increasing fingerling production through induced winterkill of naturally occurring production ponds (Shroyer 2007).

MUSKELLUNGE

In the last 35 years, Minnesota has experienced a considerable increased interest in managing Muskellunge as a trophy fish (Wingate and Younk 2007). Much of this interest stems from survey data that emerged during the 1980’s which indicated a notable difference in growth patterns of introduced Shoepack lake-strain muskellunge that had been stocked around the State from those populations that were naturally reproducing. Evaluations of four strains (Shoepack, Minocqua, Lac Courte Oreilles, and Mississippi) indicated that the growth performance of the Mississippi strain was best suited for Minnesota waters (Younk and Strand 1992). This information led to a production shift from Shoepack to Mississippi strain as well as the establishment of brood stock lakes that facilitated a more efficient means of collecting gametes. The increased interest in Muskellunge by anglers also led to increased research efforts regarding habitat use and exploitation. Habitat use, particularly spawning habitat needs, has been studied in rivers (Younk et al. 1996) and lakes (Pierce et al. 1996). The seasonal use of regions of the St. Louis River estuary and movements to Lake Superior were tracked using acoustic telemetry (Schaeffer et al. 2012). The population dynamics of Muskellunge in Elk Lake (Clearwater County, Itasca State Park) has been the focus of a long-term study and monitoring (Younk et al. draft, Study 681). Current research efforts include the role Muskellunge play in structuring food webs (MN DNR, unpublished data), competition between other predatory fishes (Glade et al. in review), and comparison of consumption between predatory fishes (MN DNR, unpublished data) as designed to further understand their role in lake ecosystems, and evaluation of alternative mark-recapture models and study designs (Shroyer and Hudgins, in review). Considerable genetic research related to Muskellunge has also been conducted in Minnesota (see Genetics section).

BLUEGILL

Determining the reason for ‘stunted’ or slow growing Bluegill *Lepomis macrochirus* populations has been of interest to managers in Minnesota for years. Consequently, research into Bluegill biology and management within the last 35 years has focused on three main areas thought to be associated with stunting and slow growth: reproductive biology, relationships between Bluegill growth and various environmental and ecological factors, and population dynamics and recruitment. Regarding reproductive ecology, research found increased fishing effort to be related to increased proportions of ‘cuckholder’ male Bluegill which can result in poor size structure (Tomcko and Pierce 1993; Drake et al. 1997). Drake et al. (1997) also found ‘parental’ (non-cuckholder) males were older and reached maturity at a larger size in lakes with low fishing effort. Examination of the relationship between Bluegill growth and population dynamics and various environmental and ecological factors found that efforts to improve Bluegill size structure should focus on factors that influence recruitment (Tomcko and Pierce 2000, 2005; Tomcko and Pereira 2006). The population dynamics, including exploitation and natural mortality, of several Bluegill populations were examined by Parsons and Reed (1998) who estimated natural mortality range from 43 to 65% and exploitation ranged from 11 to 25%. Experimental bag limit reductions, from 30 to 10, were found to significantly increase size structure of Bluegill populations (Jacobson 2004). These research efforts were helpful in identifying potential causes for slow growth, lakes most likely to benefit from special regulations and ultimately development of the Quality Sunfish Initiative.

Additional research on Bluegill included evaluating the use of trap nets as a sampling gear. Bluegill sampling with trap nets is seasonally biased with larger fish caught in early spring compared to summer, and Bluegill catch rates in summer trap nets are highly variable (Cross et al. 1995, McInerny 2014).

LARGEMOUTH BASS

Research regarding Largemouth Bass *Micropterus salmoides* in Minnesota waters has focused primarily on three areas: evaluating regulations aimed at improving Largemouth Bass size structure, various aspects of Largemouth Bass ecology, and methods to adequately sample Largemouth Bass populations. Beginning in the mid-1990's fisheries managers across the state began experimenting with various size-based restrictions on Largemouth Bass harvest to improve size structure and meet demands of anglers wanting to catch larger fish. Evaluations of these regulations found Largemouth Bass size structure could be improved with harvest limits (Carlson and Isermann 2010) and that despite high rates of catch and release angling in certain lakes, limiting harvest through regulations could be a viable options for managers wanting to improve size structure and overall quality of bass fisheries (Carlson and Isermann 2009), though other research demonstrated harvest restrictions were more likely to be successful in regions of the State where harvesting bass was more common (Isermann et al. 2013). Research efforts into the role Largemouth Bass as a predator showed the consumed mainly invertebrates and Yellow Perch (Reed and Parsons 1996). An experiment designed to increase predation on Bluegill by eliminating harvest of Largemouth Bass demonstrated the to control or improve slow growing Bluegill populations are unlikely to succeed Shroyer et al. 2003). As lake systems change, the potential for competition between Largemouth Bass and other predators has become a concern among managers and anglers. However, research suggests little diet overlap between LMB and other common predatory gamefish (Bethke and Schmalz 2020). Additional research related to diet overlap between Largemouth Bass and other fish is ongoing (e.g., Glade et al. in review).

A considerable amount of research has focused on the effective sampling of Largemouth Bass populations. Night electrofishing typically results in higher catch rates compared to day electrofishing, with catch rates being higher in the spring than fall (McInerny and Cross1996, 2000). Although spring electrofishing catch rates generally increased with bass abundance, the relationship is not linear and is affected by secchi depth, water temperature, conductivity, and percent littoral area (McInerny and Cross 2000). Electrofishing to estimate size structure of bass can be done effectively during day or night in both spring and fall with similar results when considering bass greater than 200 mm (McInerny and Cross 1996). Population estimates for Largemouth Bass should be done using multiple gears for mark and recapture using individually marked fish (McInerny and Cross 2021). Age estimates for Largemouth Bass should be done with halved otoliths given that dorsal spines possessed central lumens and underestimated ages (McInerny et al. 2017).

BLACK CRAPPIE

Although both species of crappie are present in Minnesota, the distribution of Black Crappie *Pomoxis nigromaculatus* is more widespread, and abundance is greater. As a result, researchers have focused mainly on Black Crappie. Main areas of research include population dynamics and harvest, various factors affecting recruitment, and sampling gear evaluations. Parsons and Reed (1998) studied the population dynamics of four populations of Black Crappie over a three-year period. Among their findings were that exploitation rates on some lakes can vary greatly from year to year (from 7 to 34%), that natural mortality was moderately high (averaging 59% across populations and years), and exploitation negatively affected size structure in all four populations. They also found Black Crappie frequently moved among connected basins (Parsons and Reed 2005b) and tagging with t-bar anchor tags had little effect on Black Crappie growth (Parsons and Reed 2005a). Similarly, Isermann and Carlson (2008) found no evidence that Passive Integrated Transponder tags increased Black Crappie mortality. They also found tag retention to be high (100%). Black Crappie recruitment was found to be consistent in four lakes across a three-year period (Parsons et al. 2004). They also found no relationship between abiotic factors, Yellow Perch larval abundance or zooplankton dynamics and recruitment, nor did they find any relationship between adult population size and larval abundance.

Sampling methods for Black Crappie have been evaluated in terms of catch rates and size structure. Fall trap netting catches a larger range of lengths compared to summer gill netting or trap netting (McInerny et al 1993). Catchability of Black Crappie in trap nets varies across lakes and sample periods but CPUE can be useful for within lake comparisons (McInerny and Cross 2006). Scales can be used to age Black Crappie up to age 5; however, halved otoliths should be used to estimate ages of older crappie (McInerny et al. 2020).

REGIONALLY and ECOLOGICALLY IMPORTANT SPECIES

From regionally important topics such as examining the interactions between introduced Smallmouth Bass *Micropterus dolomieu* and native Lake Trout in Northeast Minnesota lakes (Eiler and Sax 1993) to state-wide perspectives that have shown declines in ecologically important species such as Yellow Perch and White Suckers *Catostomus commersonii* (Bethke and Staples 2015), the FRU has been responsive to managers needs beyond studies on popular game species. Research into strain performance, index netting, growth, and methods to estimate yield of Lake Trout, was conducted through the 1990's (Siessenopp 1992, 1998a, 1998b, 2000). Similarly, population dynamics and movements of Flathead Catfish *Pylodictis olivaris*, , have also been a focal point of researchers (Shroyer and Logsdon 2009; Shroyer 2011; Shroyer 2018,). Cisco, an ecologically important species with wide distribution in Minnesota has been identified as an important indicator of system and watershed health (Jacobson et al 2008). As a result, considerable research effort has been directed at Cisco biology, genetics, and habitat requirements (Jacobson et al. 2010, 2012; Grow et al. 2021; Miller et al. 2021). This research has developed tools for mitigating the effects of watershed development and climate change (Jacobson et al. 2011). The fisheries survey database, populated largely through management surveys, has shed light onto population trends of important species (Bethke and Staples 2015) as well as how eutrophication and a warming climate have affected fish assemblages across Minnesota (Jacobson et al. 2017; Wagner et al. 2020). In turn, these large-scale studies have led to other research efforts, such as identifying methodologies for to further examine the mechanisms for Yellow Perch decline within Minnesota (Holbrook et al. 2021).

Studies were initiated to assess population status and life history traits of species such as Lake Sturgeon in the Kettle River (Dieterman et al. 2010) and St. Louis River (Estep et al. 2020), Redside Dace in southeast Minnesota (Dieterman et al. 2018b), and darter species in the upper Mississippi River (Dieterman et al. 2022.). A study to test assumptions of the Clean Water Act's benefits to sport fish populations in rivers and streams of Minnesota was conducted and included documentation of characteristics of several Smallmouth Bass populations scattered across the southern third of Minnesota (Dieterman et al. 2019).

Sculpin species, especially Slimy Sculpin (Cottus cognatus) are often the only non-salmonid fish in coldwater streams. MN DNR reintroduced Slimy Sculpin in 10 Driftless Area streams in the mid-2000s to reestablish their ecological role and provide forage for trout. Research in collaboration with the University of Minnesota showed that three source populations contributed disproportionately to reintroduced populations and that mixed-ancestry offspring likely had reduced fitness from outbreeding depression (Huff et al. 2010, 2011). Reintroductions have recently begun again, and researchers are studying genetic diversity, trout growth and food web changes after sculpin reintroductions.

LENTIC HABITAT

Habitat-related research generally falls into four categories: 1) large-spatial analysis that uses lake morphometry, water quality, and land use data to develop lake classification systems; 2) lake-wide physical habitat assemblages that include attributes such as aquatic vegetation and woody habitat; 3) assessments of fish assemblages and how they relate to various habitat metrics; and 4) species-specific habitat needs. Combined, this work contributed to the development of a strategic plan for managing and conserving fisheries habitat in Minnesota lakes (Jacobson et al. 2016).

Investigations of in-lake habitat and relationships with fish abundance, community composition, and ecology on a variety of spatial scales have also been the focus of research by FRU staff. For example, preferred spawning habitats of Northern Pike and Muskellunge were identified in three lakes using miniature radio transmitters that were expelled from spawning females (Pierce et al. 2005). They found Northern Pike spawned in shallow areas adjacent to or within stands of *Carex* spp. and mats of water bulrush (*Scirpus subterminalis*) in Willow Lake. Muskellunge in Elk Lake spawned on a variety of vegetation, but *Chara* spp. was common to most sites where transmitters were deposited. In Moose Lake, both species spawned adjacent to shore as well as on deeper bars. *Chara* spp. was present on substrates where spawning occurred, regardless of depth. Reed and Pereira (2009) investigated the effects of shoreline development on nest site selection by both Black Crappie and Largemouth Bass. They found Black Crappie preferred nest sites adjacent to undeveloped shorelines and locations with stands of hardstem bulrush (*Schoenoplectus acutus*). Largemouth Bass were found to be less selective in their nest site selection. Dustin and Vondracek (2017) examined the relationship between fish community assemblages and shoreline development. They found littoral habitat, including coarse woody structure and macrophytes (both emergent and submergent) declined with increased shoreline development. The increase in development also corresponded with a decline in nearshore fish diversity. As lakeshore development increased, the potential effects on fish habitat concerned fisheries managers. In response, FRU staff have examined the importance of aquatic vegetation as fish habitat, the effects of development on the loss of in-lake habitat on vegetation, fish assemblages, and spawning (Radomski and Goeman 2001; Valley et al. 2004; Reed and Pereira 2009; Dustin and Vondracek 2017;) and developed methods to predict lakeshore development using GIS (Dustin and Jacobson 2015).

Relating fish assemblages to habitat characteristics led to the development of an Index of Biotic Integrity (IBI) for lakes in Minnesota (Drake and Pereira 2002). Research and validation of the metrics within the IBI (Drake and Valley 2005; Drake 2007) has allowed managers to use this tool to reliably identify anthropogenic-caused stressors on fish species richness and assemblage composition and identify thresholds that indicate impaired and high-quality lakes (Bacigalupi et al. 2021).

The thermal preferences of Northern Pike as well as the thermal and oxygen requirements of Northern Cisco are examples of research that has examined species specific habitat needs (Pierce et al. 2013; Fang et al. 2012).

LAKE CLASSIFICATION

The ability to group lakes based on similarities for comparing management actions and identifying natural, biological variation from solvable problems has been the focus of several research efforts. Using limnological characteristics of over 3,000 lakes within Minnesota, Schupp (1992) developed a widely used lake classification system used by Section staff. This ecological classification system provided managers with a rapid means of assessing changes in a lake using intra-quartile ranges of CPUE and average size of a species of interest. As fisheries managers began to work beyond individual lakes and interest in watershed-level management increased, a classification system that included watershed characteristics was developed (Cross 2018). Using a hierarchical decision tree system, this work incorporated large-scale habitat features to separate lakes into 11 homogeneous large-scale habitat conditions. Both classification systems have allowed managers to identify management units of similar lakes for targeted management actions, stratifying lakes to gain statistical power in experimental design and extrapolating the results of management actions on specific lakes to a broader suite of lakes (Cross 2018). As land use and water quality data became more available, researchers developed and refined lake classification that will guide managers in their efforts to protect and enhance fish habitats within Minnesota (Cross and McInerny 2006; Cross and Jacobson 2013; Cross 2018).

WETLANDS

In the early 1990's the practice of raising Walleye fingerlings in wetland ponds came into question from wetland and wildlife managers because as the demand for Walleye fingerlings for stocking in lakes across the state was increasing, waterfowl populations were simultaneously declining. In response, the FRU began addressing concerns about competition between fish and waterfowl, and the ecological effects of fish production in wetland basins. Over the next 28 years these studies ranged from , experimental (i.e. treatment/control) (Reed and Parsons 1999; Herwig et al. 2004) that demonstrated minimal effects to wetlands and waterfowl from fish production, to larger, landscape-level investigations (Hanson et al. 2012; Gorman et al. 2014) that not only addressed the competition between fish and waterfowl, but provided substantive insights into ecological concepts such as alternative stable states (Zimmer et al. 2009; Vitense et al. 2021), trophic cascades and the use of biomanipulation as a tool to manage wetland fish populations (Herwig et al. 2004; Reed 2006; Ward et al. 2008; Pothoff et al. 2008), and landscape connectivity (Herwig et al. 2010). These investigations also led to ongoing cooperative investigations with Section of Wildlife researchers and academics from North Dakota State University, South Dakota State University, the University of Minnesota, and University of St. Thomas.

GENETICS

Genetic tools have contributed to the understanding of Minnesota fish at the species, population, parentage, and individual levels. The first widespread application of genetics to Minnesota fish populations was an Illinois Natural History Survey study that examined spatial genetic population structure (diversity among populations) for numerous species across Minnesota, Wisconsin, and Illinois. This study led to refined Genetic Management Units (GMUs) for Walleyes in northern Minnesota (Fields et al. 1997; MN DNR 2011). The recommendation was to obtain local broodstock sources for stocking within GMU boundaries, which generally followed major watersheds. Beginning in the late 1990s, genetic research on Minnesota fish expanded using new molecular tools, first through contracts with the University of Minnesota and then by hiring a geneticist in the FRU.

Genetics tools have been used to identify species and their hybrids. A study of crappies showed that hybrids between Black and White Crappies *Pomoxis annularis* were almost always detected in lakes with both species, but their prevalence was generally low (Miller et al. 2008). First-generation hybrids grew substantially faster than pure individuals especially compared with Black Crappies, which they most resembled. Hybrid splake (Brook Trout *Salvelinus fontinalis* × *Lake Trout Salvelinus namaycush*) have been detected in studies of Brook Trout (Miller et al. 2016), tiger muskellunge (Northern Pike *Esox lucius* × Muskellunge *E. masquinongy*) in studies of Muskellunge and saugeye (Walleye *Sander vitreus* x Sauger *S. canadensis*) in studies of Walleye (MN DNR, unpublished data).

Most genetic studies have addressed spatial genetic structure among populations and especially the assessment of ancestry when genetically distinct populations are mixed through stocking (an indicator that stocked fish have survived and reproduced). Findings include consistently detectable genetic structure among populations, with amounts of divergence depending on the species and geographic scale, and a wide range of impacts on the genetic composition (ancestry) of populations that are stocked, including no evidence for reproductive contributions by stocked fish in some cases. For example, in Muskellunge, Miller et al. (2012) found genetic differentiation region-wide and even among nearby populations in the Mississippi River headwaters area. Depending on the strain used, ancestry from stocked fish ranged from none to an almost complete replacement of native populations. Several groups of Brook Trout in southeastern Minnesota descend from remnant populations or from unknown stocked sources, but not from the known strains stocked from the 1970s onward (Hoxmeier et al. 2015). Managers are developing the current Driftless Area Brook Trout hatchery strain from these putative remnant populations. In another case, stocking of Lake Trout was halted in a lake in Voyageurs National Park when genetic data showed that native ancestry persisted with little contribution to natural reproduction by the stocked Gillis strain (MN DNR data, unpublished). Other studies addressed population structure and ancestry in Muskellunge (Miller et al. 2009; Carlson et al. 2017; Turnquist et al. 2017), Walleye (Logsdon et al. 2016; Carlson et al. 2017; Bootsma et al. 2021), Brook Trout (Miller et al 2016; Erdman et al. 2022), Cisco (Miller et al. 2021), and steelhead (Miller et al. 2020) as well as ongoing work on Northern Pike, Channel Catfish *Ictalurus punctatus* and Lake Trout. It should be noted that these molecular techniques identify genetic differences attributed to reproductive isolation of populations that may, but do not always, lead to trait and fitness differences. It takes further evidence to demonstrate trait differences. One such ongoing study is examining the persistence of a southern Minnesota strain of Walleye despite decades of stocking of northern Minnesota strains. A southern and a northern strain are being stocked simultaneously into several lakes in southern Minnesota so that their relative survival can be directly compared under the same conditions.

Genetic markers used as tags to identify individuals or parentage have proved useful in several research and management applications. Genetic markers were used to identify individual Muskellunge for mark-recapture population estimates (Miller et al. 2015, Ward et al. 2017). Anglers could participate in recapturing fish by collecting a few scales or a small fin clip rather than having to identify a physical mark or carry a tag reading device. Ongoing stocking evaluations for Walleye and Northern Pike are being aided by Parentage-based Tagging. Broodstock parents are genotyped, and stocked offspring later collected in the wild can be identified by parentage assigned to the known broodstock pairs. Parentage assignment has shown that individual male Muskellunge do not contribute equally to offspring when milt is pooled before fertilizing eggs (Miller 2017) and that reproductive contributions by individual Brook Trout are highly variable and size-dependent in a small southeastern stream (Miller et al. 2019).

HUMAN DIMENSIONS

Surveying anglers regarding their opinions about various fisheries management activities has been a focus of the Fisheries Research Unit since the early 1990's. This work has ranged from broad-scale work comparing attitudes of anglers with fisheries professionals (Cunningham and Anderson 1992) to evaluating angler perceptions of the work done by the Section (Jacobson et al. 1999) to surveying anglers regarding specific management activities (Reed and Parsons 1999). Beginning in the early 2000's a great deal of the human dimensions work was contracted with the University of Minnesota's Cooperative Fish and Wildlife Research Unit. Contracting this work has allowed the Section of Fisheries to focus on specific topics, such as habitat management (Schroeder 2015; Schroeder et al. 2018) and species-specific surveys (Schroeder 2017) as well as maintaining a consistent survey of the angling community (Miller 2018). These surveys have allowed Section managers to identify levels of support as well as constraints to policy initiatives. For example, since the first survey in 1987 (Leitch and Baltezore 1987), Minnesota anglers have consistently voiced their support for habitat protection and enhancement.

LARGE LAKES

In 1983 the Large Lake Monitoring Program (LLP) was established to standardize sampling across Minnesota's ten largest Walleye lakes, facilitating between lake comparisons (Wingate and Schupp 1984). As a result of the valuable long-term data collected, fisheries management statewide has looked to the LLP to understand fish population dynamics and the effects of management actions on fish populations and fisheries. Research has played an important role in the LLP by lending expertise to individual lake issues and conducting across-lake analyses. Research on the large lakes has focused on Walleye, including population dynamics, fisheries, and sampling methods, many of which have already been described in this document (e.g., Anderson 1998; Gangl and Pereira 2003; Schmalz and Staples 2011). In addition to the formal research projects leading to publications, the FRU contributes regularly to LLP management by providing expertise and support for decision making. For example, the FRU manager co-chairs the 1837 Fisheries Committee, which consists of tribal and state fisheries representatives for the purpose of facilitating communication between the parties regarding management within the 1837 ceded territory (Minnesota v. Mille Lacs Band of Chippewa Indians. 1999). In addition, the FRU provides support for quota and angling regulation setting for Mille Lacs (Schmalz et al. 2011; Schmalz 2022). The FRU has also provided support and expertise during large lake management planning. That support and expertise has included simulation modeling to evaluate the effects various angling regulations (Treml 2017) and stock assessment modeling to help measure stock status (Goldsworthy et al. 2017).

SENTINEL LAKES

In 2009 the Legislative-Citizen Commission on Minnesota Resources (LCCMR) awarded $825,000 to FRU staff that allowed for the establishment of the Sustaining Lakes in a Changing Environment (SLICE) program (later changed to Sentinel Lake Long-term Monitoring Program). The initial grant allowed FRU staff to work with scientists outside the realm of traditional fisheries management including paleolimnologists, lake modelers, and engineers, to gain a more holistic view of lake dynamics and how they are affected by climate change, land use and development, and aquatic invasive species. While the grant focused on the deep, cold-water lakes within the program (there are 25 in total), FRU and Section staff were also able to annually sample the fish populations from each of the lakes within the program. These annual surveys provided a wealth of information about changes in fish abundance, gear selectivity, and basic fish biology, much of which was summarized by McInerny (2014). Additionally, staff were able to evaluate the use of zooplankton and aquatic macrophytes as indicators of systematic change in lakes (Heiskary et al. 2016; Beck et al. 2014). Subsequent grants from LCCMR, allowed continued standardized sampling, particularly for cold-water species such as Cisco, as well as evaluations of Bluegill netting, White Sucker biology, the use of LiDAR to improve land use and watershed models, enhanced in-lake thermal modeling, the use of Dipterans as biological indicators, algal community composition, food web alterations as a result of zebra mussel invasion (Morrison et al. 2021), tracking juvenile and young-of-the-year Centrarchid growth, and data management and visualization (see Reed 2016, for summaries). The Sentinel Lakes Program continues to collect water chemistry, zooplankton, Cisco abundance, and water-level data.

COOPERATIVE RESEARCH

As the need to address management questions on a larger spatial scale as well as a need to address issues that have statewide policy implications have increased, FRU staff have increased collaborative work with management staff. These collaborations include providing important input on study design and site selection and importantly, assistance with data collection from field surveys. For example, managers assisted with lake selection with several state-wide Walleye stocking evaluations and provided a substantial amount of field assistance in stocking and data collection (Parsons et al. 2015; Reed and Staples 2017). Similarly, management staff have been key partners in research addressing the decline of Yellow Perch populations by identifying target populations and assisting with data collection (Holbrook et al. 2021). The partnership between FRU and management staff was key in the collection of fish population data which set a foundation for monitoring changes in 24 Sentinel Lakes (McInerny 2016). Collaboration has also led to the establishment of suites of regulations for individual lake management for popular species (Reed et al. 2008), lake and stream management planning (Dieterman et al. 2013), the development of the Quality Sunfish Initiative, and the development and evaluation of zonal regulations for Northern Pike management (Bethke et al. 2021).

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