## FEATURE

## Commercial Fisheries of the Upper Mississippi River: A Century of Sustained Harvest

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Commercial harvest is often considered as a primary cause of fish population declines in marine and inland systems throughout the world. However, much of the data supporting the negative attributes of commercial harvest are derived from marine fisheries and may not be directly applicable to inland fisheries. In this study, over 60 years of commercial fishery data from the Upper Mississippi River (UMR) was synthesized to better understand how inland commercial fisheries function and to address concerns associated with the exploitation of aquatic resources in freshwater systems. Overall, total commercial harvest in the UMR remained relatively stable over the study period and did not negatively influence fish populations or recreational fisheries. Our results address concerns associated with inland fisheries and highlight how proper management and interagency partnerships result in consistent and productive fisheries over large spatial and temporal scales.

Exploitation of aquatic resources has occurred for thousands of years and in nearly every aquatic environment in the world. Harvest was historically conducted using rudimentary equipment that limited both the distribution (e.g., water craft) and efficiency (e.g., fishing gear) of harvesters (Thurstan et al. 2010). In the late 19th century, technological advancements and the advent of industrial fishing led to increased catches in coastal and offshore areas (Pauly and Palomares 2005). Today, the majority of the world's fish products are derived from marine stocks and represent approximately 80 million metric tons of fish annually (Taylor et al. 2016). Although marine fisheries are the mainstay of fish production, inland fisheries represent an important component of global fish harvest.

The United Nations Food and Agriculture Organization estimated that approximately 10 million tons of freshwater fish are harvested annually, representing $11-12 \%$ of global commercial fish harvest (marine and freshwater; Taylor et al. 2016). Although inland fisheries contribute a relatively small percentage of global harvest, they provide important social and economic benefits. Inland fisheries generate $2.3 \%$ of total animal protein sources worldwide and contribute to global food security (Cooke et al. 2016). Furthermore, more than 60 million people directly benefit from involvement in inland fisheries supply chains (Taylor et al. 2016). In addition to the economic benefits and contributions to global food security, inland fisheries support important, highly valued recreational fisheries. Despite the myriad socio-economic benefits provided by inland fisheries, commercial and recreational fisheries in freshwater systems are complex and remain poorly understood.

Inland fisheries are highly diverse, varying from small and dispersed recreational fisheries to large-scale commercial fisheries. The various sectors of inland fisheries occur in a diverse array of habitats, countries, and management jurisdictions. The high level of diversity and diffuse nature of inland fisheries make collection of capture statistics difficult, if not impossible. Despite the limited ability to empirically evaluate inland fisheries, these fisheries are often regarded as biologically unsustainable whereby harvest negatively influences individual populations and ecosystems through overfishing and indirect effects (e.g., bycatch, habitat degradation; Welcomme et al. 2010). The presumption of unsustainability seems to originate from a litany of high-profile papers suggesting a general collapse of global fisheries (Casey and Myers 1998; Hutchings 2000; Myers and Worm 2003). Although these assessments generally focus on marine commercial fisheries rather than inland fisheries, broad "doom-and-gloom" pronouncements imply that all fisheries are poorly managed and suffer from overexploitation (Hilborn 2007). Perhaps more concerning is that the negative attributes of marine commercial fisheries have been ascribed to other fishing sectors (e.g., recreational fisheries; Coleman et al. 2004; Cooke and Cowx 2004; Lewin et al. 2006). For instance, Cooke and Cowx (2006) suggest post-release mortality
in recreational fisheries is comparable to mortality associated with bycatch in marine commercial fisheries. The authors conclude that recreational fisheries operate similar to commercial fisheries and contribute to global fishery declines. Similarly, Post et al. (2002) used declining catch rates in recreational fisheries in Canada to suggest fish populations in these systems were overexploited and collapsing, and disregarded the myriad factors that can contribute to population declines (e.g., invasive species, habitat degradation). Although many of these authors are attempting to promote freshwater fish conservation, articles with titles such as The Role of Recreational Fishing in Global Fish Crises (Cooke and Cowx 2004) encourage the notion that exploitation of natural resources is unsustainable. Undoubtedly, commercial and recreational fisheries can have deleterious effects on fish populations (Sullivan 2003; Ebener et al. 2008; Forbes et al. 2015), but characterizing entire fishing sectors negatively ignores the complexity surrounding the management and conservation of fishes. More importantly, speculating about the ills of freshwater fisheries (commercial and recreational) does little to improve our understanding of inland fisheries and marginalizes these fisheries with respect to competing resources (e.g., agricultural, industrial, and domestic sectors; Welcomme et al. 2010). If conserving and sustaining inland fisheries is the goal, then cogent examples of well-managed, successful fisheries are needed to further our understanding of how to effectively exploit aquatic resources to maintain sustained harvest. The Upper Mississippi River (UMR) may provide one such example.

## FISHERIES IN THE UPPER MISSISSIPPI RIVER

The UMR is a large, diverse floodplain system that extends approximately $2,320 \mathrm{~km}$ from Lake Itasca, Minnesota, to Cairo, Illinois, and drains portions of Minnesota, Wisconsin, Iowa, Illinois, and Missouri (Garvey et al. 2010). Originally, the UMR was a dynamic system of meandering channels and shallow bars connecting a series of deep pools (Carlander 1954). Complex, shallow channels made the river difficult or impossible to navigate at low water resulting in extensive river "improvements" in the late 19th century. The Rivers and Harbors Act sanctioned the development of a $1.37-\mathrm{m}$-deep channel maintained by dredging, wing dams, and bank improvements (Chen and Simons 1986). In the 1930s, the Rivers and Harbors Act added sanctions establishing a $2.75-\mathrm{m}$-deep channel maintained by a series of lock and dams. There are now 26 lock and dams on the UMR (primarily constructed between 1930 and 1940), effectively converting the system into a series of lakes (Carlander 1954; Figure 1). It is important to note that Lock and Dam 23 was named but never built, Pool 5A was built between pools 5 and 6 to improve navigation, and Pool 4A denotes the location of Lake Pepin. Despite extensive habitat alterations, the UMR fishery has remained an important component of the social and economic framework of the region.


Figure 1. Map of the Upper Mississippi River. Numbers represent Lock and Dams. Pools are numbered by the dam forming the pool (e.g., Pool 8 is immediately upstream of Lock and Dam 8). Pool 4A does not represent a Lock and Dam, but denotes the location of Lake Pepin.

Historically, aquatic resources were very important to the UMR and likely contributed to the development of the region (Carlander 1954; Nielsen 1999). Fishes were primarily harvested from the UMR for personal consumption during early settlement, but by the later part of the 19th century, commercial fisheries had developed to support the increasing population of the region (Carlander 1954). Despite the transition to commercial harvest, the UMR fishery remained relatively small in scale. The fishing technology in the UMR has remained relatively constant since the middle of the 20th century, relying principally on unsophisticated gear such as gill nets, trammel nets, hoop nets, and trot lines (Carlander 1954). As the region developed economically, involvement in commercial fishing declined and participation in recreational fisheries increased. Recreational fishing is now the most practiced recreational activity in the UMR and contributes to an estimated annual revenue of about US\$200 million (Black et al. 1999). Although participation in commercial fishing has waned, the yield from the UMR represented about $2 \%$ of the total inland catch in North America in 2009 (Welcomme 2011).

Despite the social and economic importance of commercial fishing in the UMR, information about the fishery and how it functions has not been synthesized. Previous research has generally been small in scope and focused on species of high economic or conservation value. For instance, various authors have evaluated different aspects of the commercial fishery for catfishes (Pitlo 1997; Slipke et al. 2002; Krogman et al. 2011). Similarly, members of the suborder Acipenseroidei have been the focus of research varying from descriptions of the commercial harvest of Paddlefish Polyodon spathula (Quist et al.
2009) to assessments of the effects of commercial harvest on Shovelnose Sturgeon Scaphirhynchus platorynchus (Koch et al. 2009b). Although previous work on select species in the UMR is valuable for management, a comprehensive description of commercial fisheries in the UMR is needed. The UMR encompasses portions of five states and represents numerous management jurisdictions, necessitating an understanding of the temporal and spatial trends in harvest. Furthermore, the general dearth of data surrounding inland fisheries necessitates a basic understanding of how inland fisheries respond to exogenous factors (e.g., market demand) and their potential for sustained harvest. Therefore, we sought to provide a synthesis of the commercial fishery in the UMR from 1953 to 2013.

## MATERIALS AND METHODS

Data were compiled by the Upper Mississippi River Conservation Committee (UMRCC). The UMRCC has collected annual commercial harvest statistics in the UMR from Minnesota, Wisconsin, Iowa, Illinois, and Missouri since 1945. Although data have been recorded since 1945, complete records were only available from 1953 to 2013. Reporting of harvest is mandatory for all licensed harvesters and is generally reported by species and location (e.g., pool) on an annual basis. In some instances, reporting was not species specific and similar species were categorized by "landing group". For instance, Silver Carp Hypophthalmichthys molitrix and Bighead Carp H. nobilis represent an "Asian carp" landing group. Nonreporting and underreporting are concerns with these types of data; however, we were primarily concerned with long-term trends and assume any reporting errors were consistent through time and space (Quist et al. 2009). In addition to harvest statistics, the UMRCC records mean market flesh and roe prices by species or landing group. Market values of roe have only recently been recorded consistently; therefore, all economic valuations used in the current study focus on flesh prices. Data on total yield prior to 1953 were obtained from Carlander (1954) and integrated to provide a broader understanding of temporal trends in commercial harvest in the UMR. Commercial harvest in the UMR occurs from St. Anthony Falls, Minnesota (Pool 1), to the Ohio River confluence; however, harvest data available from the UMRCC are restricted to pools 3-26 (Figure 1).

Total yield for the combined UMR pools was summarized for each year to investigate temporal patterns in annual harvest. Additionally, yield was calculated by species (or landing group) and decade to evaluate temporal patterns in taxaspecific harvest. Temporal patterns in harvest were further investigated by assessing potential correlations between year and taxa-specific harvest using a Spearman rank correlation (Sokal and Rohlf 1995). Declining or increasing trends in harvest were considered significant at $\alpha=0.05$. We were also interested in how harvest varied spatially. Therefore, harvest was summarized by family and pool to evaluate spatial variability in yield. Paddlefish and Shovelnose Sturgeon were combined by suborder (Acipenseroidei) due to their shared conservation concern. Families were a primary interest for evaluating spatiotemporal trends because preliminary species-specific analysis proved cumbersome and did not provide insight beyond the patterns observed by family or suborder. Annual patterns in flesh prices were examined using inflation-adjusted prices standardized to 2013 dollars US using the consumer price index (Tietenberg 1996). Certain species (e.g., Shovelnose Sturgeon, Paddlefish, Bowfin Amia calva) were also harvested
for roe, but roe prices were not included in our analysis due to the incomplete data discussed above.

Stable yield alone does not indicate stable catch composition as harvesters can target alternative species when populations are depleted. High-trophic level fishes (e.g., catfishes) are often the primary target in commercial fisheries due to high market value (Pauly et al. 1998). A shift to alternative species generally results in the harvest of lower trophic-level species (i.e., fishing down the food web; Pauly et al. 1998, 2000; Pauly and Watson 2005). As such, decreasing trophic levels through time can identify the potential for inconsistent harvest and catch composition (Pauly and Palomares 2005). In an effort to better understand the influence of commercial harvest on the species assemblage in the UMR, mean trophic index was estimated as:

$$
\mathrm{MTI}_{k}=\sum_{i}\left(\mathrm{TL}_{i}\right)\left(\mathrm{Y}_{i}\right) / \sum_{i} \mathrm{Y}_{i}
$$

where MTI is the mean trophic level of the landings in year $k, \mathrm{Y}$ is the annual landing of trophic group $i$, and TL is the trophic level of trophic group $i$ (Pennino et al. 2011).

High catches of lower trophic-level species can greatly influence estimates of MTI and obfuscate effects on fish assemblages caused by fishing (Pennino et al. 2011). Therefore, we also estimated MTI excluding fish with a trophic level lower than 3.25 (MTI-cut) to eliminate herbivores, detritivores, and planktivores from the analysis (Pauly and Watson 2005). Species-specific trophic levels were obtained from FishBase (Froese and Pauly 2017) and averaged based on the landing grouping (Table 1). In instances where species-specific trophic levels were not available, closely related species with similar ecology were combined. For instance, trophic level was not available for Goldeye Hiodon alosoides, so the trophic level for Mooneye H. tergisus (3.50) was used for both species.

Table 1. Trophic level by landing groupings (defined by Upper Mississippi River Conservation Committee) of fish caught in the commercial fishery. All trophic levels were obtained from Fishbase.com. Asterisks indicate trophic level was available for individual species.

| Grouping | Species | Trophic level |
| :--- | :--- | :---: |
| Carpsucker | River Carpsucker | 2.00 |
| Grass Carp* | Grass Carp | 2.00 |
| Asian Carp | Silver Carp, Bighead Carp | 2.16 |
| Carp* | Common Carp | 2.96 |
| Catostomids | Redhorse and suckers | 2.99 |
| Paddlefish* | Paddlefish | 3.00 |
| Buffalo | Smallmouth Buffalo, <br> Freshwater Drum* | Freshwater Drum |
| Hiodon | Goldeye, Mooneye | 3.11 |
| Shovelnose Sturgeon* | Shovelnose Sturgeon | 3.36 |
| Bullhead catfish | Black Bullhead, Brown <br> Bullhead, Yellow Bullhead | 3.50 |
| Non-bullhead catfish | Flathead Catfish, Channel <br> Catfish, Bluehead Catfish | 3.50 |
| American Eel* | American Eel | 3.58 |
| Bowfin* | Bowfin | 3.67 |
| Gar | Alligator Gar, Longnose <br> Gar, Shortnose Gar, <br> Spotted Gar | 3.81 |

Trophic-level indices (i.e., MTI, MTI-cut) were summarized over the 60 -year time series to identify potential changes in annual mean trophic level in the UMR fishery. Data compiled from Carlander (1954) were not as detailed (e.g., fewer landing groups) as data collected by the UMRCC. As such, pre-1953 data were not included in taxa-specific analyses (e.g., Spearman rank correlations, MTI).

## RESULTS

Total annual harvest in the UMR exhibited variability through time, but fluctuated about a relatively stable average (Figure 2). Prior to 1953, total annual harvest fluctuated from 3,182 tons (1931) to 5,737 tons (1894) and averaged 4,543 tons ( $\mathrm{SD}=854$ ). From 1953 to 2013, annual harvest was comparable to pre-1953 levels and varied from 2,509-6,037 tons (mean $=4,358$ tons; $\mathrm{SD}=856$ ). Harvest increased by over 200 tons in 1953-1957 and remained high until 1971. Harvest declined from 1971 to 1987, increased from 1988 to 1997, and then decreased to levels comparable to those of the 1950s.

Species composition of harvested fish was relatively constant through time (Figure 2). Common Carp Cyprinus carpio and buffalo Ictiobus spp. were the dominant taxa harvested over the period of record. Common Carp averaged $37 \%$ of the total catch and buffalo averaged $26 \%$ of the harvest from 1953 to 2013. Freshwater Drum Aplodinotus grunniens and nonbullhead catfishes (Channel Catfish Ictalurus punctatus, Blue Catfish I. furcatus, Flathead Catfish Pylodictis olivaris) were also common in the harvest, but never exceeded $25 \%$ of annual harvest. Other taxa rarely exceeded $5 \%$ of the total annual harvest.

Collectively, annual harvest from the UMR was valued from US $\$ 1.5-\$ 13.2$ million with an average value of $\$ 5.0$ million ( $\mathrm{SD}=2.8$; Figure 2). Total market value peaked in the 1950s and 1960s and steadily declined to 2013 levels. From 1953 to the late 1980s, market value mirrored harvest with peaks occurring in 1959 and 1965. Following peak values in 1959, market values declined and showed little concordance with total harvest after 1990.

Four landing groups dominated the market (Figure 3). Bullhead catfishes Ameiurus spp., non-bullhead catfishes, Shovelnose Sturgeon, and American Eel Anguilla rostrata accounted for approximately $53 \%$ of the market value of the fish harvested from the UMR. Common Carp and buffalo consistently dominated the harvest, but only represented about $12 \%$ of the market value. Paddlefish were harvested in low numbers from 1953 to 2013, but represented an average of $8 \%$ of the market share. All other species accounted for less than $5 \%$ of the market value.

Although total harvest varied over decades, distribution of harvest among pools remained relatively stable (Figure 4). Every decade, mean harvest was centered on modes at pools including 4A, 9, 13, 19, and 26. Pool 9 contributed the most harvest and accounted for $11 \%(1980-1989)$ to $17 \%(1990-1999)$ of the total mean harvest in the UMR. Pools 4A, 13, and 19 also exhibited fairly consistent harvest, but were slightly more variable than Pool 9. From 1953 to 2013, mean harvest in pools 4A, 13 , and 19 varied from $21 \%$ (1980-1989) to $30 \%$ (1953-1959). Pool 26 exhibited relatively low harvest compared to the other four high-harvest pools, but still contributed about $5 \%$ of the mean harvest across the 60 years of record. Interestingly, harvest in pools adjacent to high-yield pools was generally higher than other pools in the UMR. For example, pools adjacent to Pool 9 (i.e., pools 8 and 10) accounted for a combined $18 \%$ of


Figure 2. Total harvest and market value (adjusted to 2013 USD) by taxa and year for pools 3-26 in the Upper Mississippi River from 1953-2013. Estimates of total harvest prior to 1953 are also included and were compiled from Carlander (1954). Landing groupings are ordered by average yield (highest to lowest) and total market value is indicated by a solid line.


Figure 3. Percent market share by year for fish harvested from pools 3-26 in the Upper Mississippi River from 1953-2013.
the mean harvest produced from 1980 to 1989; whereas, pools 7 and 11 contributed $\sim 8 \%$ of mean harvest in the same decade. Harvest generally declined in pools more distant from highyield pools. For instance, pools 6,15 , and 22 never exceeded more than $3 \%$ of the mean harvest in a given decade.

Harvest of individual families was variable among pools (Figure 5). Families that exhibited consistently high catch were generally harvested throughout the UMR, but harvest
tended to be focused in high-yield pools (e.g., pools $4 \mathrm{~A}, 9$, 13, 19, 26). For instance, Cyprinidae were harvested in every pool in the UMR, but harvest was highest in pools 4 A and 9 regardless of the decade (Figure 5). Similarly, Catostomidae were harvested throughout the UMR with the majority of harvest occurring in pools 9-13. Conversely, families that generally had low yield were most often harvested in specific pools of the UMR. Acipenseroidei (Shovelnose Sturgeon,


Figure 4. Mean total harvest by decade for pools 3-26 in the Upper Mississippi River from 1953-2013.

Paddlefish), Amiidae (Bowfin), Anguillidae (American Eel), and Hiodontidae (Goldeye, Mooneye) all had highest yields in three or fewer pools. Anguillidae exhibited the highest harvest in pools 24,25 , and 26; whereas, Amiidae had the highest harvest in pools 9 and 10. Although patterns in harvest were generally consistent spatially, family-specific patterns in harvest were temporally variable.

Harvest of landing groups did not exhibit consistent patterns in harvest through time (Figure 6). For instance, yield of 11 groups declined over the study period; whereas, harvest of four taxa increased over the same time period. Yield of Common Carp, Paddlefish, bullhead catfishes, and American Eel was negatively related to year ( $P \leq 0.05$ for all taxa). Similarly, harvest of River Carpsucker Carpiodes carpio, Asian Carp, and Grass Carp Ctenopharyngodon idella was positively related to year $(P \leq 0.05$ for all taxa).

Despite the high market value of species at high trophic levels (e.g., bullhead catfishes, nonbullhead catfishes, Shovelnose Sturgeon, American Eel), exploitation of these species did not result in appreciable changes to the mean trophic level (Figure 7). For example, MTI-cut of harvested fish did not deviate from about 3.5. When benthivores, planktivores, and detritivores were included in the analysis, the MTI value was slightly more variable, but remained between 3.0 and 3.2 over 60 years.

## DISCUSSION

Total yield of the commercial fishery in the UMR has been variable between years but stable over the period of record. Harvest was relatively high at the turn of the century ( 5,737 tons in 1894) and exhibited fluctuations thereafter. During peak harvest in 1964, the commercial fishery in the UMR produced over 6,000 tons of fish and generated approximately $\$ 9$ million. Harvest has decreased in recent history, but the UMR still produced an average of about 3,000 tons
of fish per year since 2003. Despite continued exploitation of fishes over the last century, the UMR fishery is considered biologically stable and capable of supporting additional harvest (Johnson and Hagerty 2008). Risotto and Turner (1985) suggested that the commercial fishery in the UMR was near optimal harvest levels from 1965 to 1976. As such, the UMR could likely support an increase in harvest of about 3,000 tons from 2013 levels and remain stable. Fishery-independent data collected by the Long-Term Resource Monitoring Program also indicates that the UMR has not been negatively influenced by continued exploitation. Johnson and Hagerty (2008) concluded that commercial harvest was not negatively influencing fishes in the UMR based on stable catches of seven commercially important species (Bigmouth Buffalo Ictiobus cyprinellus, Smallmouth Buffalo I. bubalus, Black Buffalo I. niger, Channel Catfish, Blue Catfish, Flathead Catfish, and Freshwater Drum) from 1994 to 2004. The authors recognized that commercial harvest in the UMR had declined in recent history, but suggested that declines in catch were likely attributable to fluctuations in market demand and not habitat degradation or overharvest.

Like most markets, production in commercial fisheries is a function of market demand. However, identifying the factors influencing market dynamics is difficult due to the complex interplay between social and economic factors. Aquaculture and changes to public consumption habits appear to have led to the decline in market value for many fishes in the UMR. For instance, Krogman et al. (2011) indicated that declines in market value for wild-caught catfishes (i.e., bullhead and nonbullhead catfishes) in the UMR was related to increases in the production of cultured catfishes. The authors suggested that the exponential growth of the catfish aquaculture industry in the 1980s effectively "swamped" the market and drove down flesh prices. Our results support this assertion as evidenced by the decrease in average flesh price of catfishes from $\$ 4.19 / \mathrm{kg}$ in the 1960 s


Figure 5．Mean harvest by decade and taxa for pools 3－26 in the Upper Mississippi River from 1953－2013．Decades include 1953－1959（■），1960－1969（ $\square$ ），1970－1979（■），1980－1989（图），1990－1999（四），2000－2009（図），and 2010－2013（图）．


Figure 5. Continued
to $\$ 1.07 / \mathrm{kg}$ in the 2000 s. Similar declines in market value are apparent for every commerciallyexploited species in the UMR including buffalo ( $\$ 1.76 / \mathrm{kg}$ [1960s]- $\$ 0.60 / \mathrm{kg}$ [2000s]), bullhead catfishes ( $\$ 2.31 / \mathrm{kg}-\$ 0.93 / \mathrm{kg}$ ), Common Carp $(\$ 0.68 / \mathrm{kg}-\$ 0.24 /$ kg ), and Shovelnose Sturgeon ( $\$ 3.13 / \mathrm{kg}-\$ 1.07 / \mathrm{kg}$ ). However, few species important to the commercial fishery in the UMR directly compete with aquaculture production. Rather, market demand appears to have been influenced by changes in consumption habits of the public. For instance, Common Carp were traditionally exported to markets in the midwestern and eastern

United States (e.g., Chicago, New York). However, dwindling demand for Common Carp in the mid-1900s (Carlander 1954) and concerns with polychlorinated biphenyl contamination in the 1980s likely resulted in a decreased demand for the species (Lubinski et al. 1986). Similar declines in market demand for many species has potentially led to an overall decline in total market value of commercially exploited fishes in the UMR.

Despite the decline in total market value of the UMR commercial fishery, overall yield has not declined at a similar rate. In the 1960 s , an annual average of 1,977 $(\mathrm{SD}=221)$


Figure 6. Spearman correlations between harvest and year for individual taxa harvested from the Upper Mississippi River from 1953-2013. Solid bars indicate significant correlations ( $P \leq 0.05$ ).
licenses were held in the UMR fishery. Each licensee harvested an annual average of about 2.6 tons of fish valued at $\$ 55,616$. Conversely, only $848(\mathrm{SD}=39)$ licensees participated in the UMR commercial fishery in the 2000s and harvested a per capita annual average of 4.0 tons worth about $\$ 35,555$. From the 1960 s to the 2000 s, average total market value decreased by approximately $75 \%$; whereas, total yield decreased by only $33 \%$. Considering that most commercial fisheries are largely motivated by profit (Sethi et al. 2010), it is surprising that total yield in the UMR has not declined at a rate similar to total market value. One possible explanation is that many commercial harvesters in the UMR are thought to be "casual fishers" and participate in the commercial fishery to supplement other incomes (Carlander 1954). Therefore, participation in the commercial fishery in the UMR will likely remain active as long as the value of the catch exceeds participation costs (e.g., gear maintenance, fuel, time; Welcomme 2001).

Pool-specific harvest characteristics remained fairly consistent through time, despite annual fluctuations in yield. Pools 4A, 9, 13, 19, and 26 had the highest harvest among pools regardless of the decade considered. For instance, Pool 9 generally produced the highest yields in the UMR and represented an average of $10 \%-17 \%$ of the total harvest in the UMR through time. Pools that had consistently high harvest were also those pools that had the most open water. Pools 4A, 9, 13,19 , and 26 vary in surface area from $71.51 \mathrm{~km}^{2}$ (Pool 26) to $135.41 \mathrm{~km}^{2}(\operatorname{Pool} 4 \mathrm{~A})$; whereas, nearly every other pool has less than $60.70 \mathrm{~km}^{2}$ of open water. The fact that more fish were harvested in pools with higher amounts of open water is not particularly surprising considering the commonly reported relationship between surface area and yield (Jenkins and Morais 1971; Young and Heimbuch 1982). Although harvest in pools $4 \mathrm{~A}, 9,13,19$, and 26 was consistently high, the factors contributing to species-specific harvest are poorly understood.

Families that accounted for the majority of harvest (e.g., Common Carp, buffalo) were harvested throughout the UMR, but exhibited the highest harvest in high-yield pools. For instance, harvest of Cyprinidae was highest in pools 4A and 9 , regardless of the time period. Similarly, harvest of Catostomidae was highest in pools 9 and 13 over the study period. Many of the least-harvested taxa (e.g., Acipenseroidei, Amiidae, Anguillidae) exhibited specific spatial patterns in harvest. Paddlefish and Shovelnose Sturgeon were predominantly harvested in downstream portions of the UMR with the majority of harvest occurring in Pool 19. Harvest of Amiidae was focused on the upstream portions of the UMR with the majority of harvest occurring in pools 8 and 9 . Habitat use and the spatial distribution of individual species likely contribute to some of the taxa-specific spatial patterns in harvest. For instance, much of the UMR is comprised of low-velocity riverine habitats that is particularly suitable habitat for Cyprinidae and Catostomidae common to the system (Panek 1987; Rahel and Hubert 1991; Minckley and Deacon


Figure 7. Mean trophic index (MTI) and mean trophic index excluding fish with a trophic level less than 3.25 (MTI-cut) by year for fish harvested from pools 3-26 in the Upper Mississippi River from 1953-2013.
1991). Harvest of Paddlefish and Shovelnose Sturgeon, on the other hand, appears to have been primarily influenced by harvest regulations. In the 1950s, trammel nets were restricted in the boundary waters between Wisconsin and Minnesota (e.g., pools 3-8) and commercial harvest of Paddlefish has been closed upstream of Pool 9 since the 1930s (Gengerke 1978). Similarly, much of the harvest of Shovelnose Sturgeon in the UMR is regulated by length limits and season closures (Koch and Quist 2010). Regardless of the exact mechanism(s) underlying harvest dynamics in the UMR, simply understanding spatial trends in harvest provides valuable insight into where to direct research, management actions, and(or) monitor potential effects of the commercial fishery.

## A Model of Interagency Cooperation, Management, and Sustained Harvest

Commercial harvest is often posited as a primary cause of declines in fish populations in freshwater and marine systems (Myers and Worm 2003; Allan et al. 2005; Cooke and Cowx 2006). Commercial harvest can negatively affect fish populations through food web disruptions, fishery-induced selection, habitat degradation, and overexploitation (Jennings and Kaiser 1998). Overharvest of Lake Whitefish Coregonus clupeaformis was implicated in declines in catch from 11 million kg in 1879 to 0.7 million kg in 1959 in the Great Lakes (Ebener et al. 2008). However, the negative effects of commercial fishing are often specific to particular fisheries and do not represent the entire commercial fishery sector. Our results suggest commercial harvest in the UMR has not adversely affected fish populations or severely altered fish assemblages. Harvest prior to 1953 averaged 4,543 tons; whereas, harvest averaged 4,358 tons from 1953 to 2013. Per capita harvest by licensee in the UMR has exhibited an increasing trend from 1953 to 2013. Similarly, catch per unit effort of seven commercially harvested species in pools $4 \mathrm{~A}, 13$, and 26 were increasing or stable from 1994 to 2004 (Johnson and Hagerty 2008). Species richness in pools $4 \mathrm{~A}, 8,13$, and 26 was also categorized as stable from 1993 to 2004. Consistent harvest alone is not indicative of a stable fishery as harvesters can target different trophic levels through time (e.g., fishing down the food web; Pauly et al. 1998). Pauly and Palomares (2005) suggested the use of mean trophic levels (e.g., MTI, MTI-cut) to indicate consistent catch composition and the occurrence (or absence) of sustainable harvest. For instance, mean trophic level of catches in the Chinese marine fishery declined from 1950 to 2000 despite an increasing trend in overall harvest (Pauly and Palomares 2005). Estimates of mean MTI and MTI-cut indicate that catch composition has remained consistent in the UMR and suggest that the fishery has been harvested at sustainable levels over the period of record. In addition to direct effects, commercial harvest can alter trophic dynamics and indirectly influence other fishing sectors. High exploitation of Bloaters Coregonus hoyi in the Great Lakes likely contributed to the instability and decline of recreationally valuable Lake Trout Salvelinus namaycush populations by reducing available prey (Smith 1968). Despite continued harvest in the UMR, commercial harvest does not appear to be negatively influencing nontarget species as evidenced by fishery-dependent and fishery-independent data. Periodic creel surveys (every 5 years) in pools 4 and 4A indicated that recreational harvest of Sauger Sander canadensis and Walleye S. vitreus remained relatively stable (mean $=41,745 \mathrm{~kg} /$ year; $\mathrm{SD}=12,503$ ) from 1967 to 2007 (Meerbeek 2008). Fishery-independent
surveys have revealed similar trends in sport fish populations. Standardized surveys in pools $4,8,13$, and 26 indicated that catch rates of Bluegill Lepomis macrochirus, Channel Catfish, Sauger, and Smallmouth Buffalo were stable or improving from 1994 to 2004 (Johnson and Hagerty 2008). Collectively, our results suggest the commercial fishery in the UMR is not negatively influencing fish populations or concurrent recreational fisheries.

The commercial fishery in the UMR provides evidence that consistently productive fisheries are achievable. Relatively low harvest is at least partially responsible for the apparent stability of the commercial fishery in the UMR (e.g., Risotto and Turner 1985). The entire Mississippi River exhibits moderate annual harvest ( 30,000 tons) when compared to systems with similar discharge rates (McIntyre et al. 2016). The Ob-Irtysh and Mekong rivers (Asia) exceed the annual harvest of the Mississippi commercial fishery by about 16,500 tons (Ob-Irtysh) and 2.61 million tons (Mekong). In contrast, annual harvest in the Mississippi River exceeds that of the Parana River (South America) by about 26,000 tons. McIntyre et al. (2016) suggested that consumption habits and economic status of the region surrounding a given fishery greatly influences its reliance on wild-caught freshwater fishes. As such, the UMR is likely subject to less fishing pressure than would be expected in a less prosperous region. In addition to low fishing effort, the majority of the harvest in the UMR is focused on species (e.g., Common Carp, buffalo) that exhibit life-history characteristics (e.g., early age-at-maturity, high fecundity) that likely support higher levels of exploitation. Common Carp have been the focus of a numerous suppression efforts that have been largely unsuccessful (Weber et al. 2011). The general inability to successfully suppress Common Carp is often attributed to the species' high fecundity and fast growth rate. In fact, targeting species in accordance with their natural productivity has recently been proposed as a way to achieve sustainability and maintain biodiversity in other commercial fisheries (Garcia et al. 2012; Reid et al. 2016). Notwithstanding, any fish population can be overfished and requires consistent, proactive, and extensive management to remain stable.

The UMR is managed through a number of interstate and interagency partnerships (e.g., federal agencies, state agencies, nonprofit organizations, and universities) that have direct involvement in management of the system (Garvey et al. 2010). Through such partnerships, the aquatic resources of the UMR can be monitored and interjurisdictional management actions can be implemented to address current, emerging, and future concerns in the system. For example, a general decline in nonbullhead catfish (e.g., Channel Catfish, Flathead Catfish) harvest in pools 9-19 raised concerns for the commercial and recreational fishery in the UMR from the 1950s to the early 1980s (Pitlo 1987). The decline in catfish harvest was attributed to overharvest and resulted in the institution of a 380 mm minimum length limit for commercially harvested catfish throughout the UMR. Following implementation of the length limit in 1985, recruitment improved and commercial harvest of catfish in pools 9-19 increased (Pitlo 1997; Slipke et al. 2002). Similarly, collapse of sturgeon populations in Europe in the 1990s raised concerns about potential increases in commercial harvest of Shovelnose Sturgeon in the UMR to support the caviar market (Koch et al. 2009b). Accordingly, Iowa, Wisconsin, and Illinois proactively implemented length restrictions for commercial fisheries in UMR border waters. In addition, the Iowa Department of Natural Resources partnered with Iowa State University
researchers to undertake a study evaluating the influence of commercial harvest on populations of Shovelnose Sturgeon in the UMR. The study resulted in a suggested 685 mm minimum length limit to avoid growth and recruitment overfishing of Shovelnose Sturgeon in the UMR (Koch et al. 2009b). Bowfin are also targeted in commercial fisheries for sale in the caviar market (Koch et al. 2009a); however, the Bowfin market has remained relatively small in the UMR. Notwithstanding, Iowa Department of Natural Resources implemented research to understand how increasing demand for Bowfin roe in the UMR may influence the species. Koch et al. (2009a) concluded that Bowfin were not currently overexploited, but a 635 mm minimum length limit would prevent recruitment overfishing in the instance of increased exploitation. Such intensive management may not be feasible in many inland commercial fisheries, but the UMR highlights the importance of interagency cooperation, coordination, and active management for achieving consistently productive fisheries.

The UMR may be uncommon in terms of management and the stability of catch composition and harvest levels. However, we argue that far too much emphasis is placed on failed fisheries creating a perception that all commercial and recreational fisheries are untenable. Failed fisheries should not be discounted, but casting all fisheries in a negative light focuses on failures rather than learning from the varied successful fisheries around the world. Although it may be tempting to malign entire fishing sectors, understanding the factors that contribute to successes or failures and adjusting management practices accordingly is likely the only way to ensure the future sustainability of global fisheries.

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## REFERENCES

Allan, J. D., R. Abell, Z. Hogan, C. Revenga, B. W. Taylor, R. L. Welcomme, and K. Winemiller. 2005. Overfishing in inland waters. BioScience 55:1041-1051.
Black, R., B. McKenney, A. O’Connor, E. Gray, and R. Unsworth. 1999. Economic profile of the upper Mississippi River region. Industrial Economics Incorporated, Cambridge, Massachusetts.
Carlander, H. B. 1954. A history of fish and fishing in the upper Mississippi River. Upper Mississippi River Conservation Committee, Marion, Illinois.
Casey, J. M., and R. A. Myers. 1998. Near extinction of a large widely distributed fish. Science 281:690-692.
Chen, Y. H., and D. B. Simons. 1986. Hydrology, hydraulics, and geomorphology of the upper Mississippi River system. Hydrobiologia 136:5-20.
Coleman, F. C., W. F. Figueira, J. S. Ueland, and L. B. Crowder. 2004. The impact of United States recreational fisheries on marine fish populations. Science 305:1958-1960.
Cooke, S. J., and I. G. Cowx. 2004. The role of recreational fishing in global fish crises. BioScience 54:857-859.

Cooke, S. J., and I. G. Cowx. 2006. Contrasting recreational and commercial fishing: searching for common issues to promote unified conservation of fisheries resources and aquatic environments. Biological Conservation 128:93-108.
Cooke, S. J., V. M. Nguyen, J. M. Dettmers, R. Arlinghaus, M. C. Quist, D. Tweddle, O. L. F. Weyl, R. Raghavan, M. Portocarrero-Aya, E. A. Cordoba, and I. G. Cowx. 2016. Sustainable inland fisheries-perspectives from the recreational, commercial and subsistence sectors from around the globe. Pages 467-505 in G. P. Closs, M. Krkosek and J. D. Olden, editors. Conservation of freshwater fishes. Cambridge University Press, Cambridge, United Kingdom.
Ebener, M. P., R. E. Kinnunen, L. C. Mohr, P.J. Schneeberger, J. A. Hoyle, and P. Peeters. 2008. Management of commercial fisheries for Lake Whitefish in the Laurentian Great Lakes of North America. Pages 99-143 in M. G. Schechter, W. W. Taylor and N. J. Leonard, editors. International governance of fisheries ecosystems: learning from the past, finding solutions for the future. American Fisheries Society, Bethesda, Maryland.
Forbes, J. P., R. J. Watts, W. A. Robinson, L. J. Baumgartner, A. S. Steffe, and J. J. Murphy. 2015. Recreational fishing effort, catch, and harvest for Murray Cod and Golden Perch in the Murrumbidgee River, Australia. North American Journal of Fisheries Management 35:649-658.
Froese, R., and D. Pauly, editors. 2017. FishBase. Available: www.fishbase.org (October 2017).
Garcia, S. M., J. Kolding, J. Rice, M. J. Rochet, S. Zhou, T. Arimoto, J. E. Beyer, L. Borges, A. Bundy, D. Dunn, E. A. Fulton, M. Hall, M. Heino, R. Law, M. Makino, A. D. Rijnsdorp, F. Simard, and A. D. M. Smith. 2012. Reconsidering the consequences of selective fisheries. Science 335:1045-1047.
Garvey, J., B. Ickes, and S. Ziegler. 2010. Challenges in merging fisheries research and management: the upper Mississippi River experience. Hydrobiologia 640:125-144.
Gengerke, T. W. 1978. Paddlefish investigations. Iowa Conservation Commission, commercial fishery investigations, completion report, No. 2-225-R. Des Moines, Iowa.
Hilborn, R. 2007. Moving to sustainability by learning from successful fisheries. AMBIO: A Journal of the Human Environment 36:296-303.
Hutchings, J. A. 2000. Collapse and recovery of marine fishes. Nature 406:882-885.
Jenkins, R. M., and D. I. Morais. 1971. Reservoir sport fishing effort and harvest in relation to environmental variables. Pages 371-384 in G. E. Hall, editor. Reservoir fisheries and limnology. American Fisheries Society, Bethesda, Maryland.
Jennings, S., and M. J. Kaiser. 1998. The effects of fishing on marine ecosystems. Advances in Marine Biology 34:201-212.
Johnson, B. L., and K. H. Hagerty, editors. 2008. Status and trends of selected resources of the upper Mississippi River System. U.S. Geological Survey, Upper Midwest Environmental Sciences Center. La Crosse, Wisconsin.
Koch, J. D., and M. C. Quist. 2010. Current status and trends in Shovelnose Sturgeon (Scaphirhynchus platorynchus) management and conservation. Journal of Applied Ichthyology 26:491-498.
Koch, J. D., M. C. Quist, K. A. Hansen, and G. A. Jones. 2009a. Population dynamics and potential management of Bowfin (Amia calva) in the upper Mississippi River. Journal of Applied Ichthyology 25:545-550.
Koch, J. D., M. C. Quist, C. L. Pierce, K. A. Hansen, and M. J. Steuck. 2009b. Effects of commercial harvest on Shovelnose Sturgeon populations in the upper Mississippi River. North American Journal of Fisheries Management 29:34-100.
Krogman, R. M., J. R. Fischer, M. C. Quist, M. J. Steuck, and M. M. Marron. 2011. Historical trends in ictalurid catfish commercial harvest in the upper Mississippi River. Pages 127-140 in P. H. Michaletz and V. H. Travnicheck, editors. Conservation, ecology, and management of catfish: the second international symposium. American Fisheries Society, Bethesda, Maryland.
Lewin, W. C., R. Arlinghaus, and T. Mehner. 2006. Documented and potential biological impacts of recreational fishing: insights for management and conservation. Reviews in Fisheries Science 14:305-367.
Lubinski, K. S., A. Vanvooren, G. Farabee, J. Janecek, and S. D. Jackson. 1986. Common Carp in the upper Mississippi River. Hydrobiologia 136:141-153.
McIntyre, P. B., C. A. Reidy Liermann, and Carmen Revenga. 2016. Linking freshwater fishery management to global food security and biodiversity conservation. PNAS 113:12880-12885.
Meerbeek, J. R. 2008. Angler survey of Lake Pepin and Pool 4 of the Mississippi River, from 2005 to 2007. Minnesota Department of

Natural Resources Section of Fisheries Completion Report, F-29-R(P)-27. St. Paul, Minnesota.
Minckley, W. L., and J. E. Deacon, editors. 1991. Battle against extinction: native fish management in the American West. The University of Arizona Press, Tucson, Arizona.
Myers, R. A., and B. Worm. 2003. Rapid worldwide depletion of predatory fish communities. Nature 423:280-283.
Nielsen, L. A. 1999. History of inland fisheries management in North America. Pages 3-30 in C. C. Kohler and W. A. Hubert, editors. Inland fisheries management, 2nd edition. American Fisheries Society, Bethesda, Maryland.
Panek, F. M. 1987. Biology and ecology of carp. Pages 1-15 in E. L. Cooper, editor. Carp in North America. American Fisheries Society, Bethesda, Maryland.
Pauly, D., V. Christensen, J. Dalsgaard, R. Froese, and F. C. Torres Jr. 1998. Fishing down marine food webs. Science 279:860-863.
Pauly, D., and M. L. Palomares. 2005. Fishing down marine food web: it is far more pervasive than we thought. Bulletin of Marine Science 76:197-211.
Pauly, D., and R. Watson. 2005. Background and interpretation of the 'Marine Trophic Index' as a measure of biodiversity. The Royal Society 360:415-423.
Pauly, D., R. Watson, and J. Alder. 2000. Global trends in world fisheries: impacts on marine ecosystems and food security. Philosophical Transactions of the Royal Society B: Biological Sciences 360:5-12.
Pennino, M. G., J. M. Bellido, D. Conesa, and A. López-Quílez. 2011. Trophic indicators to measure the impact of fishing on an exploited ecosystem. Animal Biodiversity and Conservation 34:123-131.
Pitlo, J. Jr. 1987. Standing stock of fishes in the upper Mississippi River. Iowa Department of Natural Resources. Fish Technical Section, Upper Mississippi River Conservation Committee, Rock Island, Illinois.
Pitlo, J. Jr. 1997. Response of upper Mississippi River Channel Catfish populations to changes in commercial harvest regulations. North American Journal of Fisheries Management 17:848-859.
Post, J. R., M. Sullivan, S. Cox, N. P. Lester, C. J. Walters, E. A. Parkinson, A. J. Paul, L. Jackson, and B. J. Shuter. 2002. Canada's recreational fisheries: the invisible collapse? Fisheries 27:6-17.
Quist, M. C., M. J. Steuck, and M. M. Marron. 2009. Pages 345-355 in C. P. Paukert, and G. Scholten, editors. Paddlefish management,
propagation, and conservation in the 21st century: building from 20 years of research and management. American Fisheries Society, Symposium 66, Bethesda, Maryland.
Rahel, F. J., and W. A. Hubert. 1991. Fish assemblages and habitat gradients in a Rocky Mountain Great Plains stream: biotic zonation and additive patterns of community change. Transactions of the American Fisheries Society 120:319-332.
Reid, D. G., N. Graham, P. Suuronen, P. He, and M. Pol. 2016. Implementing balanced harvesting: practical challenges and other implications. ICES Journal of Marine Science 73:1690-1696.
Risotto, S. P., and R. E. Turner. 1985. Annual fluctuation in abundance of the commercial fisheries of the Mississippi River and tributaries. North American Journal of Fisheries Management 5:557-574.
Sethi, S. A., T. A. Branch, and R. Watson. 2010. Global fishery development patterns are driven by profit not trophic level. PNAS 107:12163-12167.
Slipke, J. W., A. D. Martin, J. Pitlo Jr., and M. J. Maceina. 2002. Use of spawning potential ratio for the upper Mississippi River Channel Catfish fishery. North American Journal of Fisheries Management 22:1295-1300.
Smith, S. H. 1968. Species succession and fishery exploitation in the Great Lakes. Journal of the Fisheries Research Board of Canada 25:667-693.
Sokal, R. R., and F.J. Rohlf. 1995. Biometry, 3rd edition. Freeman, New York.
Sullivan, M. G. 2003. Active management of Walleye fisheries in Alberta: dilemmas of managing recovering fisheries. North American Journal of Fisheries Management 23:1343-1358.
Taylor, W. W., D. M. Bartley, C. I. Goddard, N. J. Leonard, and R. Welcomme, editors. 2016. Freshwater, fish and the future: proceedings of the global cross-sectoral conference. American Fisheries Society, Bethesda, Maryland.
Thurstan, R. H., S. Brockington, and C. M. Roberts. 2010. The effects of 118 years of industrial fishing on UK bottom trawl fisheries. Nature Communications 1:1-6.
Tietenberg, T. 1996. Environmental and natural resource economics, 4th addition. Harper Collins College Publishers, New York.
Weber, M. J., M. J. Hennen, and M. L. Brown. 2011. Simulated population responses of Common Carp to commercial exploitation. North American Journal of Fisheries Management 31:269-279.
Welcomme, R. L. 2001. Inland fisheries: ecology and management. WileyBlackwell, Hoboken, New York.
Welcomme, R. L. 2011. Review of the state of the world fishery resources: inland fisheries. Food and Agriculture Organization of the United Nations, Fisheries and Aquaculture Circular No. 942. Rome.
Welcomme, R. L., I. G. Cowx, D. Coates, C. Béné, S. Funge-Smith, A. Halls, and K. Lorenzen. 2010. Inland capture fisheries. Philosophical Transaction of the Royal Society B 365:2881-2896.
Young, W. D., and D. G. Heimbuch. 1982. Another consideration of the morphoedaphic index. Transactions of the American Fisheries Society 111:151-153. AFS

