REGIONAL ASSESSMENT OF INLAND FISH MORTALITIES ASSOCIATED WITH WINTER AND COLD-SHOCK STRESSES

by

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ABSTRACT

The winter is generally regarded as a stressful period for ectothermic animals (i.e., Winter Stress Syndrome), which can be exacerbated by cold shock stress associated with major arctic freezes. Although loosely defined, major arctic freezes consist of abnormally colder air, and therefore abnormally colder water temperatures, for several days (e.g., 2021's Winter Storm Uri). During major arctic freezes in the 1980s and in 2021, 35 million Texas marine and estuarine fishes were killed attributed to cold shock stress. Interestingly, few studies report the effects of winter stress or cold shock stress on fishes in inland waters. Purpose of this study was to describe patterns in cold weather fish mortalities attributed to winter stress and cold-shock stress within inland waters of Texas between 1969 and 2021 using records contained within Texas Parks and Wildlife Department's Pollution Response Inventory and Species Mortality (PRISM) database. Among 53 years, reports of cold weather inland fish mortalities occurred in 66% of the years with greatest percentages of the reports occurring during three major arctic freezes in 1981, 1983, and 2021. Majority of the reports were from urbanized counties (79%) and from lentic environments (56%). Sixteen taxa and 1,000,000 individuals were reported killed during the 53 years. Numbers of inland fish mortalities were greater in years with major arctic freezes than in years without major arctic freezes, attributed primarily to mortalities of non-native fishes (e.g., Blue Tilapia *Oreochromis aureus*, Suckermouth Catfish *Hypostomus plecostomus*). Numbers of native fish mortalities, primarily clupeids and catostomids, were not different between years with and without major arctic freezes.

The 43,000 inland fish mortalities reported during the three major arctic freezes are in stark contrast to the 35 million marine and estuarine fish mortalities. Proposed mechanisms to explain cold shock mortalities in coastal environments (e.g., species within the northern extent of their range, lack of access to deeper water) are similar in inland environments, yet inland environments do not have the same level of mortalities. Consequently, the disparity between mortalities in coastal and inland environments are not readily discernable at this time.

I. REGIONAL ASSESSMENT OF INLAND FISH MORTALITIES ASSOCIATED WITH WINTER AND COLD-SHOCK STRESSES

Introduction

The winter season is usually a stressful period for fishes and is described as Winter Stress Syndrome (Lemly 1993). Seasonally, colder temperatures and shorter photoperiod affect various aspects of a fish's body (Lemly 1993, Suski and Ridgeway 2009) and cause individuals to shift energy from reproduction and growth to homeostasis (Wendelaar-Bonga 1997). Primarily, metabolism slows and inhibits an individual's ability to swim and capture prey, which can deplete energy reserves (Hurst 2007). Coupled with limiting food resources (Cushing 1975), Winter Stress Syndrome results in sublethal (e.g., stunted growth) and lethal effects (Hurst 2007, Brown et al. 2011, Shuter et al 2012). However, responses to Winter Stress Syndrome differ among fishes. Temperate, warm-water fishes have a higher tolerance to lower lipid energy reserves than cold-water fishes, thus making them more resilient to the effects of limiting food resources than cold-water fishes (Sullivan 1986). Also, not all fishes develop energy reserves equally or have the enzymatic ability to compensate for colder temperatures (Suski and Ridgeway 2009). Conspecifics store more lipids at higher latitudes than those at lower latitudes (Berg et al. 2011), cold-water fishes tend to store more lipids than warm-water fishes (Sullivan 1986), and individuals and species with greater body mass tend to store more lipids than those with lesser body mass (Cargnelli and Gross 1997). Regardless of latitude, cold or warm-water type, or body size, freshwater fishes move to low current velocities areas (Magnuson 1985) or areas with warm groundwater discharges (Cunjak 1996) during the winter season, theoretically, to minimize energy expenditures. Others enter a period of dormancy marked by inactivity and fasting (Crawshaw 1984, Speers-Roesch et al. 2018), which is similar to hibernation in mammals (Soyano and Mushirobira 2018).

An additional stressor for fishes during the winter season is cold shock, which occurs when fishes are exposed to a rapid decrease in water temperature (Donaldson 2008). Cold shock typically results in large numbers of fish mortalities, causes public alarm, and can lead to emergency changes in fisheries harvest regulations to protect remaining populations. Unlike Winter Stress Syndrome, fish responses to cold shock are poorly understood because cold shock occurs infrequently and usually during major arctic freezes. Major arctic freezes, loosely defined by National Oceanic and Atmospheric Administration (NOAA) based on the extensiveness of agriculture crop losses, occur on average about every 13 years in Texas (1899, 1949, 1951, 1962, 1983, and two in 1989; NOAA 2021) and recently, Winter Storm Uri in 2021. Effects of the major arctic freezes attributed to cold shock are documented for marine and estuarine fishes in Texas following the 1983 and 1989 events, reporting 103 species of fish killed totaling about 31 million individuals (McEachron et al. 1994). Published accounts on the effects of major arctic freezes are less known in inland waters of Texas.

Purposes of this study were to describe patterns in cold weather fish mortalities attributed to winter stress and cold-shock stress within inland waters of Texas between 1969 and 2021, including three years with major arctic freezes. Study objectives were to 1) summarize the number of reports, taxa, individuals, location (i.e., urban, rural), and habitats (i.e., lentic and lotic environments) of cold weather mortalities recorded from inland waters of Texas, 2) associate numbers of fish mortality reports, taxa, and individuals to years with major arctic freeze (i.e., high potential for cold-shock stress) and without major arctic freeze (i.e., winter stress), and 3) assess differences in cold weather mortality between native and non-native fishes. Predictions were that a large proportion of the fish mortalities would coincide with cold-shock stress during major arctic freezes of 1983, 1989, and 2021 and that large proportion of fish mortalities would consist of non-native taxa, especially among non-native taxa that occur in more tropical regions (e.g., cichlids). Documenting patterns in fish mortalities attributed to winter stress and cold-shock stress during major arctic freezes provides a perspective on the pervasiveness of cold weather mortalities in Texas and potentially species and habitats most affected by cold weather, due to either winter stress or cold-shock stress. Additionally, management biologists will be better informed to address public concerns with cold weather mortalities and possibly recommend emergency restrictions on the harvest of freshwater fishes, similar to emergency harvest restrictions commonly placed on saltwater sport fishes following major arctic freezes (e.g., emergency spotted seatrout regulations extend 60 days in Laguna Madre; Texas Parks and Wildlife Department media release, TPWD 2021b).

Methods

Reports of fish mortalities were compiled by Texas Parks and Wildlife Department (TPWD) Kills and Spills Team from 1969 to March 2021, including fish mortalities attributed to Winter Storm Uri. A total of 262 reports, taken from inland and coastal waters and attributed to cold-weather fish mortalities, was entered in the TPWD Pollution Response Inventory and Species Mortality (PRISM) database. A total of 136 reports involved fish mortalities in inland waters, defined as water bodies (e.g., rivers, streams, reservoirs) found in Texas generally upstream from transitory freshwater-saltwater boundaries (Craig and Bonner 2019), and were selected for analysis. Reports, with a few exceptions, consisted of water body name, geo-referenced location, date of report or fish kill, and description of fish mortalities, ranging from generic information (e.g., "fishes killed") to specific information (e.g., "100 Blue Tilapia were killed").

Number of reports with generic and specific descriptions of fish mortalities (N = 136) were summed within each year. Fish mortalities reported in the first 11 days of each month were assigned to the month prior to account for lag times in the mortality event and posting on the PRISM database. Water body name and geo-referenced locations were used to classify mortality events as occurring in urban or rural areas (U.S. Census Bureau 2021) and in lentic (e.g., reservoirs, ponds) or lotic (e.g., rivers, streams) environments. Numbers of reports by year were compared to a minimum mean temperature index with linear regression analysis ($\alpha = 0.05$) with the number of reports log (N+1) transformed to improve assumptions of linearity and equal variance. Minimum mean temperature index was calculated by obtaining minimum low reported air temperatures per year from San Antonio, George Bush Intercontinental Airport, and the Dallas/Fort Worth International Airport (NWS 2022) between 1969 and 2021. Yearly minimum low temperatures were z-scored transformed (Curtis et al. 2016) for each location. Z-score transformation of temperature data was necessary to compare among locations with different mean low temperatures attributed to latitudinal position. Z-scored transformed temperatures were averaged across locations for each year. The three lowest minimum mean temperatures between 1969 and 2021 corresponded to the major arctic freezes of 1983, 1989, and

2021, hereafter referred to as years with a major arctic freeze. Differences in the number of reports (log N+1 transformed) in years with major arctic freezes (N = 3) and those in years with non-major arctic freezes (N = 50) were assessed with a one-tailed Fisher's t-test.

Number of reports with specific descriptions of fish mortalities (N = 76) were used to quantify taxa mortalities and numbers of mortalities. Since specific descriptions provide a more robust assessment of fish mortalities, about 20% of the reports with quasi-generic description were converted to specific descriptions and retained as part of the 76 reports. For example, "thousands of individuals" was converted to "2,000 individuals", and "some", "several" and "few" individuals were converted to "2" individuals. Species names were often not used in the specific descriptions. From the specific descriptions, a list of 16 taxa was compiled and at various levels of taxonomic classification. The 16 taxa, with description nomenclatures in parentheses, were: Lepisosteidae (Alligator Gar *Atractosteus spatula*, Spotted Gar *Lepisosteus oculatus*, gar), *Dorosoma* (Gizzard Shad *Dorosoma cepedianum*, Threadfin Shad *Dorosoma petenense*, shad), native Cyprinidae (minnows), non-native Cyprinidae (Common Carp *Cyprinus carpio*, carp), Catostomidae (River Carpsucker *Carpiodes carpio*, buffalo), Mexican Tetra *Astyanax mexicanus*, Ictaluridae (Channel Catfish *Ictalurus punctatus*, Blue Catfish *Ictalurus furcatus*, catfish), Loricariidae (Suckermouth Catfish *Hypostomus plecostomus*, armored catfish), Striped Mullet *Mugil cephalus*, White Bass *Morone chrysops*, *Micropterus* (Largemouth Bass *Micropterus salmoides*, Smallmouth Bass *Micropterus dolomieu*, bass), *Pomoxis* (crappie), *Lepomis* (Bluegill *Lepomis macrochirus*, sunfish), Sciaenidae (Red Drum *Sciaenops ocellatus*, Freshwater Drum *Aplodinotus grunniens*), non-native Cichlidae

(Blue Tilapia *Oreochromis aureus*, tilapia, exotic cichlids), and Rio Grande Cichlid *Herichthys cyanoguttatus*. Numbers of reports, taxa, and individual mortalities were calculated overall and by year for all, native, and non-native taxa. Numbers of mortalities by year (log N+1 transformed) were compared to a minimum mean temperature index with linear regression analysis for all taxa, native taxa, and non-native taxa. Differences in annual mortality (log N+1 transformed) between major arctic freezes and non-major arctic freezes were assessed with Fisher's t-tests for all, native, and non-native taxa.

Results

Among 136 reports with generic and specific descriptions, mean (± 1 SE) number of reports per year was 2.6 (± 0.54; range: 0 - 21). Majority of reports (79%) were from urban areas, including Houston (21%), San Antonio (21%), and Dallas-Fort Worth (8%) (Figure 1), and from lentic environments (56%). Cold weather mortalities were reported September through May with the greatest percentages of reports occurring in January (44%) and December (28%) (Figure 2). Among 53 years, cold weather mortalities were reported in 66% of the years. The number of reports was inversely related (b = -0.14, df: 1, 52, $r^2 = 0.13$, $P < 0.01$) to the minimum mean temperature index. Years with the greatest percentage of reports were in 2021 (15%), 1989 (11%), and 1983 (7%) (Figure 3). Numbers of reports were greater ($\text{t-statistic}_{1,51} = 8.9$, $P < 0.01$) for years with a major arctic freeze (transformed mean: 1.19, 1 SE: 0.08, N: 3) than years without a major arctic freeze (mean: 0.33, 1 SE: 0.04, N:50).

Among 76 reports with specific descriptions, mortalities of 16 taxa and 1,021,217 individuals were reported (Table 1). Mean (± 1 SE) number of taxa reported per year was

1.6 (± 0.28; range: 0 - 8), and mean number of mortalities per year was 19,268 (± 17,301; range 0 – 917,900). Non-native Cichlidae represented 91% of the total number of mortalities, followed by *Dorosoma* (3.6%) and Catostomidae (1.2%) (Table 1). Years with the greatest percentage of mortalities by individuals was 1990 (89%), followed by 2021 (3.6%) and 2009 (2.2%) (Figure 4). Fish mortality was unrelated ($P = 0.24$) to the minimum mean temperature index. Numbers of mortalities were greater (t-statistic $_{1,51}$ = 4.8, $P < 0.01$) for years with a major arctic freeze (transformed mean: 3.78, 1 SE: 0.41, N: 3) than years without a major arctic freeze (mean: 1.48, 1 SE: 0.22, N:50), despite one year (1990) without a major arctic freeze having 915,450 Tilapia mortalities.

Forty-three percent (N = 33) of the 76 reports included native taxa mortalities. Thirteen (81%) of the 16 taxa reported were native taxa, representing 7.9% (N = 81,003) of total mortalities. Mean (± 1 SE) number of mortalities per year was 1,528 (± 752; range 0 – 34,400). *Dorosoma* was the most abundant (45%) among mortalities of native taxa, followed by Catostomidae (15%) and Ictaluridae (14%) (Table 2). Years with the greatest percentage of native mortality by individuals was 2021 (42%), followed by 2009 (22%), and 1995 (12%). The number of mortalities by native individuals was unrelated ($P = 0.50$) to the minimum mean temperature index. Numbers of mortalities were not different (t-statistic $_{1,51}$ = 1.7, $P = 0.11$) for years with a major arctic freeze (transformed mean: 2.78, 1 SE: 1.09, N: 3) than years without a major arctic freeze (mean: 0.86, 1 SE: 0.19, N:50).

Sixty-three percent (N = 48) of the 76 reports included non-native taxa mortalities. Three (19%) of the 16 taxa reported were non-native taxa, representing 92% (N = 940,214) of total mortalities. Mean (± 1 SE) number of mortalities per year was

17,739 (± 17,311; range 0 – 917,900). Non-native Cichlidae was the most abundant (99%) among mortalities of non-native taxa, followed by non-native Cyprinidae (<1%) and Loricariidae (<1%) (Table 3). Years with the greatest percentage of non-native mortality by individuals was 1990 (97%), followed by 1989 (0.5%), and 2009 (0.4%). The number of mortalities by non-native individuals was unrelated ($P = 0.07$) to the minimum mean temperature index. Numbers of mortalities were greater (t-statistic $_{1,51}$ = 4.6, $P < 0.01$) for years with a major arctic freeze (transformed mean: 3.13, 1 SE: 0.39, N: 3) than years without a major arctic freeze (mean: 1.07, 1 SE: 0.83, N:50).

Discussion

As predicted, numbers of cold weather mortality reports were greater during years with major arctic freezes (1983, 1989, 2021) than in years without major arctic freezes. Likewise, number of mortalities were greater in years with major arctic freezes, attributed to non-native fish mortalities. Native fish mortalities were not different between years with and without major arctic freezes. Cold weather mortalities were reported over a protracted time period (September – May) and in a majority of years (66%, 1970 – 2021) during major arctic freeze years and non-major arctic freeze years. Fishes are more susceptible to cold-water mortalities than warm-water mortalities, because colder waters inhibit fish metabolism and, therefore, fishes are less likely to move to warmer water refugia, whereas fishes at warmer temperatures are more likely to move to cooler water refugia (Beitinger 2000). The effects of cooling water on fish mobility might be less influenced by the temperature minima and more influenced by the rate of water cooling (Donaldson 2008). In one laboratory study, rate of cooling was demonstrated to have more of an effect on fish death than temperature minima (Stauffer et al. 1988). Patterns in cold weather fish mortalities in this study (i.e., over a protracted time period, during non-major arctic freeze years) provide additional support for the rate of water cooling is more influential than temperature minima in cold-weather fish mortalities.

Greater numbers of reports were observed in urban areas more than rural areas and in lentic environments more than lotic environments. This pattern could be related to the greater number of people in urban areas to detect and report fish mortalities to TPWD. Spatial biases, such as the tendency for citizen scientists to report wildlife-related observations closer to their home (Dennis and Thomas 2000), commonly occur among observations reported by citizens (Johnston et al. 2020). Alternatively, greater number of cold-weather fish mortalities observed in urban areas could be related to additional water quality stressors often found in urban streams (i.e., urban stream syndrome; Walsh et al. 2005), which synergistically could increase cold-weather fish mortalities (Hall et al. 1999, Contreras 2003, La and Cooke 2011). A slightly greater percentage (56%) of cold weather fish mortality reports occurred in lentic environments than lotic environments. In more northern lentic environments, ice coverage impedes gas exchange between the aquatic and terrestrial environments (Fang and Stefan 2000), thereby potentially limiting oxygen within the system. However, in Texas, it is unlikely that cold-weather events, including major arctic freeze events, are sufficient to produce substantial ice coverage on lentic environments. Alternatively, the primary fishes affected by cold weather (e.g., Tilapia, *Dorosoma*) are more abundant in lentic environments (Miller 1960, Shafland 1979, Johnson et al. 1988). *Dorosoma* accounted for 45% of the native fish mortalities in this study and are commonly reported to die during cold weather throughout their range

(Porath 2006), which includes most of the USA east of the Rocky Mountains and as far north as South Dakota (Wuellner et al. 2008, Haberyan 2021). Despite having a lower lethal temperature similar to other native fishes (4°C; Fetzer et al. 2011), *Dorosoma* frequently reported cold weather mortality is thought to be related to their inability to access stored lipids at colder temperatures (White et al. 1986, as cited in Fetzer et al. 2011). Based on the results of this study, lentic environments with abundant Tilapia and *Dorosoma* populations are most susceptible to cold weather, excluding lentic environments that have sources of warm water (e.g., power plants).

Number of native and non-native taxa (N = 8) and total number of inland fish mortalities (N = 42,827) during three major arctic freeze years are in stark contrast to the 103 fish species and 31 million individuals reported killed in coastal waters of Texas during two major arctic freezes (McEachron 1994) and the number of fishes killed in coastal waters of Texas following Winter Storm Uri (3.8 million, TPWD 2021a). The large differences between reported inland and marine fish mortalities could be attributed to underreporting of inland fish kills. As demonstrated herein, 44% of the reports between 1969 and 2021 lacked estimates of taxa and counts. Underreporting of inland fish mortalities could also be related to greater amounts of aquatic habitats in inland waters of Texas (estimated length of streams and rivers: 310,000 km; TWDB, no date) compared to coastal waters of Texas (estimated length 5,400 km; NOAA 1975), where fish mortalities could be more easily observed within a shorter distance of available aquatic habitats. Alternatively, large differences between reported inland and marine fish mortalities could be attributed to species-specific and habitat-specific differences between inland and marine environments. Large numbers of fish mortalities during a major arctic freeze have been attributed to many marine species being at their northern most range, and therefore more susceptible to cold weather (Storey 1936, Holt and Holt 1982), and shallow water fishes having limited access to deeper waters of the Gulf of Mexico (McEachron 1994). However, many of the marine fishes reported to be susceptible to cold shock are not at their northern most extent in Texas (e.g., Spotted Seatrout *Cynoscion nebulosus* found as far north as New York along the Atlantic coast; Guest and Gunter 1958) and shallow waters with limited access to deep waters are common within rivers and streams of Texas, especially in low order streams and in prairie streams (Ruppel et al. 2020). Consequently, mechanisms that explain cold weather marine fish mortalities should be the same in inland waters, yet fewer inland fishes are reported killed.

The prediction that non-native fishes would be more susceptible to cold weather mortalities than native fishes was supported. Although not a natural northern range extension, non-native Blue Tilapia and other tilapia species (Mozambique Tilapia *Oreochromis mossambicus* and Redbelly Tilapia *Tilapia zillii*) were stocked extensively throughout Texas (Hubbs 1982), a non-natural northern range introduction, from their native range of tropical and subtropical regions of Africa and the Middle East (Fryer and Iles 1972). Tilapia species were the most abundant taxa killed (91% of all reported fish mortalities) during cold weather, providing support that cold weather events can be a limiting factor in species natural and human-assisted range extensions from equatorial regions to polar regions as suggested by Storey (1936) and Holt and Holt (1982). Higher mortalities of introduced tropical and subtropical fishes (e.g., non-native Cichlidae, Loricariidae) than native fishes did not correspond with lower lethal temperatures reported for some of the species. Lower lethal temperatures range from 6.2 °C in Blue Tilapia to 11.2°C in Suckermouth Catfish (Shafland and Pestrak 1982) for non-native taxa, which are similar to the lower lethal temperatures for native taxa (range: <1.0°C in Largemouth Bass (Guest 1985) to 11.3°C in Sheepshead Minnow (*Cyprinodon variegatus*; Bennet and Beitinger 1997).

Winter mortality commonly occurs in Texas with greater number of mortalities being reported during major arctic freezes, but the number of inland fish mortalities is much less than those reported in coastal waters of Texas during major arctic freezes and less than the number of inland fish mortalities reported among other causes in Texas (14% mortality attributed to cold weather, compared to 75% mortality attributed to toxic algal blooms, pollution, and low dissolved oxygen; Contreras 2003). Underreporting of inland fish mortalities is likely, but it is unlikely that millions of fish dying in inland waters at the levels observed along the Texas coast are not being reported. As such, the disparity in fish mortalities between coastal environments and inland environments, especially during major arctic freezes, is not readily discernable at this time. Insights into the underlying mechanisms explaining the disparity would benefit future management and conservation of fishes in coastal and inland environments, especially since the number of major arctic freezes are predicted to increase (Kim et al. 2014) with global climate change.

Table 1. Taxa reported from 76 quantifiable inland cold weather fish kill reports, number of estimated mortalities, and the percent (%) of estimated mortalities reported for each taxa, 1969 - 2021.

Taxa	N of estimated mortalities	Percent estimated mortality
Non-native Cichlidae	934,626	91
Dorosoma	36,724	3.6
Catostomidae	12,324	1.2
Ictaluridae	11,643	1.1
Non-native Cyprinidae	4,943	0.48
Sciaenidae	4,839	0.47
Pomoxis	4,592	0.45
Morone chrysops	4,554	0.44
Lepomis	3,479	0.34
Lepisosteidae	1,990	0.19
Loricariidae	645	< 0.1
Herichthys cyanoguttatus	296	< 0.1
Astyanax mexicanus	260	< 0.1
Mugil cephalus	250	< 0.1
Micropterus	50	< 0.1
Native Cyprinidae	2	< 0.1

Table 2. Native taxa reported from 33 quantifiable inland cold weather fish kill reports, number of estimated mortalities, and the percent (%) of estimated mortalities for each native taxa, 1969 - 2021.

Taxa	**N of estimated mortalities**	**Percent estimated mortality**
Dorosoma	36,724	45
Catostomidae	12,324	15
Ictaluridae	11,643	14
Sciaenidae	4,839	6
Pomoxis	4,592	5.66
Morone chrysops	4,554	5.62
Lepomis	3,479	4.29
Lepisosteidae	1,990	2.45
Herichthys cyanoguttatus	296	< 1
Astyanax mexicanus	260	< 1
Mugil cephalus	250	< 1
Micropterus	50	< 1
Native Cyprinidae	2	< 1

Table 3. Non-Native taxa reported from 48 quantifiable inland cold weather fish kill reports, number of estimated mortalities, and the percent (%) of estimated mortalities for each native taxa, 1969 – 2021.

Taxa	N of estimated mortalities	Percent estimated mortality
Non-native Cichlidae	934,626	99
Non-native Cyprinidae	4,943	< 1
Loricariidae	645	< 1

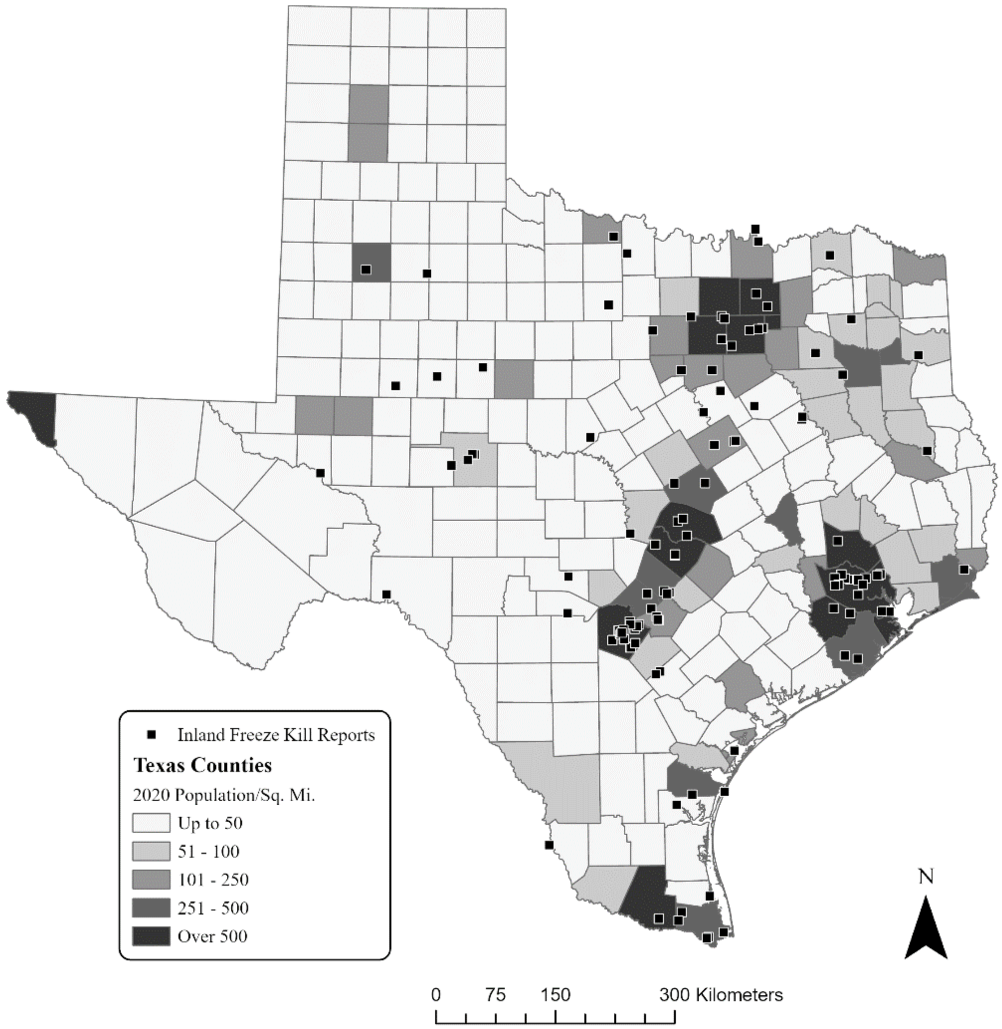

Figure 1. Map of Texas with individual counties outlined, each dot represents coordinates for each inland cold weather fish kill reports (N=127, 1969 - 2021), counties are shaded based off population density per square mile. Population data is from the 2020 US Census.

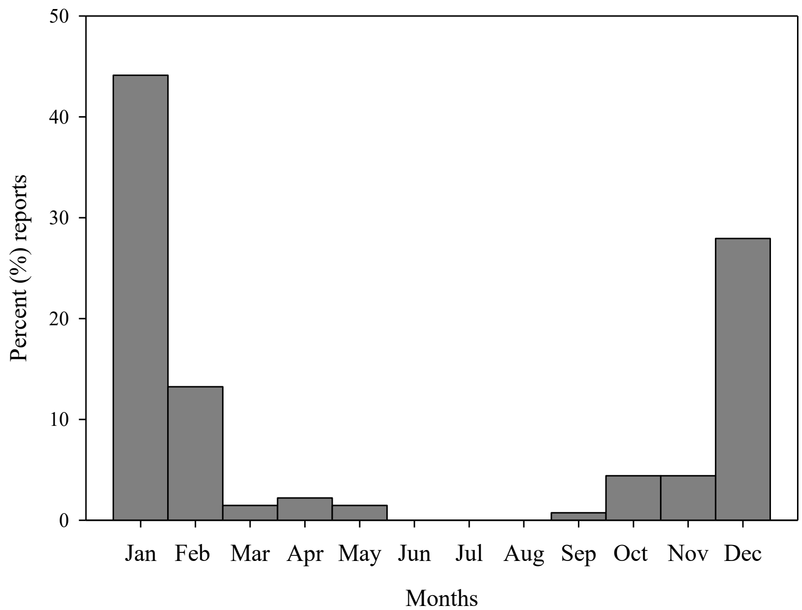

Figure 2. Percent (%) of inland cold weather fish kill reports by month (N = 136), 1969 - 2021.

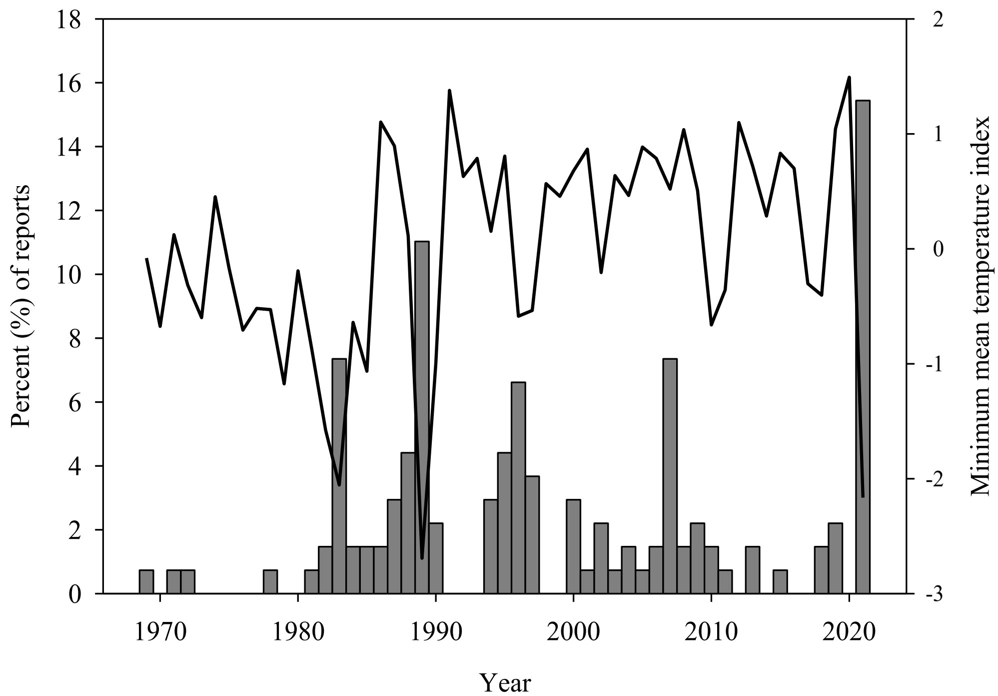

Figure 3. Percent (%) of inland cold weather fish kill reports by year (N = 136), bar represent percentage of reports, line represents the minimum mean temperature index, 1969 - 2021.

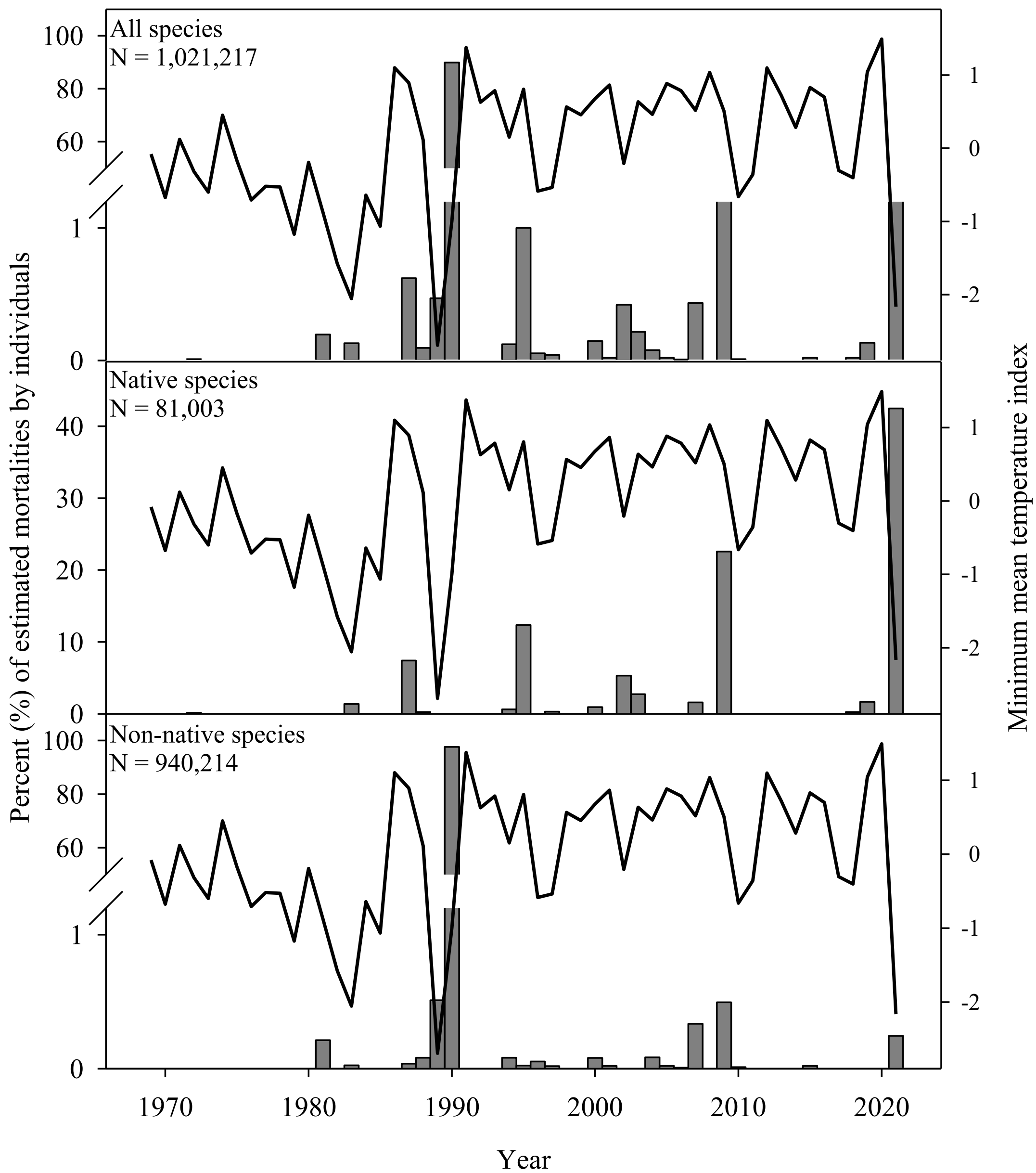

Figure 4. Percent (%) of inland cold weather fish kill mortalities, categorized by native and non-native taxa, bars represent percentage of individual mortalities, line represents the minimum mean temperature index, 1969 - 2021.

LITERATURE CITED

Beitinger, T. L., W. A. Bennett, and R. W. McCauley. 2000. Temperature tolerances of North American freshwater fishes exposed to dynamic changes in temperature. Environmental Biology of Fishes 58:237-275.

Bennett, W. A. and T. L. Beitinger. 1997. Temperature tolerance of sheepshead minnow, *Cyprinodon variegatus*. Copeia 77–87.

Berg, O. K., G. Rød, Ø. Solem, and A. G. Finstad. 2011. Pre-winter lipid stores in brown trout Salmo trutta along altitudinal and latitudinal gradients. Journal of Fish Biology 79:1156-1166.

Brown, R., W. Hubert, and S. Daly. 2011. A primer on winter, ice, and fish: what fisheries biologists should know about winter ice processes and stream-dwelling fish. Fisheries 36:8-26.

Brunson, K. L. 1986. Summary of reported fish kills in Kansas during 1983. Transactions of the Kansas Academy of Science 1903:134-145.

Cargnelli, L. M., and M. R. Gross. 1997. Fish energetics: larger individuals emerge from winter in better condition. Transactions of the American Fisheries Society 126:153-156.

Craig, C. A., and T. H. Bonner. 2019. Drainage basin checklists and dichotomous keys for inland fishes of Texas. ZooKeys 874:31-45.

Crawshaw, L. I. 1984. Low-temperature dormancy in fish. American Journal of Physiology-Regulatory, Integrative and Comparative Physiology 246:R479-R486.

Cunjak, R. A. 1996. Winter habitat of selected stream fishes and potential impacts from land-use activity. Canadian Journal of Fisheries and Aquatic Sciences 53:267-282.

Curtis, A. E., T. A. Smith, B. A. Ziganshin, and J. A. 2016. The mystery of the Z-score. Aorta. 4:124-130.

Cushing, D. H. 1975. Marine ecology and fisheries. Cambridge University Press, Cambridge, UK

Dennis, R. L. H., and C. D. Thomas. 2000. Bias in butterfly distribution maps: the influence of hot spots and recorder's home range. Journal of Insect Conservation 4:73-77.

Donaldson, M. R., S. J. Cooke, D. A. Patterson, and J. S. Macdonald. 2008. Cold shock and fish. Journal of Fish Biology 73:1491-1530.

Fang, X., and Stefan, H. G. 2000. Projected climate change effects on winterkill in shallow lakes in the northern United States. Environmental Management 25:291-304.

Fetzer, W., T. E. Brooking, J. R. Jackson, and L. G. Rudstam. 2011. Overwinter mortality of gizzard shad: evaluation of starvation and cold temperature stress. Transactions of the American Fisheries Society 140:1460-1471.

Fryer, G., and T. D. Iles. 1972. The cichlid fishes of the great lakes of Africa. T.F.H. Publications, Neptune City, New Jersey.

Guest, W. C. .1985. Temperature tolerance of Florida and northern largemouth bass: effects of subspecies, fish size, and season. Texas Journal of Science 37:75-84.

Guest, W. C., and G. Gunter. 1958. The sea trout or weakfishes (Genus Cynoscion) of the Gulf of Mexico. Gulf States Marine Fisheries Commission.

Haberyan, K. A. 2021. A trophic cascade following the introduction of an omnivorous fish, *Dorosoma cepedianum*, in a mid-continental reservoir (Mozingo studies IV). The American Midland Naturalist 186:176-198.

Hall, R. I., P. R. Leavitt, R. Quinlan, A. S. Dixit, and J. P. Smol. 1999. Effects of agriculture, urbanization, and climate on water quality in the northern Great Plains. Limnology and Oceanography 44:739-756.

Hazel, J. R., and C. L. Prosser. 1974. Molecular mechanisms of temperature compensation in poikilotherms. Physiological Reviews 54:620-677.

Holt, S. A., and G. J. Holt. 1983. Cold death of fishes at Port Aransas, Texas: January 1982. The Southwestern Naturalist 28:464-466.

Hubbs, C. 1982. Occurrence of exotic fishes in Texas waters. Pearce-Sellards Series, Texas Memorial Museum 36:l-19.

Hurst, T. P. 2007. Causes and consequences of winter mortality in fishes. Journal of Fish Biology 71:315-345.

Johnson, B. M., R. A. Stein, and R. F. Carline. 1988. Use of a quadrat rotenone technique and bioenergetics modeling to evaluate prey availability to stocked piscivores. Transactions of the American Fisheries Society 117:127-141

Johnston, A., N. Moran, A. Musgrove, D. Fink, and S. R. Baillie. 2020. Estimating species distributions from spatially biased citizen science data. Ecological Modelling 422:108927.

Kim, B. M., S. W. Son, S. K. Min, J. H. Jeong, S. J. Kim, X. Zhang, T. Shim, and J. H. Yoon. 2014. Weakening of the stratospheric polar vortex by Arctic sea-ice loss. Nature Communications 5:1-8.

Lemly, A. D. 1993. Metabolic stress during winter increases the toxicity of selenium to fish. Aquatic Toxicology 27:33-158.

Linam, G. W., L. J. Kleinsasser, K. B. Mayes. 2002. Regionalization of the index of biotic integrity for Texas streams, Report, Austin, Texas.

Magnuson, J., A. Beckel, K. Mills, and S. Brandt. 1985. Surviving winter hypoxia: behavioral adaptations of fishes in a northern Wisconsin winterkill lake. Environmental Biology of Fishes 14:241-250.

McEachron, L. W., G. C. Matlock, C. E. Bryan, P. Unger, T. J. Cody, and J. H. Martin. 1994. Winter mass mortality of animals in Texas bays. Gulf of Mexico Science 13:6

Miller, R. R. 1960. Systematics and biology of the gizzard shad *(Dorosoma cepedianum)* and related fishes. Fish Bull 60: 371-392

NOAA (National Oceanic and Atmospheric Administration). 1975. The coastline of the United States, Report, Washington, D.C.

NOAA (National Oceanic and Atmospheric Administration). 2021. Valentine's week winter outbreak 2021: snow, ice, and record cold, Report, Houston.

NWS (National Weather Service). 2022. NOWData, NOAA online weather data, report, Texas.

Porath, M. T. 2006. Climate and habitat factors related to a localized extirpation of gizzard shad (*Dorosoma cepedianum*). Great Plains Research 16:127-135.

Ruppel, D. S., V. A. Sotola, C. A. Craig, N. H. Martin, and T. H. Bonner. 2020. Assessing functions of movement in a Great Plains endemic fish. Environmental Biology of Fishes 103:795-814.

Shafland, P. L. 1979. Non-native fish introductions with special reference to Florida. Fisheries 4(3): 18-24.

Shafland, P. L., and J. M. Pestrak. 1982. Lower lethal temperatures for fourteen non-native fishes in Florida. Environmental biology of fishes 7:149-156.

Shuter, B. J., A. G. Finstad, I. P. Helland, I. Zweimüller, and F. Hölker. 2012. The role of winter phenology in shaping the ecology of freshwater fish and their sensitivities to climate change. Aquatic Sciences 74:637-657.

Soyano, K., and Y. Mushirobira. 2018. The mechanism of low-temperature tolerance in fish. Pages 149-164 *in* M. Iwaya-Inoue, M. Sakurai, M. Uemura, editors. Survival Strategies in Extreme Cold and Desiccation. Experimental Medicine and Biology 1081.

Speers-Roesch, B., T. Norin, and W. R. Driedzic. 2018. The benefit of being still: energy savings during winter dormancy in fish come from inactivity and the cold, not from metabolic rate depression. Proceedings Royal Society B [online serial] 285:20181593. DOI: 10.1098/rspb.2018.1593.

Stauffer Jr, J. R., S. E. Boltz, and J. M. Boltz. 1988. Cold shock susceptibility of blue tilapia from the Susquehanna River, Pennsylvania. North American Journal of Fisheries Management 8:329-332.

Storey, M., and E. W. Gudger.1936. Mortality of fishes due to cold at Sanibel Island, Florida, 1886-1936. Ecology 17:640-648.

Sullivan, K. M. 1986. Physiology of feeding and starvation tolerance in overwintering freshwater fishes. Pages 259-268 *in* C. A. Simenstad and C. M. Cailliet, editors. Contemporary studies on fish feeding: the proceedings of GUTSHOP ’84. Developments in Environmental Biology of Fishes 7, Germany.

Suski, C. D., M. S. Ridgway. 2009. Winter biology of centrarchid fishes. Pages 264-292. *In* C. J. Cooke and P. D. Philipp, editors. Centrarchid Fishes: Biology, Diversity, and Conservation. United Kingdom.

Thronson, A. and A. Quigg. 2008. Fifty-five years of fish kills in coastal Texas. Estuaries and Coasts 31:802-813.

TPWD (Texas Parks and Wildlife Department). 2021a. At least 3.8 million fish killed by winter weather on Texas coast, News release, Austin, Texas.

TPWD (Texas Parks and Wildlife Department). 2021b. Emergency Spotted Seatrout regulations extended 60 days in Laguna Madre, News release, Austin, Texas.

TWDB (Texas Water Development Board). River Basins and reservoirs, Website, Austin, Texas.

U.S. Census Bureau. 2021. Metropolitan and micropolitan: about. Report, Washington D. C.

La, V. T., and S. J. Cooke. 2011. Advancing the science and practice of fish kill investigations. Reviews in Fisheries Science 19:21-33.

Walsh, C. J., A. H. Roy, J. W. Feminella, P. D. Cottingham, P. M. Groffman, and R. P. Morgan. 2005. The urban stream syndrome: current knowledge and the search for a cure. Journal of the North American Benthological Society 24:706-723.

Wendelaar-Bonga, S. E. 1997. The stress response in fish. Physiological Reviews 77:591-625.

White, A. M., F. D. Moore, N. A. Alldridge, and D. M. Loucks. 1987. The effects of natural winter stresses on the mortality of the eastern gizzard shad, *Dorosoma cepedianum*, in Lake Erie. Report to Cleveland Electrical Illuminating Company, Cleveland, Ohio, and Ohio Edison Company, Report 78, Akron, Ohio.

Wuellner, M. R., B. D. Graeb, M. J. Ward, and D. W. 2008. Review of gizzard shad population dynamics at the northwestern edge of its range in balancing fisheries management and water uses for impounded river systems. American Fisheries Society Symposium 62:637-653.