Fish assemblages above and below three road crossing types are similar in a prairie stream

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Background. The North American prairie biome is considered one of the most endangered ecoregions. Prairie fishes have been affected by many anthropogenic disturbances, including the construction of bridges and culverts as road crossings over streams. The objective of our study was to test fish assemblage characteristics upstream and downstream of single- and double-barreled culverts and compare them with assemblages at bridges within a single prairie stream watershed.

Methods. Eight sites located near public or private roads were selected on the South Loup River, Nebraska, USA. Fish were sampled monthly from April through October 2013 using backpack electrofishing. Sampling occurred upstream and downstream of each road crossing structure. Fish collections from all months were combined to calculate species richness; species diversity; the relative abundance of two species of conservation concern in North American Great Plains streams (brassy minnow *Hybognatus hankinsoni* and plains topminnow *Fundulus sciadicus*); the relative abundance of two introduced predators (largemouth bass *Micropterus salmoides* and northern pike *Esox lucius*), and the relative abundance of both introduced predators combined. A two-way analysis of variance (ANOVA) test was used to determine whether these seven fish assemblage characteristics were different between upstream and downstream reaches, among road crossing structures, and between the interaction of these two factors followed by pairwise comparisons by either road crossing type, direction, or the interaction of both using a Tukey's honest significant difference (HSD) test.

Results. Only two fish assemblage characteristics appeared to be related to road crossing type or direction: species richness and relative abundance of brassy minnows. Species richness was significantly higher at bridges compared to single-barreled culverts. The relative abundance of brassy minnows was significantly different between bridges and both types of culverts but was not significantly different between the two culvert types.

Discussion. Several reasons could explain the overall results of our study. First, road crossings on prairie streams may not have much effect on fish passage or fish habitat due to the low gradient of these streams. Secondly, because of bank stabilization, bridges could affect prairie fish communities and their habitats as severely as culverts within this watershed. Third, the fish communities upstream and downstream of all crossing types may represent fishes that are mostly tolerant of disturbances in general. Our study indicates that prairie streams and their fish communities could be at least somewhat tolerant and resilient to disturbances associated with road crossings, even though the small-bodied nature of many native species potentially pose higher risks of disconnection within the population.

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ABSTRACT

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INTRODUCTION

The North American prairie is considered one of the most endangered ecoregions in North America (Samson & Knopf, 1994; Ostile et al., 1997). Biodiversity of prairie streams is often greater than streams in other ecoregions (e.g., mountain streams), and the risk of extirpation for many aquatic organisms in prairie systems is greater than in other regions (Samson & Knopf, 1994; Ostile et al., 1997). Prairie streams often experience wide variation in natural disturbances such as flooding and drying, resulting in unstable flow regimes and changing habitat characteristics (Matthews, 1988; Dodds et al., 2004). Most endemic prairie stream fishes are considered to be tolerant of such disturbances (Matthews, 1988). However, human disturbances may exacerbate the relative harshness of these natural conditions or create unnatural barriers that reduce resilience of the communities.

Within the past 100 years, changes to prairie landscapes associated with human settlement, including urbanization and a large-scale conversion to agriculture have occurred (Matthews 1988; Dodds et al. 2004). Such changes on the terrestrial landscape have altered hydrology, lowered groundwater tables, reduced connectivity, altered turbidity, provided a source of pollution, and promoted the introduction and survival of non-endemic species within prairie streams (Cross & Moss, 1987; Samson & Knopf, 1994). The construction of road crossings (e.g., bridges, culverts) across streams to support human settlement in the prairie ecosystem are a type of anthropogenic disturbance that may directly and indirectly affect prairie fish communities (Bouska & Paukert, 2010; Bouska et al., 2010).

Direct effects of road crossings may include a restriction in the upstream and downstream movement of fishes within a stream, especially small-bodied fishes (Prenosil et al. 2015). Such movement may be prohibited by increases in water velocities and turbulence (Davies & Nelson, 1993, Eaglin & Hubert, 1993, Schnackenberg & MacDonald, 1998; Cornish 2001; Bouska et al., 2010), the creation of artificial drops between the crossing structures and the main channel of the stream (Bouska et al., 2010), the concentration of debris (Votapka, 1991; Jones et al., 2000; Wall and Berry, 2004; Coffman, 2005), or a decrease in water depths through the structure (Warren & Pardew, 1998). Further, these barriers to fish passage may be either one-way (i.e., allowing fish to pass downstream but not upstream) or two-way (Bouska & Paukert, 2010). Such effects may depend on the species, life stage (e.g., adults v. juveniles), and the time of year (e.g., drier period v. wetter periods; Warren & Pardew, 1998; Bouska & Paukert, 2010). These barriers may prevent movement to feeding and spawning habitats and artificially create sources and sinks within a stream, thus increasing the risk of local extirpations and a reduction in genetic and organismal diversity (Winston et al., 1991; O'Hanley & Tomberlin, 2005; Sheer & Steel, 2006).

Indirect effects of road crossings on fishes may include various factors that affect population dynamics of native fishes. Road crossings may alter sediment movement within a stream and increase sediment deposition downstream of a road crossing (Wellman et al., 2000; Clarkin et al., 2005; Bouska et al. 2010). Increases in deposition may reduce the availability of substrates for lithophilic spawners or reduce the survival of eggs laid in interstitial spaces (Fischer & Paukert, 2008; Fischer et al. 2010; Stewart et al., 2016). Additionally, sedimentation may decrease macroinvertebrate abundance and diversity within the same areas (Gray & Ward, 1982; Richards & Bacon, 1994), subsequently reducing food and subsequent growth and survival of those fishes feeding in these areas. Finally, the creation of deep pools immediately downstream of some road crossings may improve conditions for survival and growth of piscivores not normally found in these streams; these newer community members may consume native small-bodied fishes (Cross et al., 1986; Matthews, 1988; Dodds et al., 2004). In total, these indirect effects may reduce recruitment of native fishes and lead to more homogeneous assemblages dominated by tolerant native and non-native species (Poff & Allan, 1995).

The effects of stream road crossings on stream habitat and fish assemblages may depend the crossing type. Bridges that go over rather than through streams may increase sedimentation, especially in the period immediately following construction (Wellman et al., 2000); however, some studies have shown that fish communities recover within one year of the disturbance (Peterson & Nyquist, 1972; Barton, 1977). Culverts come in many configurations (e.g., single- or double-barrel, drop, corrugated, etc.). Several studies have demonstrated that culverts cause greater damage to fish communities (Little & Mayer, 1993; Orth & White, 1993), and the effects may be long-lasting (Wellman et al., 2000). These studies have generally been associated with eastern or western regions where streams have higher gradients and different fish assemblages. To date, only a few studies have examined the effects of road crossings on prairie fish assemblages (Wall & Berry, 2004; Rosenthal, 2007; Bouska & Paukert 2010), and these studies have each examined box culverts and corrugated culverts. To our knowledge, this is the first study to compare the effects of single- and double-barreled culverts on prairie fish assemblages compared to each other and to bridges. In this study, we selected seven fish assemblage characteristics that we hypothesized would differ upstream and downstream of single- and double-barreled culverts and compared them to fish assemblages around bridges within a single prairie stream watershed.

MATERIALS AND METHODS

This study was conducted in the South Loup River watershed located in central Nebraska (Figure 1). This watershed was selected due to the perennial nature of the systems and the quantity, diversity, and accessibility of road crossings over streams within the system. Eight sites located near public or private roads were selected for this study. Single-barreled culverts were installed at four of the sites, and double-barreled culverts and bridges were installed at two sites each (Figure 1). Strahler (1957) stream orders of the selected sites varied from 1 – 3.

Fish were sampled monthly from April through October 2013 using a Smith-Root LR-24 backpack electrofishing unit with pulsed DC. Sampling occurred both upstream and downstream of each road crossing structure. The length of each upstream and downstream sample reach was 40 times the wetted width of the stream measured 50 m upstream of the road crossing structure to reduce the influence of the structure on stream morphology (Arend & Bain, 1999). The minimum reach length was 150 m and the maximum reach length was 300 m. Fish sampling began at the downstream end of each reach and moved upward to minimize disturbance.

Fish collection information from all sample months were combined to calculate various fish assemblage characteristics in order to summarize the entire assemblage at each sample reach. These characteristics included: species richness; species diversity; the relative abundance of two species of conservation concern in North American Great Plains streams [brassy minnow *Hybognatus hankinsoni* (Sheurer et al., 2003; Falke et al., 2010) and plains topminnow *Fundulus sciadicus* (Pasbrig et al., 2012)]; the relative abundance of two introduced predators [largemouth bass *Micropterus salmoides* and northern pike *Esox lucius* (Hrabik et al., 2015)], and the relative abundance of both introduced predators combined. The Shannon-Weiner diversity index was used to calculate species diversity following the formula described by Smith & Wilson (1996). Relative abundance of individual fishes and groups of fishes was indexed as catch per unit effort (CPUE), calculated as the total number of individuals collected divided by the total number of electrofishing hours at each sample reach.

A two-way analysis of variance (ANOVA) test was used to determine whether fish assemblage characteristics were different between upstream and downstream reaches, between road crossing structures, and between the interaction of these two factors. Because count and CPUE data were not normally distributed, all of the fish assemblage characteristics were transformed. Species richness was transformed using the square root function, and species diversity and CPUE metrics were transformed by adding one to each value before computing the natural log. If the ANOVA tests indicated significant differences existed, then pairwise comparisons of the metric were compared by either road crossing type, direction, or the interaction of both using a Tukey's honest significant difference (HSD) test. All statistical analyses were conducted in SAS Version 9.3.1 (2011, SAS Institute, Cary, North Carolina) using the PROC GLM function, and all comparisons were assessed for statistical significance at $\alpha = 0.10$.

RESULTS

Fish species diversity and the relative abundance of plains topminnow were nearly identical upstream and downstream of all crossing types but patterns among other metrics varied (Table 1). The relative abundance of brassy minnows was higher upstream of all road crossing structures compared to downstream, but all other fish assemblage characteristics were higher downstream than upstream of all road crossings (Table 1).

Species richness, species diversity, and the relative abundance of brassy minnows were higher around bridges compared to single-barreled culverts and double-barreled culverts, and the relative abundance of northern pike was highest around double-barreled culverts. No northern pike were collected around bridges. All other fish assemblage characteristics were highest around single-barreled culverts (Table 2).

Only two fish assemblage characteristics appeared to be related to road crossing type or direction: species richness ($F_{5, 10} = 2.97$; $p = 0.07$; Figure 2) and relative abundance of brassy minnows ($F_{5, 10} = 2.82$; $p = 0.08$; Figure 3). Further analysis noted variability by road crossing type (species richness: $F_2 = 5.77$; $p = 0.02$ and brassy minnow: $F_2 = 6.56$; $p = 0.02$) but neither variable differed significantly between upstream and downstream reaches (species richness: $F_1 = 2.82$; $p = 0.12$ and brassy minnow: $F_1 = 0.18$; $p = 0.68$ or between the interaction of road crossing type and stream direction ($F_2 = 0.25$; $p = 0.78$ and brassy minnow: $F_2 = 0.39$; $p = 0.69$).

Species richness was significantly higher around bridges than single-barreled culverts ($p < 0.10$); no significant differences in species richness were found between bridges and double-barreled culverts or between the two culvert types ($p > 0.10$; Figure 2). Catch per unit effort of brassy minnows was significantly different between bridges and both types of culverts ($p < 0.10$) but was not significantly different between the two culvert types ($p > 0.10$; Figure 3). All other fish assemblage characteristics were not significantly related to road crossing type, direction, or the interaction of the two variables.

DISCUSSION

We expected that all of the fish community metrics we examined in this study would respond significantly and reflect the relatively greater negative direct and indirect impacts of single- and double-barreled culverts on prairie fish communities and their habitat compared to bridges within this watershed. However, we found few significant differences related to road crossing type or by upstream versus downstream at a crossing type. Other studies have found similar results when studying fish community responses to road crossings in other ecosystems.

For example, Vander Pluym et al. (2008) found no significant differences in fish population size, species diversity, and fish index of biotic integrity between crossing types and position (upstream and downstream) within the Piedmont region of the Cape Fear River basin of North Carolina, USA. A long-term study of the impacts of bridge and culvert construction on fish communities throughout Tennessee, USA, also found no statistical differences in fish diversity, abundance, or richness between streams with bridges, culverts, or no crossings (Wellman et al., 2000). Several reasons may exist that could explain our study results.

First, road crossings on prairie streams may not have much of an effect on fish passage or fish habitat. Prairie fishes may still be able to traverse these potential barriers. Culverts often can prevent fish from moving upstream, either because of discharges that are too fast or because of downstream erosion leading to drops that are too high (Warren & Pardew, 1998; Rosenthal, 2007; Bouska et al., 2010). Prenosil et al. (2016) found that some small-bodied prairie fishes have mean swimming velocities that exceed 40 cm/s, maximum swimming velocities between 50 and 90 cm/s, and jumping heights of 1 – 6 cm. Further, Bouska & Paukert (2010) found that at least a portion of small-bodied fishes in the Flint Hills of northeastern Kansas, USA, could move upstream at velocities greater than 80 cm/s. In this study of the South Loup River, mean velocities within all three road-crossing types varied between 31 (bridges) and 124 (single-barreled culverts) cm/s, and discharge varied between 0.3 (single-barreled culverts) and 1.53 (bridges) m^3/s (Grauf 2014). Further, pool depths downstream of crossings varied between 1 (bridges) and 131 cm (single-barreled culverts), and outlet drops varied between 0 (bridges) and 3 cm (single-barreled culverts) (Grauf 2014). Thus, fishes within the South Loup River may still be able to move up- and downstream of these crossings as flows and waterfalls do not appear to pose significant impacts around these crossings.

In addition, these road crossings may have less impact on fish habitat in prairie streams compared to other ecosystems. Prairie streams are frequently of lower gradient, and stream flow and velocities are often lower in prairie ecosystems than observed for streams in other ecosystems (Dodds et al., 2004). The impact of culverts in streams with lower flows may be comparatively reduced, resulting in limited scouring and subsequent waterfall and pool formation (Rosenthal, 2007; Bouska & Paukert, 2010). Rosenthal (2007) found that most culverts within two tributaries of the Yellowstone River, Montana, USA, had similar gradients and low water velocities compared to more natural areas of these streams with no road crossings. Further, these culverts had low outlet drops and maintained water for most of the year (Rosenthal, 2007). Flows in the South Loup River appear to be generally stable both within and between years (personal observation) and flooding and drying are relatively uncommon. Thus, geomorphological changes in the stream channel due to road crossings may be relatively minimal.

Conversely, bridges could affect prairie fish communities and their habitats as severely as culverts within this watershed. Previous research in other ecosystems has found that bridges influence both stream fish communities and stream habitat. Bridge construction has been linked to decreases in the number and weight of fish (Whitney & Bailey, 1959; King & Ball, 1964; Peterson & Nyquist, 1972) and fish diversity (Barton 1977). Vander Pluym et al. (2008) found significantly lower species richness in streams with bridges than streams with arch culverts. Increased sediment deposition downstream of bridge crossings and local scouring around bridge pillars installed within the streambed have been documented (Wellman et al., 2000). In spite of changes in the habitat, some fish communities may recover from bridge construction within one year (Peterson & Nyquist, 1972; Barton 1977).

In our study, it appears that fish richness and relative abundance of native fishes tended to be higher and predator relative abundance generally lower around bridges compared to either culvert type. Further, bridge crossings had the lowest water velocity, stream discharge, and pool depth (see more details above). However, we did not compare fish metrics around bridges to those of more natural areas of the watershed with no road crossings. Future research could focus more directly on examining the influences that bridges may have on stream fish communities and habitat.

Third, the fish communities upstream and downstream of all crossing types may represent fishes that are mostly tolerant of disturbances in general. Many prairie fishes are categorized as generalists (Matthews, 1987; Bramblett & Fausch, 1991; Goldstein & Simon, 1999; Bramblett et al., 2005; Wuellner et al., 2013), and the frequency and duration of natural disturbances such as drought and anthropogenic disturbances such as intensive agriculture have favored the prevalence of tolerant taxa in prairie streams (Matthews, 1988; Bramblett et al., 2005). Fish communities, in general, could recover from road crossings over time (Peterson & Nyquist, 1972; Barton, 1977; Wellman et al., 2000; Vander Pluym et al., 2008), but the recovered community may represent an alternative stable state (Scheffer et al., 2001; Carpenter, 2002; Vander Pluym et al., 2008). Our study was conducted decades after these road crossings were constructed. Thus, we are uncertain as to whether the fish communities in this watershed were altered immediately after and permanently after road crossing installation. Future research could use either historical records or areas of the watershed without any road crossings in order to evaluate whether fish communities at these road crossings represent what might be expected for unimpaired prairie streams or if the current communities represent an alternative stable state.

As surprising as it was to find that few native, small-bodied fish metrics responded as expected to road crossings, it was equally surprising that predator metrics showed no significant differences by road crossing type. Previous research has suggested that disturbances such as road crossings may alter stream habitat in such a way as to support survival and natural recruitment of predators in prairie streams, either those that have been introduced or ones that have colonized new locations from higher order streams and rivers (Cross et al., 1986; Matthews, 1988; Dodds et al., 2004).

In our study, we found both northern pike and largemouth bass to be generally more abundant downstream of each crossing type. Further, largemouth bass were more abundant around single-barreled culverts and northern pike were more abundant around double-barreled culverts. The lack of significance in these metrics may be related to their variability in abundance. At some locations, very few to no largemouth bass or northern pike were collected; at others, several individuals were collected. Thus, the abundance of either predator may not be related in a statistically significant way to road crossing type or direction. However, the biological significance of the presence of each predator has yet to be evaluated in this prairie stream. The abundance of both predators has increased across Nebraska within the past 30 years (Hrabik et al., 2015). Introductions of and increases in northern pike abundance over time have been linked to reduced abundances of native fishes in the Niobrara River, Nebraska (Spurgeon et al., 2014), USA, but no data on the impacts of largemouth bass on Nebraska prairie streams exists to our knowledge. Future research should examine relationships between the distribution of both predators and small-bodied native fishes to determine whether these predators are exacerbating the influences of road crossings on prairie fish communities.

CONCLUSIONS

Road crossings represent anthropogenic barriers that potentially impede upstream and downstream migration of fishes, leading to the possibility of lower genetic diversity, local extirpations, and reduced species diversity (Winston et al., 1991; O'Hanley & Tomberlin, 2005; Sheer & Steel, 2006). Many published studies have examined the effects that various types of road crossing have on individual fish species (e.g., Toepfer et al., 1999; Wall & Berry, 2004) and fish communities (e.g., Wellman et al., 2000; Vander Pluym et al., 2008; Bouska and Paukert, 2010) and the physical changes that these structures induce on stream habitat (e.g., Barton, 1977; Wellman et al., 2000; Bouska et al., 2010). To date, the research indicates that at least some species and some ecosystems may be more sensitive to disturbances from road crossings than others. Our study may indicate that prairie streams and their fish communities could be somewhat tolerant and resilient to these types of disturbances, even though the small-bodied nature of many native species have been thought to put these fish at higher risk of disconnection within a population (Ficke et al., 2011; Grauf 2104; Prenosil et al., 2016; Lorenzen 2016; Schumann 2017). If road crossings within prairie streams can maintain similar habitat conditions (e.g., water depths, velocities, discharge, drop heights, and pool depths) to those of undisturbed stream segments at some points in the year, connectivity within a population could be maintained.

Other areas of research involving road crossings have identified how these structures may be constructed or modified so that most, if not all, fish can pass upstream and downstream freely (e.g., Bouska & Paukert, 2010; Ficke et al., 2011; Lorenzen 2016; Schumann 2017). We recommend that information on the swimming performance and jumping abilities of fish and the influence of road crossing engineering on fish passage and stream habitat be coupled with in-the-field research that examines how individual fishes and fish communities and their habitats are affected by road crossings of all types. Such a combination of information will provide more comprehensive look on how road crossings may be constructed or modified for the specific fish community and ecosystem in question.

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Figure 1(on next page)

Map of the South LoupRiver, Nebraska, USA with sampling locations and the type of stream crossingsat each location.

Fish were sampled upstream and downstream of each location for this study.

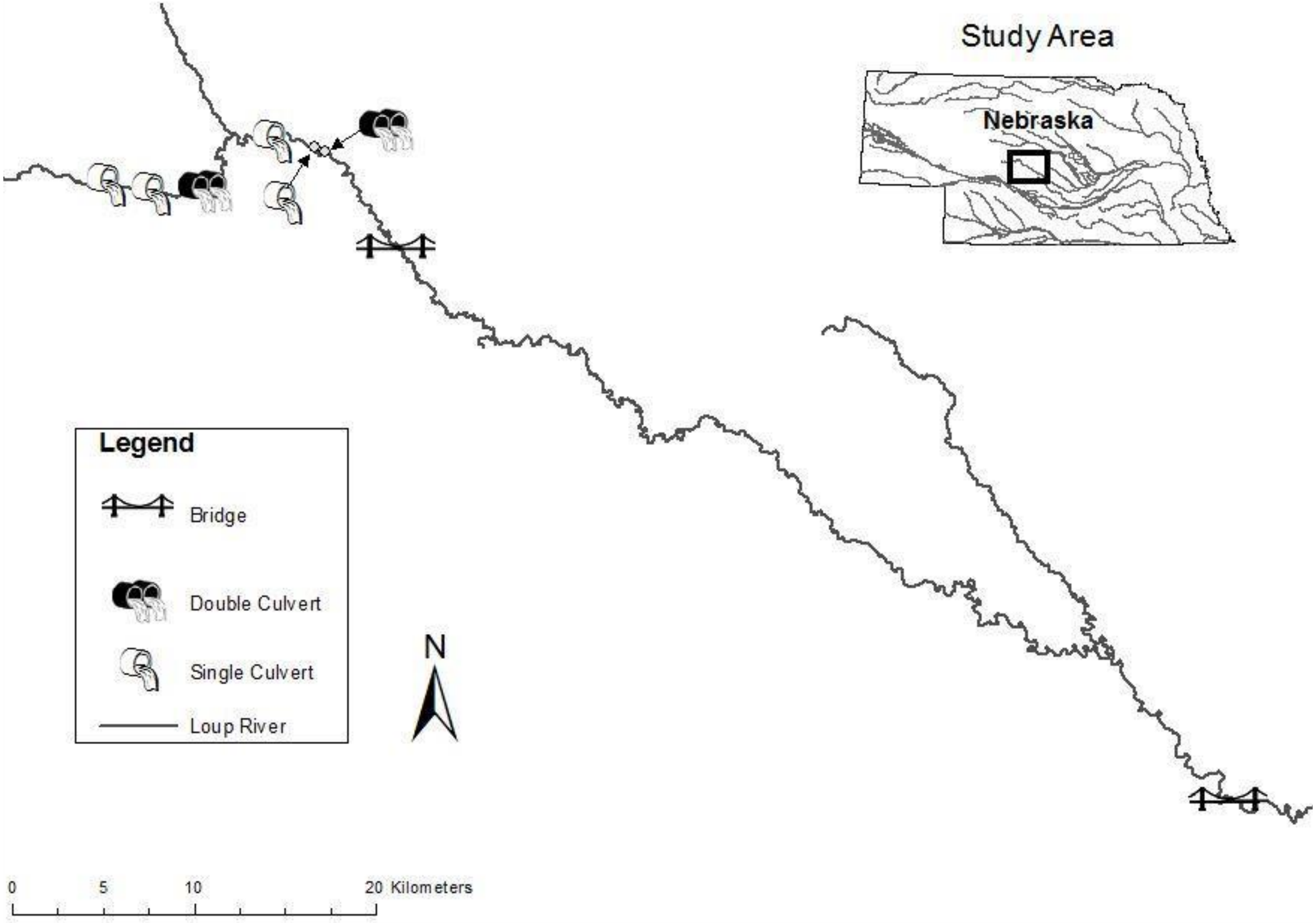

Figure 1: Map of the South Loup River, Nebraska, USA with sampling locations and the type of stream crossings at each location. Fish were sampled upstream and downstream of each location for this study.

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Figure 2(on next page)

Comparison of speciesrichness by stream crossing type and direction (upstream versus downstream).

Error bars represent one standard error. Species richness significantly differed ($p < 0.10$) by crossing type. Letters above each crossing type indicate significance of pairwise comparisons. Crossing types that share the same letter were not significantly different from one another. Species richness did not differ significantly between direction across all stream crossing types or by the interaction of stream crossing type and direction.

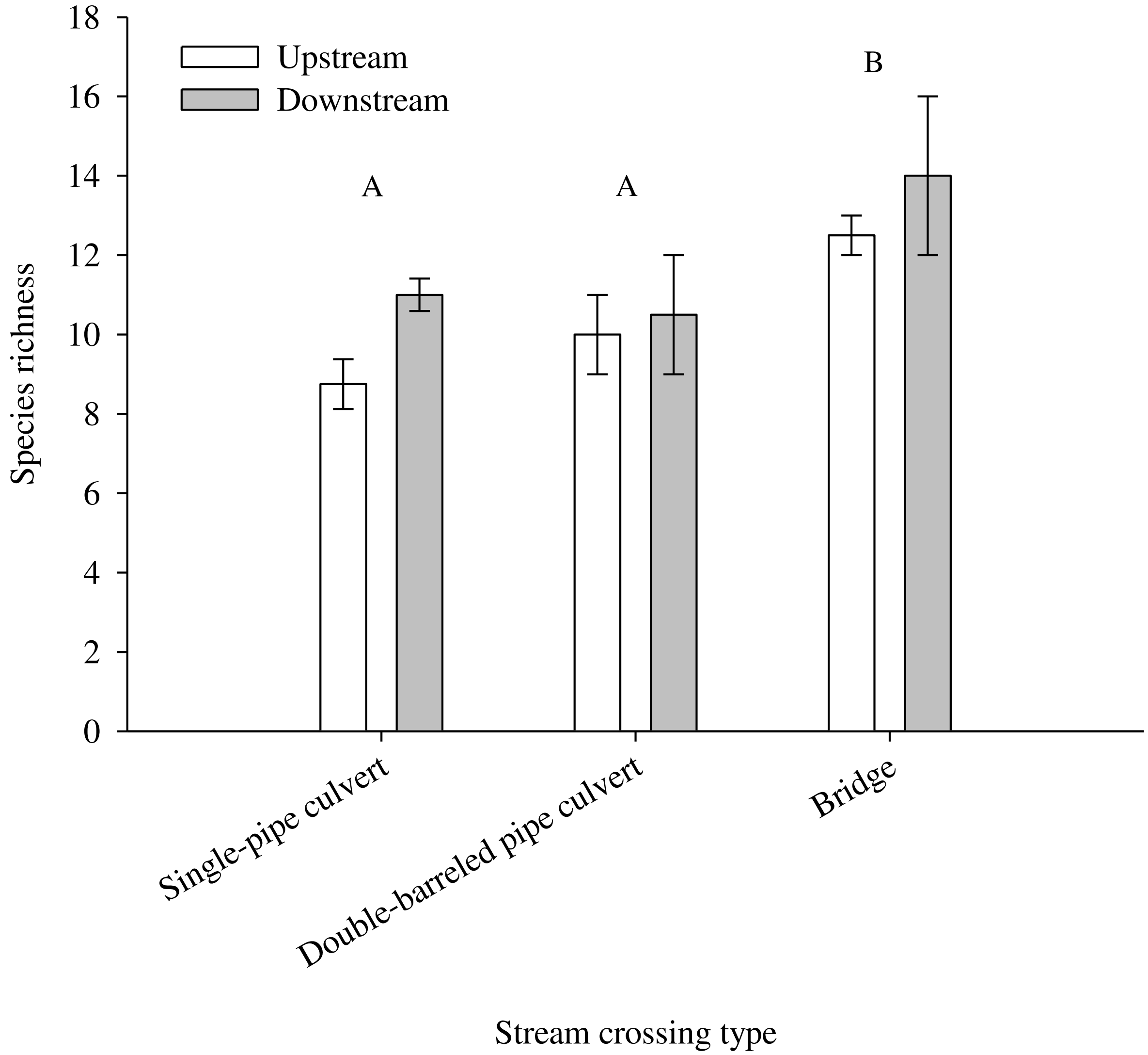

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Figure 3(on next page)

Comparison of catchper unit effort (CPUE) of brassy minnow by stream crossing type and direction(upstream versus downstream).

Error bars represent one standard error. Brassy minnow CPUE significantly differed ($p < 0.10$) by crossing type. Letters above each crossing type indicate significance of pairwise comparisons. Crossing types that share the same letter were not significantly different from one another. Brassy minnow CPUE did not differ significantly between direction across all stream crossing types or by the interaction of stream crossing type and direction.

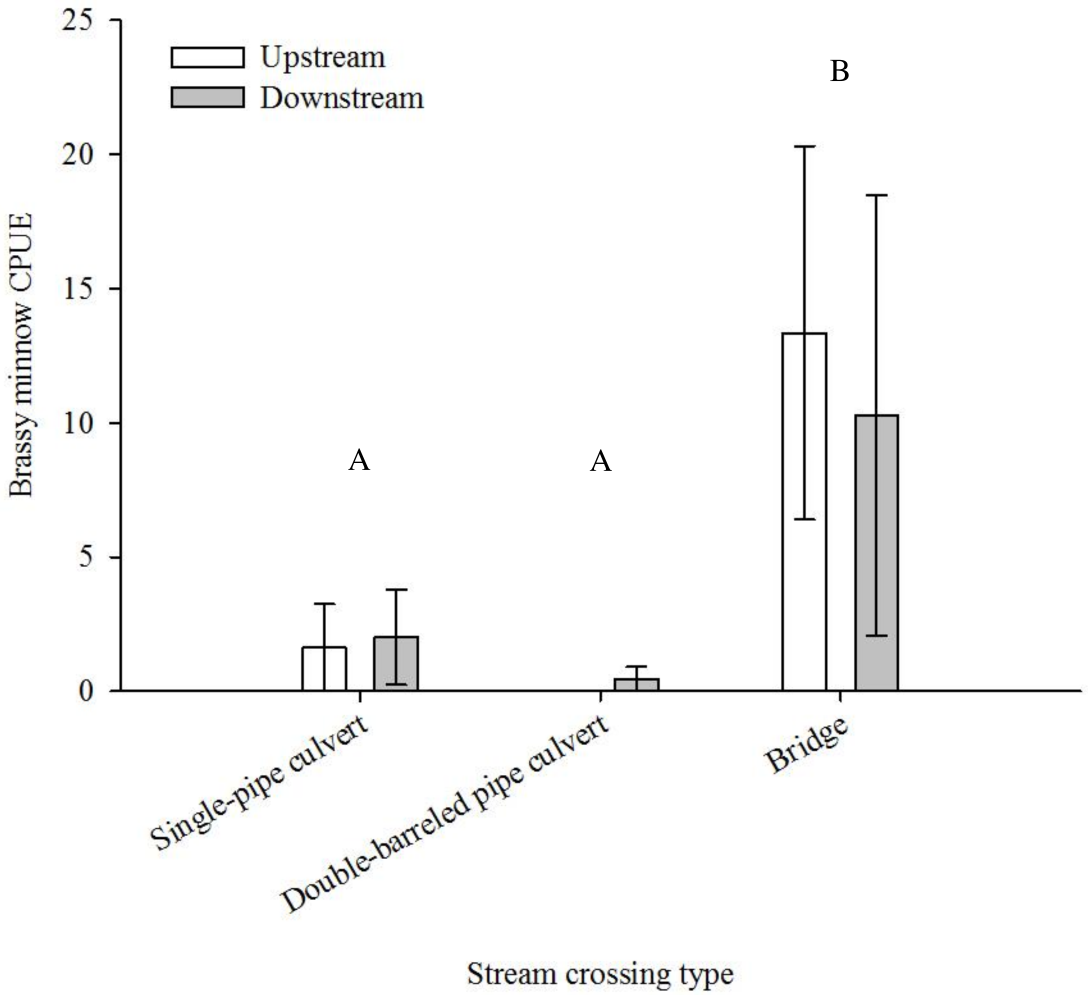

Figure 3: Comparison of catch per unit effort (CPUE) of brassy minnow by stream crossing type and direction (upstream versus downstream). Error bars represent one standard error. Brassy minnow CPUE significantly differed ($p < 0.10$) by crossing type. Letters above each crossing type indicate significance of pairwise comparisons. Crossing types that share the same letter were not significantly different from one another. Brassy minnow CPUE did not differ significantly between direction across all stream crossing types or by the interaction of stream crossing type and direction.

Table 1(on next page)

Comparisons ofvarious fish assemblage characteristics upstream and downstream of all threestream crossing types (bridges, pipe culverts, and double-barreled culverts)

Numbers in parentheses represent one standard error.

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Table 1:

Comparisons of various fish assemblage characteristics upstream and downstream of all three stream crossing types (bridges, pipe culverts, and double-barreled culverts). Numbers in parentheses represent one standard error.

Characteristics	**Upstream**	**Downstream**
Species richness	10 (0.68)	12 (0.73)
Species diversity	0.91 (0.13)	0.95 (0.13)
Brassy minnow catch per unit effort (number of fish * hour^{-1})	4.15 (2.53)	3.68 (2.82)
Plains topminnow catch per unit effort (number of fish * hour^{-1})	2.19 (1.01)	2.12 (0.49)
Largemouth bass catch per unit effort(number of fish * hour^{-1})	0.53 (0.22)	1.65 (0.85)
Northern pike catch per unit effort (number of fish * hour^{-1})	0.25 (0.26)	0.83 (0.42)
All predator catch per unit effort (number of fish * hour^{-1})	0.79 (0.39)	2.48 (1.11)

Table 2(on next page)

Comparisons ofvarious fish assemblage characteristics between all three stream crossing types(bridges, pipe culverts, and double-barreled culverts).

Numbers in parentheses represent one standard error.

Table 2:

Comparisons of various fish assemblage characteristics between all three stream crossing types (bridges, pipe culverts, and double-barreled culverts). Numbers in parentheses represent one standard error.

Characteristics	**Bridge**	**Single-barreled culverts**	**Double-barreled culverts**
Species richness	13 (0.95)	10 (0.55)	10 (0.75)
Species diversity	1.00 (0.08)	0.82 (0.16)	0.89 (0.16)
Brassy minnow catch per unit effort (number of fish * h^{-1})	11.82 (4.48)	1.81 (1.12)	0.23 (0.23)
Plains topminnow catch per unit effort (number of fish * h^{-1})	1.43 (0.44)	2.67 (0.94)	1.83 (1.07)
Largemouth bass catch per unit effort (number of fish * h^{-1})	0.17 (0.17)	1.77 (0.83)	0.66 (0.40)
Northern pike catch per unit effort (number of fish * h^{-1})	0.00 (0.00)	0.42 (0.24)	1.33 (0.81)
All predator catch per unit effort (number of fish * h^{-1})	0.17 (0.17)	2.19 (1.03)	1.99 (1.21)

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