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Dean, Cortney R. ***Assessing the Impacts of Beavers on Biodiversity and Water Quality in Class II Trout Streams in Northwest Wisconsin***

Abstract

North American beavers (*Castor canadensis*) are a much maligned and aggressively managed species in Wisconsin, particularly on classified trout streams. However, there is a substantial lack of data and research in the region to support current management practices. Furthermore, there has been no consideration of beaver impacts to species other than trout. I assessed biodiversity and water quality at six pairs of beaver and control stream sites in western Wisconsin between May and October 2024. I used bioacoustic recording units to assess both bat and avian diversity and camera traps to capture species utilization of beaver ponds, dams, and control stream reaches. I collected water depth, dam length, water temperature, turbidity, and conductivity readings for all sites on four separate collections across the study period. Overall biodiversity measures were not statistically significantly different between beaver and control sites, but bat activity was 73% (27%, 119%) higher at beaver pond locations ($t = 4.0$, $df = 5$, $p = 0.005$). Based on linear mixed effect models, temperatures in beaver ponds and downstream of ponds were not significantly different than control streams, and precipitation was the only statistically significant factor impacting water turbidity values ($p = 0.009$). Evidence that beaver activity does not significantly increase water temperatures, particularly in reference to trout thermal tolerances, indicates that perceived negative impacts of beavers on stream temperatures are not supported. Furthermore, novel evidence of a link between beaver ponded locations and increased bat activity suggests that beavers can be leveraged as tools to support bat conservation efforts.

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Table of Contents

List of Tables

List of Figures

Chapter I: Introduction

In the Midwest region, very little modern research has been completed on beavers in general, despite increasing evidence that beavers provide a host of ecosystem services ranging from boosting biodiversity to increasing resilience to natural disasters. What research has been undertaken in the region is specifically related to beaver-trout relationships. Much of this available information is anecdotal, done in limited watersheds, and completed in the early part of the 20th century (Johnson-Bice et al., 2018). These regional data gaps, paired with limited knowledge of existing beaver populations by state, suggest that many state beaver policies, including those in Wisconsin, are based on incomplete assessments and lack consideration to the ways beavers impact ecosystems.

Further complicating matters are the conflicting perceptions of and attitudes towards beavers among both the general public and wildlife and fisheries managers. A survey of Driftless Area stream restoration practitioners found discord amongst practitioners and across educational backgrounds on a host of topics including beaver utility, tree presence along stream banks, streambank grading, use of riprap, and even the purpose and goals of restoration work (Lundberg et al., 2022). Community surveys to evaluate attitudes and concerns about beavers often yield conflicting information and perceptions, with specific topics like wetland/pond creation, tree felling, and impacts to cattle being listed as both a “pro” and a “con” within the sampled population (Yarmey & Hood, 2020). This study also identified misperceptions about beavers and dams that had become normalized within the community, ranging from “beavers reduce water quality” to “beavers invade private property” to “beavers cut down trees for no reason” (Yarmey & Hood, 2020). Unsurprisingly, such disparities in perceptions and understandings of beaver impacts to ecosystems and communities promote a lack of consensus on beaver management policies, with roughly half of the participants advocating for coexistence with beavers and the remaining half advocating for aggressive removal and population management (Yarmey & Hood, 2020). Given the lack of relevant, modern data in this region, combined with the lack of consensus among and across varying stakeholders, it is clear that local research focusing on the large-scale, ecosystem wide impacts beavers generate is needed to help inform policy, communities, and stakeholders.

Beavers' role in creating critical wetland habitats on streams has been recognized in recent years as an effective and low-cost tool in conservation efforts aimed at other species and concerns (Hood & Larsen, 2015). While the number of beaver wetlands lost over time is not well-documented, estimates regarding wetlands in general indicate that over half of wetland acres have been lost to development since European settlement (Wohl, 2021). Many western US states have leveraged beaver dams and activity to increase water storage, recharge groundwater, and restore river hydrogeomorphology (Grudzinski et al., 2022; Levine & Meyer, 2019; Thompson et al., 2021; U.S. Fish & Wildlife Service, n.d.). Conversely, states with programs featuring aggressive removal of beavers and their dams could create cascading impacts to threatened and endangered species that rely on wetland habitats or beaver ponds. Policies aimed at removing beavers from the landscape could also negatively impact ecosystem resilience and hydrologic processes.

Beavers can also help ecosystems recover more quickly from extreme weather events and fires (Fairfax & Whittle, 2020; Thompson et al., 2021). Beaver dams serve as fire breaks and provide refugia for numerous species during both average and extreme fire events (Fairfax & Whittle, 2020). They mitigate flood-related disasters through the slowing of water flow rates and by directing water laterally onto the landscape and into floodplains (Auster et al., 2022; Brazier et al., 2021). Beaver impounded water increases groundwater storage and connectivity and recharges local water stores (Brazier et al., 2021; Fairfax & Whittle, 2020; Grudzinski et al., 2022). Estimations of the economic value of beaver-driven biodiversity were over $130 million annually (Thompson et al., 2021). As climate change impacts become more pronounced, the landscape's ability to sequester and slow water will become increasingly important across the continent and beavers are a critical component to meeting these needs. Beaver impacts to mitigating extreme weather events, improving water quality, and increasing water supplies combined were valued at over $80 million per year, a number that is sure to grow with increased climate-related events and growing water needs (Thompson et al., 2021).

Few studies have been done on ecosystem-level impacts of beavers in eastern or midwestern US states. In New England, beaver ponds contained a higher abundance of predatory zooplankton, lower incidences of algal blooms, increased dissolved organic carbon (DOC), increased rates of denitrification, and lower phosphorous levels (Błędzki et al., 2011; Grudzinski et al., 2022). Beaver dams minimized stream channel migration and improved both sediment aggradation and bank stability in Virginia streams (Curran & Cannatelli, 2014; Grudzinski et al., 2022). European countries (e.g., United Kingdom, Scotland, Germany) that have undertaken beaver reintroductions have documented increases in flood resilience, groundwater connectivity, reduced water pollutant levels, increased biodiversity and increased sediment storage (Orazi et al., 2022; Puttock et al., 2017; Smith & Mather, 2013). Extensive research on the ecosystem impacts of beavers in Finland have shown benefits to frog and toad populations (Vehkaoja & Nummi, 2015), waterbirds (Nummi & Hattola, 2008; Nummi & Holopainen, 2014), and bats (Nummi et al., 2011) and that beaver ponds store large amounts of carbon in sediments (Nummi et al., 2018).

From increasing wetland acres to restoring incised streams to creating beneficial habitat for at-risk species, beaver-built dams are a low-to-no-cost, nature-based tool that can be used across ecosystems, climates, and geographies. Beaver dams slow the flow of water and direct it laterally out onto the surrounding land (Brazier et al., 2021; Grudzinski et al., 2022; Larsen et al., 2021). This process serves a number of purposes in restoration work including reconnecting streams with their floodplains, establishing new wetland habitats, increasing habitat heterogeneity, and recharging groundwater stores (Grudzinski et al., 2022; Larsen et al., 2021). Beaver excavation activity and the hydrologic impacts of dam structures alter stream morphology and increase in-stream habitat complexity (Brazier et al., 2021; Hood & Larsen, 2015; Levine & Meyer, 2019). By increasing both in-stream and land-based habitat complexity, beaver activity increases biodiversity across animal species and vegetation along with overall habitat resilience to external factors such as drought, flooding, or other weather extremes (Brazier et al., 2021; Hood & Larsen, 2015; Levine & Meyer, 2019). Despite these studies, much of this research has been disregarded in beaver management policy development in the Midwest, often referencing a lack of similarity between states in terms of geology and habitat types, climate, and stream grades. Regrettably, the acknowledgment of these differences has not resulted in an abundance of beaver-related research in the Midwest.

Statement of the Problem

The purpose of this study is to address the physical and biological impacts of beavers on trout streams in Wisconsin. Beaver removal policies and traditional stream restoration projects represent ongoing fiscal expenditures for the state of Wisconsin. These policies also neglect the potential for beavers to be leveraged as low-to-no cost tools to aid species of conservation concern and habitat restoration work. This study will provide better data to inform Wisconsin's beaver management policies and more information on the potential role of beavers in both conservation and restoration efforts.

Assumptions of the Study

For the purposes of this study, the following assumptions exist:

1. Streams with the same Wisconsin Department of Natural Resources (WIDNR) classification grade (ex: Class II trout stream), situated within the same sub-watershed, share enough characteristics to be used as paired comparisons.
2. Randomized scheduling of sample collection dates for each sampling session is an adequate means to address temporal variations across the season.
3. Sampling from May-October is a sufficiently long window to capture activity for both bird and bat species.
4. A single pair of acoustic and ultrasonic recording units per site is sufficient to capture species richness for avian and bat populations.

Definition of Terms

For the purposes of this paper, the following terms are defined:

Acoustic Complexity Index

A quantification of the difference in the intensity of biotic songs in the presence of anthropogenic noise.

Alpha Diversity

The mean species diversity at a local scale (ex: a single beaver pond).

Aggradation

The increase in the elevation of land, particularly stream or riverbeds, due to the accumulation or deposition of sediments.

Beaver Deceiver

A device designed to facilitate non-lethal beaver management by creating protected outflows in beaver dams. These outflows maintain water levels at approved depths and prevent beaver activity to raise water levels beyond acceptable levels. Typically, these devices are built with cages around both intake and outflow pipes to prevent the flow of water from being blocked by beaver activity. The pipes are inserted into beaver dams or culverts at the desired water level and facilitate the reduction in water volumes stored behind dams.

Beaver Meadow

The area of recolonized vegetation that forms in the place of a beaver pond, after the pond has been removed from the landscape. These meadows are characterized by flat terraces of rich soil and lush vegetative growth.

Bioacoustic

The study of sounds produced by an ecosystem, including (but not limited to) weather, vocalizations, geologic processes, and other auditory components.

Breached Dam

When a portion of a beaver dam has been damaged, allowing water to flow freely through the damaged area. This can be a natural process or the result of human activity.

Conductivity

A measure of how well water conducts electricity. Higher levels of dissolved ions result in high conductivity readings. Conductivity readings are a proxy for measuring the levels of dissolved chloride in surface waters.

Critical Thermal Maximum

The temperature at which extended exposure will likely result in death for a given species.

Denitrification

The process by which bacteria convert nitrates present in water and soils into nitrogen gas, which is released into the atmosphere.

Diel Temperatures

The shift in surface water temperatures over the course of a day, which is highly linked to changes in air temperatures.

Driftless Area

The unglaciated region of the Midwestern United States which includes much of western Wisconsin, a small portion of northwestern Illinois, northeastern Iowa, and southeastern Minnesota. This region is characterized by steep hills and deep river valleys, featuring karst geology and abundant spring-fed surface waters and cold-water streams. This region is known for agriculture, sand mining, and exceptional trout streams.

Facultative Species

Any species that frequently occurs in wetlands but is not limited to wetland habitats.

Fluvial

Relating to streams or rivers, or a result of stream or river action.

Gamma Diversity

The total species diversity within a landscape (ex: an entire watershed).

Hibernacula

Any location used by bat species during hibernation. Often includes caves, anthropogenic structures, and cavities.

Hyperphagia

A period of increased food consumption, usually linked to preparations for hibernation, nursing, or migration.

Hyporheic

The area of soil and substrate beneath a stream or riverbed where surface water readily mixes with groundwater.

Incised Stream

Any stream that has become disconnected from its floodplain through erosion. These streams are characterized by steep, vertical banks, increased bank erosion, and higher flow rates.

Non-Point Source Pollution

Non-Point Source (NPS) Pollution are pollutants that enter a water source from many, non-specific locales within the watershed. These are commonly related to agricultural and landscape practices and water run-off. Common NPS pollutants include (but are not limited to) substances like nitrogen, nitrates, ammonia, phosphorous, chloride, herbicides, and pesticides.

Notched Dam

Notching is the practice of intentionally removing a portion of a beaver dam to restore stream flow. Notching can be done without heavy equipment as it does not require removing the entirety of the dam, only a portion of it.

Obligate Species

Any species that is restricted to wetland-type habitats.

Plunge Pool

A stream feature usually located immediately below a waterfall or area where water increases downward velocity when passing over a solid object, like a beaver dam, and creates a depression in the stream bed resulting in a deeper pool of water.

Pond Leveler

Similar to a Beaver Deceiver this is a non-lethal beaver management tool designed to reduce beaver pond depths and maintain them at approved levels without harming or removing beavers. These devices usually consist of corrugated tubing or piping inserted within a beaver dam at the desired water height. This facilitates water flow out of the dam while allowing the beaver pond to persist.

Preferred Thermal Maximum

The temperature at which extended exposure will likely result in reduced fitness, decreased survival rates, or migration for a given species.

Riprap

Large rocks and boulders installed along stream banks to lock in the meander and banks of the stream and/or minimize erosion.

Salmonids

Fishes in the ray-finned fish family Salmonidae, which encompasses salmon, char, and trout among other species. These fish are characterized by their requirement of cold-water habitats and predatory feeding habits.

Secchi disk

A disk that is divided into quadrants, with alternating white and black sections. This disk is used to measure water turbidity by lowering it into water or filling a tube with water. The depth of water at which the disk becomes visible is the measure of water turbidity.

Thalweg

The deepest part of a stream at a given location.

Vagrants

Species, usually birds, that are documented in locations outside of their normal range.

Volancy

The period in which young bats, or pups, begin flying and foraging on their own. Bat surveys are traditionally conducted, at least in part, during periods immediately after volancy to capture population changes resulting from the birthing season.

Limitations of the Study

The limitations of this study primarily relate to the inability to collect acoustic and ultrasonic data concurrently at all sample sites. Access to only four acoustic recording units prohibited one-to-one comparisons across study sites and time. This study is also limited by duration, as data was only collected during one six-month field season.

Methodology

In an effort to quantify the physical and biological impacts of beavers, I surveyed six beaver impounded streams and six paired control streams in northwestern Wisconsin between May and October 2024. I measured water quality metrics (i.e., temperature, turbidity, and conductivity) four times for each site over the course of the study. These measures also included water depths, dam lengths, and site vegetation cover. I installed bioacoustic recording units during each session, programming the units to record for 6 consecutive days for each acoustic and ultrasonic recording unit. This was repeated three times for each study site. I installed camera traps at the same time and for the same duration of the bioacoustic recordings at each site to capture non-vocalizing species presence. I modeled water temperature and turbidity values as a function of beaver presence, pair, land use and date. I assessed species richness and created avian species accumulation curves. I analyzed the frequency of bat calls as a function of habitat type. Precipitation levels were monitored throughout the study, and I evaluated land use within the modeled watershed of each site.

Chapter II: Literature Review

Beavers (*Castor canadensis*) are the largest native rodent species in North America. In Wisconsin, beavers are an unprotected but regulated, furbearing species as outlined in the Wisconsin Beaver Management Plan 2015-2025 (Wisconsin Department of Natural Resources [WIDNR], 2015). Exceptions to the outlined trapping regulations and established seasons are made for beavers deemed to be nuisances. This nuisance determination is made at landowner discretion without requirements for evidence, permits, carcass registration, or notification (Wisconsin DNR, 2015; Wisconsin DNR, 2022). These beavers-as-a-nuisance policies, and similar guidelines across the Midwest, have created ambivalent attitudes at best and hostile practices at worst throughout the region (Kirwan, 2022; Lundberg et al., 2022; Payne & Peterson, 1986). Longstanding negative attitudes towards beavers are also evident in the types of research that have been conducted in Wisconsin, ranging from lists of beaver-based complaints (Payne & Peterson, 1986) to impacts on ecosystems after beaver and dam removal (Avery, 1992; Popelars, 2008) and nuisance beaver removal/control practices (Dickerson, 1989; Peterson, 1979). Critically, much of the region's beaver-based research has focused on the potential benefits to trout populations through beaver and beaver dam removal; lacks modern perspectives on habitat, biodiversity, ecosystem connectivity; and is often deficient in statistical analysis and rigor.

There is very little modern published research at this date on the broader impacts of beavers in temperate forest or grassland biomes in the U.S. Upper Midwest (i.e., Wisconsin, Minnesota, Iowa, Illinois, Indiana, Michigan). What research has been completed, particularly in Minnesota, Wisconsin, and Michigan, is largely focused on how beavers affect native trout species, brook trout (*Salvinis fontinalis*). Many of these trout-centric studies feature anecdotal information and ignore ecosystem services and impacts not directly related to trout (Johnson-Bice et al., 2018). A common claim is that beaver activity adversely impacts brook trout by raising stream temperatures (Wisconsin DNR, 2019; Wisconsin DNR, 2015). However, a 2018 literature review and three Wisconsin-based studies identified a lack of confidence in that claim, instead indicating that most studies found no change in stream temperatures as a result of beaver impoundment (Johnson-Bice et al., 2018; McRae & Edwards, 1994; Renik & Hafs, 2020; Weber et al., 2017). In fact, beaver ponds reduced temperature fluctuations and produced lower downstream temperatures compared to control stretches, while dam removal was intermittently documented to increase stream temperatures (McRae & Edwards, 1994; Weber et al., 2017). The Wisconsin Beaver Management Plan relies on a 1992 study by Avery that apparently found a link between beaver activity and increased stream temperatures as justification for beaver and beaver dam removal from trout streams (Wisconsin DNR, 2015). However, modern statistical analysis of Avery's data did not show a statistically significant link between beaver dams and increased water temperatures, refuting Avery's claims (Popelars, 2008). Beaver ponds near Lake Superior, particularly those with dissolved oxygen (DO) levels of at least 4.2 mg/L, provided high-quality brook trout habitat, suggesting that beaver removal from trout streams in an effort to increase trout populations may be counterproductive (Renik & Hafs, 2020). As such, there is a lack of both evidence and understanding of how beavers impact riparian and wetland ecosystems, biodiversity, hydrology, habitat resilience, and water quality for these biomes. The lack of consensus in conclusions paired with the absence of ecosystem-scale analysis underscores the need for additional research to better inform beaver management policies.

Hydrology and Water Quality

Beavers are well known as ecosystem engineers and have, in recent years, been leveraged in U.S. Mountain West regions and European countries to address broader hydrological and stream condition concerns. Evidence from western U.S. states indicates beaver dams provide increases in hydrologic connectivity and lower stream temperatures (Dittbrenner et al., 2022; Larsen et al., 2021; Weber et al., 2017), increase water quality (Maret et al., 1987; Murray et al., 2021; Stevenson et al., 2021), increase carbon storage (Wohl, 2013), and attenuate erosion through increased geomorphologic complexity (Larsen et al., 2021; Pollock et al., 2014).

Beaver dams facilitate sediment aggradation, primarily due to decreased water velocities and increased hydrologic residence times provided by dam structures. This deceleration of water allows heavier suspended sediments to fall out of the water column and deposit at the bottom of the beaver pond. Sediment aggradation is a complex subject that can be both beneficial and detrimental to streams, depending on the context. In some areas, sediment aggradation is a beneficial tool to reverse stream incision (Bouwes et al., 2016). In other areas, sediments washed downstream after dam breaches are believed to damage trout spawning habitats. A lack of uniformity in sediment accumulation rates behind beaver ponds suggests that aggradation rates are site-specific and dependent upon dam age, stream gradient, local geology, land use, and weather patterns (Butler & Malanson, 2005). Furthermore, after beaver dam failures, the majority of sediments were retained in the previously dammed section of streams and this preserved, exposed sediment was rapidly revegetated with both grasses and shrubs, albeit with less plant diversity than pre-failure conditions (Butler & Malanson, 2005). Sediment transport was strongly linked to stream condition and beaver pond connectivity to floodplains, suggesting that sediments trapped in beaver ponds connected to the surrounding floodplain are less likely to dislodge and be transported downstream in the event of dam failure or breach (Kroes & Bason, 2015). Regionally, in Minnesota only trace evidence of fluvial sediment deposition was found in beaver meadows, indicating that the surrounding landscape’s low slope and high percent of forested land minimized overall erosion and therefore reduced sediment aggradation behind beaver dams (Johnston et al., 1995). This suggests that within-watershed land use and slopes may substantially impact sediment loads in stream and aggradation rates behind dams. Lastly, beaver activity was identified as a catalyst for riparian plant regeneration and reproduction via both disturbance and sediment aggradation, allowing riparian pioneer and early successional species to readily colonize exposed areas of aggregated sediments (Levine & Meyer, 2019).

Beaver pond ability to slow water and increase storage capacity also has impacts on non-point source pollutants in surface waters. Decreases in nitrates, phosphorous, and sediments were found below beaver dams in the United Kingdom (UK; Puttock et al., 2017). Decreases in water temperature, nitrates, phosphorous and turbidity was found downstream of beaver dams in New England, while increases in chlorophyll, zooplankton, and dissolved organic carbon were found within beaver ponds (Błędzki et al., 2011). The increases in DOC are noteworthy as it is traditionally the limiting factor for denitrification. Beaver ponds can also serve as an important nitrogen sink on the landscape, with ponds capable of removing between 5-45% of total watershed nitrogen inputs annually (Lazar et al., 2015). Notably, any given beaver pond’s capacity to mitigate NPS pollutants is often dependent upon the pond’s morphology, surrounding geology, local land use, and weather patterns (Błędzki et al., 2011; Fuller & Peckarsky, 2011; Larsen et al., 2021; Lazar et al., 2015).

As previously stated, much of the current North American research has been focused within western, arid ecosystems that are seeking ways to increase water storage on the landscape or benefit communities heavily impacted by flooding and fires. Beaver introduction into riparian and wetland habitats in Canada increased volume-to-surface water ratios by 50%, increased wetland perimeters nearly 600%, and increased the wetland-forest interface, all while increasing ecosystem processes and resilience (Hood & Larsen, 2015). Beaver-initiated processes in Montana streams generated disturbances which then led to increased in-stream and vegetative diversity well beyond the immediate dam area (Levine & Meyer, 2019). Satellite analysis of vegetation before and after mega-fire events in Colorado, California, Idaho, Oregon, and Wyoming showed that beaver ponded sections of streams retained more greenness, an indicator of healthy vegetation, post-fire than control streams (Fairfax & Whittle, 2020). This response suggests that beaver ponds and complexes serve a valuable role in ecosystem recovery post-fires and may also provide refugia for numerous species during fire events. In Oregon, beaver impounded streams improved native juvenile trout survival by 52% but also decreased stream water temperatures and increased groundwater storage (Bouwes et al., 2016).

Ecosystem Services

The cumulative ecosystem services provided by beavers has not been well documented, but one study estimated that the cumulative value of beaver-based ecosystem services in the Northern Hemisphere was over $600 million U.S. dollars annually (Thompson et al., 2021). The largest single drivers of this estimate were habitat and biodiversity at $133 million and greenhouse gas sequestration at $75 million (Thompson et al., 2021). Moderation of extreme weather events was, at the time of publishing, valued at $32 million, while water purification and water supply were valued at $28 and $20 million respectively, however it is expected that the value of water-based services will grow in the coming decades (Thompson et al., 2021). A literature review of 267 beaver-based studies highlighted variability in beaver impacts across biomes, but did find that beaver activity promoted stream sedimentation and stream channel complexity (Grudzinski et al., 2022). Furthermore, across biomes, beaver dam presence increases surface water connectivity with hyporheic zones, therefore increasing hydrologic stability, increasing water retention time, and decreasing water flow rates (Brazier et al., 2020; Grudzinski et al., 2022). These examples illustrate the ecological and fiscal value of beavers on the landscape and as a part of habitat restoration practices and provide frameworks for quantifying these ecosystem services while also highlighting variability in responses across biomes.

In Europe, there have been multiple documented linkages between the introduction of beaver and increases in biodiversity (Law et al., 2016; Law et al., 2019; Orazi et al., 2022), however there is little information for Midwestern ecosystems. Some UK beaver ponds showed decreased alpha diversity at beaver impounded sites, however large-scale increases in habitat heterogeneity broadly leads to an overall increase in gamma diversity (Law et al., 2016) and overall species richness (Law et al., 2019). These studies suggest that the scope of analysis, when confined to beaver ponds, may miss large-scale increases in species composition at the landscape level, which encompasses both impounded and un-impounded stream reaches (Law et al., 2016).

Lastly, linkages between beavers and other species have not been well studied. With exceptions for avian species, there is no published data on any beaver-species relationships in the Midwestern region. Two European studies have shown linkages between beaver wetlands and increased bat activity (Hooker et al., 2024; Nummi et al., 2011). In the UK, overall avian species richness increased after beavers were introduced along stream stretches (Fedyń et al., 2024). Amphibian species richness was found to be 2.7 times higher in beaver ponds than free-flowing streams in Washington state, particularly benefitting species with slow development rates (Romansic et al., 2020). This suggests that the hydrologic stability of beaver ponds is a critical feature in both the development and survival of slow-to-mature animals like some salamander and frog species (Corline et al., 2023). Intensive camera trap monitoring of a single beaver lodge in Nebraska found that the exterior of the lodge was utilized by 28 unique species over the course of a year, a number that is nearly three times greater than previous estimates (Tye et al., 2021). Despite these studies and trends in increased biodiversity, significant data gaps exist across species and ecoregions.

Beaver-Trout Relationships

Beaver-trout and beaver-salmonid research has been completed across a range of biomes in North America. Both floodplains and beaver ponds are a source of increased zooplankton densities, which is a key food source for juvenile salmonids, resulting in larger fry growth rates and increased biomass production (Jeffres et al., 2020; Jeffres et al., 2008; Malison et al., 2015; Smith et al., 2013). A similar pattern of increased juvenile salmonid presence in beaver ponds was found in Oregon streams (Bouwes et al., 2016). Beaver ponds and dams are a source of increased riparian habitat heterogeneity, which is positively correlated with both fish species richness and abundance, as well as macroinvertebrate densities across U.S. regions (Bouwes et al., 2016; Lokteff et al., 2013; Longcore et al., 2006; Smith & Mather, 2013).

Common claims regarding the perceived negative impact of beaver activity on trout populations include dams posing barriers to trout movement, increased water temperatures, and a reduction of critical trout habitat. Beaver dams did not act as impediments to brook trout movement but did prevent non-native brown trout (*Salmo trutta*) movement (Lokteff et al., 2013). This suggests that brook trout of all sizes are more adept at navigating side channels around beaver dams, jumping over smaller dams, and passing through dam structures than non-native brown trout (Lokteff et al., 2013). This may indicate that where brown and book trout cohabitate, the presence of beaver dams may shift the competitive advantage towards brook trout (Lokteff et al., 2013). Regarding critical and limited trout habitat, brook trout need slow, deep water with in-stream cover and groundwater discharge for thermal refugia in Great Lakes drainages during winter months (Cunjak, 1996). Each of these four features are typical characteristics of beaver ponds, including preferred sources of in-stream cover for brook trout; macroinvertebrate mats, woody debris, and bank undercuts (Cunjak, 1996; Larsen et al., 2021). Beaver ponds have been specifically identified as a source of ideal winter habitat particularly in stretches where large, deep pools are limited in number or unavailable, going as far as suggesting that beaver ponds are underappreciated and a critical source of habitat that may be limited in many watersheds (Cunjak,1996). Lastly, the most commonly cited concern with beaver ponds is the perception that they increase stream water temperature, rendering them thermally unsuitable for coldwater species like salmonids. Across many biomes, increases in stream water temperatures in the wake of beaver pond creation has not been consistently documented, suggesting that beaver ponds buffer diel temperature cycles and/or increase groundwater connectivity resulting in cooler water temperatures (Bouwes et al., 2016; Dewey et al., 2022; Dittbrenner et al., 2022; Weber et al., 2017). In fact, high beaver dam density increased thermal heterogeneity within the length of stream reach, providing both lower minimum and maximum daily water temperatures (Weber et al., 2017).

This data is in direct conflict with current Wisconsin DNR policies and management practices regarding beaver activity impacts to trout populations (Wisconsin DNR, 2015; Wisconsin DNR, 2019). Cumulatively, modern research points to numerous potential benefits to trout by beaver impoundments, none of which are reflected in Wisconsin’s current beaver or trout management plans. The frequent rationale for not implementing this data into Wisconsin’s management plans is that the data is not local and therefore cannot be applied to Wisconsin or Midwestern ecosystems (Wisconsin DNR, 2015).

Beaver-Bat Relationships

Currently, no direct analysis has been done on bat utilization of beaver modified habitats in North America. Primarily, U.S.-based research has been conducted on bat use of traditional wetlands, finding that bat activity is generally higher around wetland habitats, but that the disconnected nature of many wetlands can increase the distance of travel between foraging locations (Francl, 2004; Lookingbill et al., 2010; Mas et al., 2021; Salvarina, 2016). Notably, trees intentionally felled in forested wetlands to mimic beaver activity resulted in higher bat activity levels in all native species compared to non-treated control sites (Wright et al., 2023).

The majority of beaver-bat research has been conducted in Europe. In Finland, two species of bats preferred beaver pond habitats over wetlands and the foraging groups utilizing beaver ponds were larger in number than those over wetlands (Nummi et al., 2011). In Poland, the canopy gaps created through beaver tree cutting and still water habitat created by dams were identified as the primary drivers of increased habitat selection and foraging activity for bats (Ciechanowski et al., 2010). In the UK wetland habitats with beaver reintroductions, seven bat species exhibited 40% higher activity over sites with reintroduced beavers compared to beaver-free control sites (Hooker et al., 2024). This demonstrates the capacity of beaver-created wetlands to restore historical aquatic-terrestrial food webs through increasing riparian habitat complexity and vegetative diversity, both of which support increases in invertebrate biomass and, in turn, support increases in bat foraging activity (Hooker et al., 2024). The results of European studies indicate that similar positive relationships between beaver-mediated wetlands and bat foraging activity may exist in North America.

The lack of research and data in North America represents an area of critical need. Five out of Wisconsin's seven bat species are listed as threatened at the state level, two of which are either already on the Endangered Species List (northern long eared bat; *Myotis septentrionalis*) or pending addition to the list (tricolor bat; *Perimyotis subflavus*). Up to 95% of Wisconsin's cave-dwelling bats have been lost to the highly pathogenic fungal infection known as White Nose Syndrome (WNS; *Pseudogymnoascus destructans*) (Wisconsin DNR, n.d.-a). Additional, non-species-specific losses such as habitat degradation, climate fluctuations, domestic and feral cat attacks, and pulmonary hemorrhage from passage through wind turbine blades have also negatively impacted populations (Hopkins et al., 2021).

Beavers represent a potential method to improve both the habitats and food webs that support bat species. The increased frequency of bat activity over beaver ponds are likely related to increases in foraging activity over the flat, low-velocity water which is ideal for echolocation (Hooker et al., 2024). Bats across multiple taxonomic groups and from disparate geographical regions identify all extended duration echo-acoustically smooth signals as bodies of water (Greif & Siemers, 2010). Equating all flat, smooth surfaces as water, even in the face of competing and conflicting sensory data, implies that this behavior is innate and linked to the criticality of identifying sources of drinking water for all bat species (Greif & Siemers, 2010). Within the context of beaver ponds, it could indicate that the flat water of beaver ponds is more readily identifiable as water than turbulent stretches of streams.

Survivability studies on Midwestern bats suggest that bats able to meet pre-hibernation hyperphagia goals without expending excessive effort to do so are more likely to survive a WNS infection (Hopkins et al., 2021). Furthermore, these same bats are more likely to tolerate negative impacts from early emergence or temperature swings during pre-emergence periods (Hopkins et al., 2021). The increased habitat complexity and volume of stored water in beaver ponds represents an increase in overall gamma diversity which corresponds to an increase in overall biomass as it includes boosts to terrestrial, aquatic, and semi-aquatic species (Law et al., 2016, Malison et al., 2015; Nummi et al., 2011). The increase in terrestrial invertebrates is linked to increased food availability for all native bat species, given their primary food sources include beetles (*Coleoptera spp.),* flies (*Diptera spp.)*, and moth (*Lepidoptera spp.)* species (Maslo et al., 2022). This highlights the biological and conservation significance of high-density, low-effort food sources for bat populations, which may be provided by beaver ponds.

Beaver-Avian Relationships

The impact of beaver impoundments on avian species has been well studied, however, limited data is available specific to Wisconsin. An overall increase in scrub-shrub species at beaver inhabited sites in Massachusetts, links the increase in avian abundance with the increase in habitat and vegetative complexity created by beaver activity (Chandler et al., 2009). In fact, increased habitat complexity and vegetative diversity is positively correlated with bird species abundance across multiple biomes (Bradshaw et al., 2020; Edwards & Otis, 1999; Fedyń et al., 2024; Glisson et al., 2015; Longcore et al., 2006). Avian richness and abundance, regardless of species, was positively correlated with beaver ponds in Wyoming (Brown et al., 1996; Cooke & Zack, 2008; McKinstry & Anderson, 1999). Higher avian species richness was identified at beaver ponded sites across Europe, illustrating how the positive impact from beaver ponds can extend more than 100 meters from the dam site (Fedyń et al., 2024; Nummi & Holopainen, 2014).

Summary

The persistence of anti-beaver management programs, beaver-exclusion policies, and generalized negative attitudes in Wisconsin may be rooted in the lack of local data regarding beavers. However, the abundance published data illustrating the positive impacts beavers can have on avian and bat populations, biodiversity, erosion control, stream restoration, water quality, habitat complexity, and resilience to climate change and natural disasters. While the vast majority of this research has been done outside the biomes of the upper Midwest, the results illuminate the numerous potential benefits Wisconsin may be missing out on by removing beavers from the landscape instead of viewing them as a tool for conservation.

Chapter III: Methodology

To better understand the biological and physical impacts of beaver ponds, this study's approach was to assess biodiversity, through bioacoustic surveys, and water quality metrics. Camera traps were also used to document non-vocalizing species utilization of the study sites. A paired study design was employed to minimize meteorological, geographical, and spatial variability between study sites, as beaver dam locations spanned three counties and five watersheds.

Site Selection and Descriptions

Searches for beaver dams and ponds were conducted through social media inquiries and satellite imagery analysis. Sites were chosen based on the following criteria: 1) beaver dam was active as noted by either landowner or personal inspection, 2) beaver dam was situated on a WIDNR Class II trout stream and a suitable Class II control stream was present within the same WIDNR defined sub-watershed, 3) beaver dam was not at risk for landowner or DNR removal or situated across property boundaries. Class II trout streams were chosen for the study because they are the most common trout stream type within the study area and possess at least some naturally breeding trout populations. These are also streams that could potentially be improved to Class I status, meaning the stream has high enough natural reproduction to sustain wild populations, with habitat improvements. Any sites on streams scheduled for beaver and dam removal were eliminated from the study. If a beaver dam was abandoned between initial identification and the start date, it was removed from the study. Beaver activity and/or presence was determined by one or more of the following criteria: 1) intact beaver dam and pond, 2) evidence of recent tree or shrub cutting, 3) evidence of active drag sites, dam construction or excavation activity, or 4) visual confirmation of beaver. Sites with multiple beaver dams were not excluded. All streams within the study are WIDNR Class II trout streams and are considered low gradient, coldwater streams. While variations in stream site proximity to roads, geology, vegetation, land use, and stream morphology were present, pairing of control sites and beaver impounded sites was completed within the same sub-watershed to minimize differences (See Table 1).

Table 1

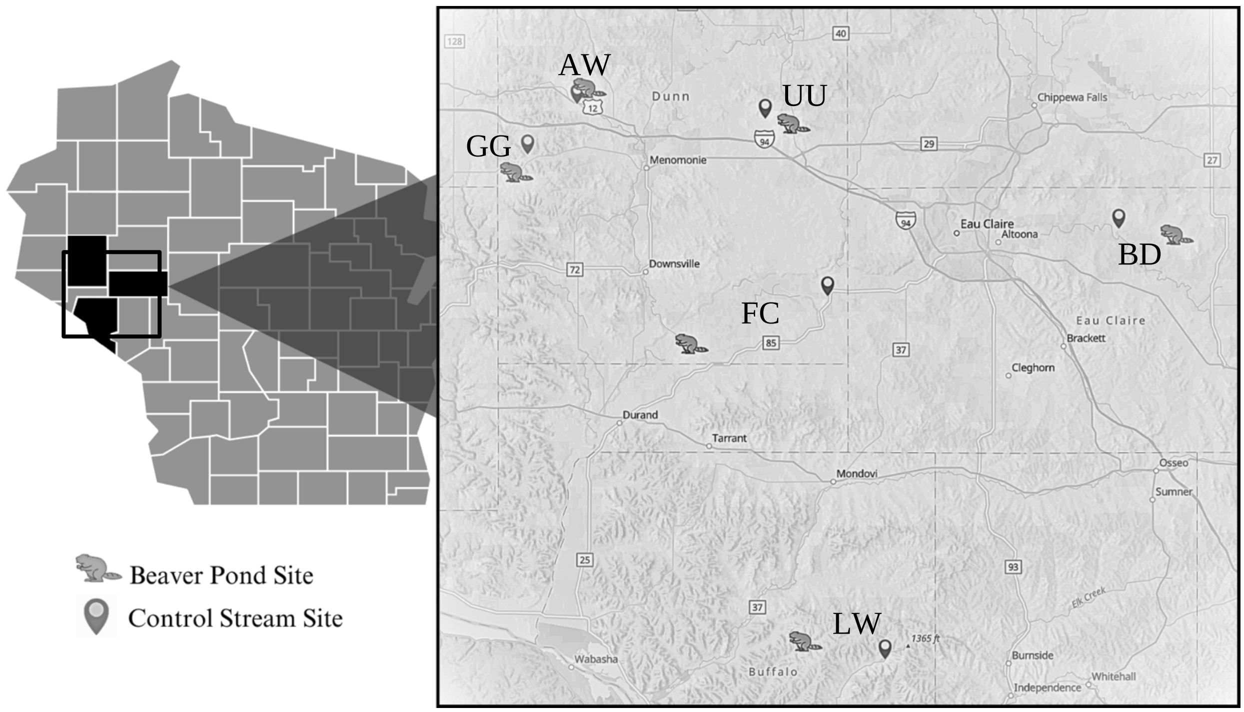
Stream Characteristics

County	Pair	Creek	Site type	Length (km)	Incised	Stream order	Stream gradient %
Dunn	AW	Annis	Beaver	9.61	Yes	3rd	0.0
		Wilson	Control	17.72	Yes	4th	1.5
	FC	Fall	Beaver	13.26	Yes	3rd	0.0
		Coon	Control	11.28	Yes	3rd	0.0
	GG	South Branch, Gilbert	Beaver	4.43	Yes	2nd	3.11
		North Branch, Gilbert	Control	3.22	No	3rd	0.15
	UU	Unnamed 8-3	Beaver	3.86	No	2nd	1.07
		Unnamed 7-12	Control	4.06	No	2nd	0.75
Eau Claire	BD	Beaver	Beaver	12.96	No	3rd	0.32
		Dienhammer	Control	5.25	Yes	2nd	1.58
Buffalo	LW	Little Waumandee	Beaver	16.27	Yes	3rd	1.11
		Waumandee	Control	19.92	Yes	4th	0.11

Study sites covered three counties in northwestern Wisconsin (See Table 1 and Figure 1). Buffalo County sites (LW) were situated on Little Waumandee Creek (beaver impounded) and Waumandee Creek (control site), both within the Waumandee Creek watershed and both on private land. Little Waumandee is a cool-cold stream listed in excellent condition with no runoff impairment (Wisconsin DNR, n.d.-b). This site is situated at the bottom of a valley and is surrounded by restored prairie and oak savanna. At least two active beaver dams were present at this site. Waumandee Creek is a cool-warm stream listed in poor condition with high levels of phosphorous runoff (Wisconsin DNR, n.d.-b). This site is highly incised and has been rip-rapped to minimize erosion. This stream bisects two large agricultural fields (approximately 740 acres at the study location) in a large valley bottom.

Figure 1

Map of Study Sites



Note. Paired sites are labeled following the designations in Table 1.

The Eau Claire County sites (BD) were located on Beaver Creek (beaver impounded) and Dienhammer Creek (control site), both within the Eau Claire River watershed. Both sites were located on property under the care of Beaver Creek Reserve (See Figure 2). The Beaver Creek site is located on private land and the Dienhammer Creek site is on public land. Beaver Creek is a cool-cold stream listed as impaired and in poor condition (Wisconsin DNR, n.d.-b). The sample site for Beaver Creek is near the headwaters of the stream and is surrounded by hardwood forest, shrubby grasslands, restored prairies, and is not incised. At least two beaver dams were active throughout the study. Dienhammer Creek is a cool-cold stream in good condition with no listed impairments (Wisconsin DNR, n.d.-b). This stream is incised and was the historical site of a splash dam used for logging activity. The sample sites for Dienhammer Creek were situated near a campground with abundant walking trails and human activity and are surrounded by hardwood forest.

The remaining four pairs of sites are all located within Dunn County (See Figure 2). The northeastern pair of sites (UU) are Unnamed Creek 8-3 (UNC8-3) (beaver impounded) and Unnamed Creek 7-12 (UNC7-12) (control site), located in the Muddy & Elk Creek watershed and both on private property. UNC8-3 is a coldwater stream listed as “unknown condition” but has no listed impairments (Wisconsin DNR, n.d.-b). This site is situated in an open floodplain, surrounded by flooded grass and bordered by hardwood forests. It is an unincised stream and at least two active beaver dams are present along with numerous historical dams. Additionally, this site is proximate to a high-traffic county highway, with the lodge located approximately 18 meters west of the road, and the dam averaging 55 meters west of the road. UNC7-12 is also a coldwater, stream listed as “unknown condition” with no information is available on its impairment status (Wisconsin DNR, n.d.-b). This site is situated in an open floodplain, surrounded by flooded grass and bordered by hardwood forests to the east and agricultural fields to the west, it is an unincised stream.

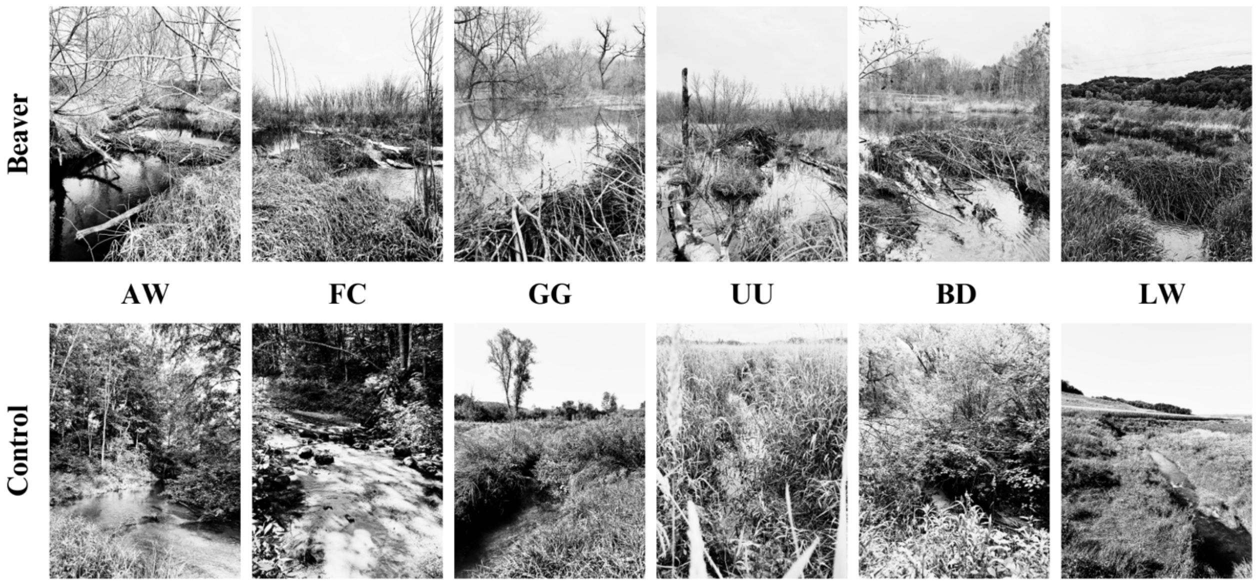
The southeastern pair of sites are Fall Creek (beaver impounded) and Coon Creek (control site) within the Lowes & Rock Creek watershed, both are located on public, state owned land (FC; See Figure 2). Fall Creek is a cool-cold stream listed as poor condition with phosphorous impairments (Wisconsin DNR, n.d.-b). This site is near the termination of the stream, where it empties into the Chippewa River. It is surrounded by hardwood forest and is incised, with one beaver dam present. Coon Creek is a cool-warm, stream is listed as “unknown” condition, but not impaired (Wisconsin DNR, n.d.-b). This site is surrounded by hardwood forest and the stream is incised.

The western pair of sites (GG) are the north (control site) and south (beaver impounded) branches of Gilbert Creek, located in the Wilson Creek watershed (See Figure 2). The site on South Branch Gilbert Creek (S. Gilbert) is located on private land and is a coldwater stream listed in good condition, but its impairment status is listed as high with unknown sources (Wisconsin DNR, n.d.-b). This site is located near the headwaters of the stream and is surrounded by hardwood forest. This section of stream is unincised, featuring one large beaver dam. The site on the North Branch Gilbert Creek (N. Gilbert) is located on public, state-owned land and is a coldwater stream listed as good condition, but with an impairment status of high with unknown sources (Wisconsin DNR, n.d.-b). The site on N. Gilbert Creek is located on a restored section of stream, featuring graded slopes and planted rip-rap banks resulting in a stream surrounded by grass and wet prairie and focal patches of hardwood trees.

The northwestern pair of sites are located on Annis Creek (beaver impounded) and Wilson Creek (control site) within the Wilson Creek watershed (AW). The Annis Creek site is located on private land and is a cool-cold stream listed in poor condition, with phosphorous impairment restricting aquatic life (Wisconsin DNR, n.d.-b). The study site is located along a narrowly forested stretch of the stream, which is incised, surrounded by approximately 250 acres of agricultural fields. At least two active beaver dams were present during the course of the study. Wilson Creek is a cool-cold stream listed as poor condition with phosphorous impairment restricting aquatic life (Wisconsin DNR, n.d.-b). This site is located on a narrow strip of public, state-owned land and is incised, surrounded by hardwood forest and dairy and cattle farms both up and downstream. Additionally, this site is proximate to a high-traffic county highway, with the sample site approximately 45 meters south of the road.

Figure 2

Site Photographs



Sites were sampled across four different sessions from May-October 2024. Paired sites were randomly scheduled for each of the first three sessions, which included bioacoustic, camera trap, and water-related data collection (See Table 2). Session 1 ran from May 21 - July 1, Session 2 ran from July 2 - August 12, and Session 3 from August 13 - September 23. Bioacoustic and camera trap data was collected for an average of 6.5 days per site, from Tuesday morning to Monday afternoon, weekly, while water-related data was only collected on the first day, Tuesday, of the sampling period. A fourth session was completed within a two-day window, from October 26-27, 2024, and only included water-related data collection. One site, North Gilbert Creek, was unavailable for data collection during this fourth session due to landowner scheduling conflict, therefore data for the GG pair for session 4 was omitted. Only the first (May

21-27, AQ) and last (September 17-23, UU) sampling dates coincided with peak migration dates (Dokter, n.d.).

Table 2

Sampling Dates and Avian Migration Periods

	Session 1						Session 2						Session 3					
Pair	May 21-27	May 28-June 3	June 4-10	June 11-16	June 14-24	June 25-July 1	July 2-8	July 9-15	Julu 16-22	July 23-29	July 30-Aug 5	Aug 6-12	Aug 13-19	Aug 20-26	Aug 27-Sept 2	Sept 3-9	Sept 10-16	Sept 17-23
AW		■									■			■				
FC				■				■									■	
GG					■		■								■			
UU			■							■								■
BD						■			■				■					
LW	■											■				■		

Note. Gray squares indicate avian migration periods with dark gray indicating peak migration. Black squares indicate which pair was being monitored each week.

The weather pattern across the sampling sessions did not exemplify the average weather patterns for the region. The online Community Collaborative Rain, Hail and Snow Network (n.d.) was used to collect precipitation data for all sites. Data collection stations were chosen based on the nearest available data for each study site. However, data collection sites that did not share the same sub-watershed were not used, in favor of the nearest station within the same sub-watershed. Precipitation data was collected for each site for the 48 hours prior to deployment, the seven days prior to deployment, the seven days during deployment, and the monthly totals for the duration of the study.

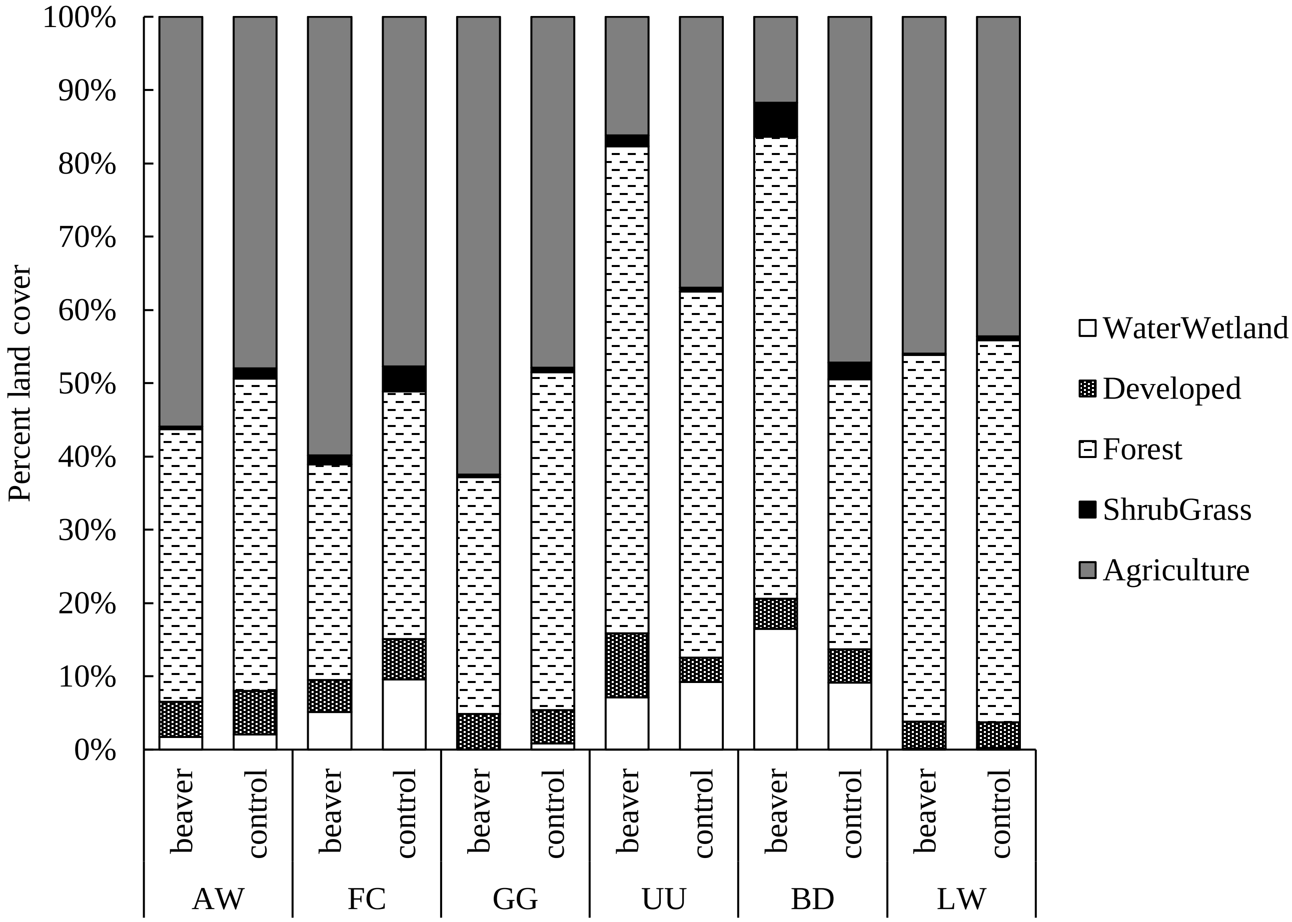
Waterway Morphology

For all sample sites, air temperature, dam length, stream incision status, site stream gradient, riparian buffer width, and estimated percent of cover type were recorded during each session. Air temperature was measured using the same Fishpond Riverkeeper digital thermometer and dam length was measured with a metric tape measure, both of which were collected in the field. Stream stage and impairment status was documented using the Wisconsin DNR Surface Water Data Viewer Mapping Application (Wisconsin DNR, n.d.-b). Riparian buffer width, stream gradient, and stream length were calculated using software measurement tools within the OnX web-based mapping application (OnX, n.d.). Stream incision status (yes/no) and percent cover type (i.e., grasses, forbs, bare ground, crop/pasture, woody and percent overhead cover) were documented in the field based on visual estimates.

Land use and watershed data were collected for each site using the online program Model My Watershed (Stroud Water Research Center, n.d.). The “delineate watershed” function was used for each site, using the continental US dataset, by entering in the GPS coordinates for each sample collection site. Total stream kilometers, average stream gradient, total watershed area (km^2), and the percentage of each type of land cover were documented for each delineation. Using this data, land use categories and percentages were combined into the following categories: Developed, Forest, Shrub/Grass, Agriculture, and Water/Wetland (See Figure 3). Variations within land use were present across sites, but for all sites, the combination of forested land and agricultural land comprised the vast majority of land cover (range: 74.7-96.0%, mean: 88.6%). There were no notable differences in the percentage of forested land versus agricultural land when comparing beaver sites to control sites.

Figure 3

Land Use Within Site Watersheds



Bioacoustic Sampling

Passive bioacoustic monitoring using autonomous recording units (ARU) were chosen to capture both avian and bat vocalizations. This method was primarily chosen due to its ability to record for long periods of time and the ability to schedule recording sessions. Additional benefits of ARUs include a reduction in habitat disturbance, minimizing observer bias, and capturing evidence of difficult to observe species (La et al., 2016; Teixeira et al., 2019). Furthermore, stationary recording units are more effective at accurately documenting bat species presence than traditional walking or driving transect audio recordings (Stahlschmidt & Brühl, 2012). ARU deployment is also more cost effective and results in greater volume of recording events with less in-person time requirements (La et al., 2016; Teixeira et al., 2019).

Four SongMeter Mini Bat (Wildlife Acoustics, Inc., Maynard, Massachusetts, USA) ARUs were deployed during each session. At each site, one ARU equipped with an acoustic stub microphone, and one ARU with only the pre-installed ultrasonic microphone were deployed. Whenever possible, the units were installed on the same tree or PVC post, at least 2 meters above ground or water surface, and 4 meters wherever possible. Units were aimed towards clearings along the riparian channel or out over beaver ponds and kept clear from interfering branches and leaves. Units were aimed away from known sources of persistent background noise such as running water, roads, or farming activity whenever possible. Recording parameters were scheduled and defined using SM Mini/Micro Configurator software (Wildlife Acoustics, Inc., Maynard, Massachusetts, USA) and activated in the field using the Song Meter Configurator iPhone app (Wildlife Acoustics, Inc., Maynard, Massachusetts, USA) where time, date, and GPS locations were updated once the units were installed.

Ultrasonic ARUs for bat vocalization capture were programmed to the system default settings, recording from 30 minutes prior to sunset to 30 minutes after sunrise subject to ultrasonic sound triggering. The default recorder settings (Full spectrum sample rate: 256kHz, Minimum trigger frequency: 16kHz, Maximum recording length: 15 seconds, Trigger window: 3 seconds) and recording range were chosen due to a lack of regionally specific published data or consensus within the literature. Because these recordings were subject to triggering, the number of minutes recorded per day was not consistent across sites (Beaver sites- Min: 100.4 minutes, Max: 670.1 minutes, Ave: 345.9 minutes; Control sites- Min: 33.0 minutes, Max: 773.8 minutes, Ave: 230.7 minutes).

Acoustic ARUs for non-bat vocalizations were programmed to record 1 minute of every 10 minutes, meaning units would record for 1 minute and be off for 9 minutes. During session 1, recordings were scheduled from 0600 to 1700 each day, yielding 64 minutes of recordings per day and 416 minutes (approximately 7 hours) of recording per deployment. During sessions 2 and 3, to minimize bias against nocturnally or irregularly vocalizing birds, acoustic ARUs were reprogrammed to record 0000 to 2400 daily (La et al., 2016). This yielded 144 minutes of recordings per day and 936 minutes (approximately 16 hours) of recordings per deployment. The default recorder settings (Sample rate: 24000 kHz, Maximum recording length: 60 s, Left and Right channel gain: 18 dB) were chosen as per manufacturer instructions for soundscape recordings (Wildlife Acoustics, Inc., Maynard, Massachusetts, USA). The 1-of-10-minute recording frequency was chosen based on previously published literature that found average species identifications at 1-in-10-minute intervals approached 97% correlation with the Acoustic Complexity Index for a given site (Cifuentes et al., 2021; Cole et al., 2022). This reduction in overall sampling volume, as compared with continuous data recording, decreases processing time, data storage needs, and increases analysis efficiency (Cifuentes et al., 2021; La et al., 2016).

Camera Traps

Camera traps were installed at each site at the same time the ARUs were installed. Two cameras were set up at each site, using three different brands of cameras, two StealthCam STC-G42NG (GSM Outdoors Inc., Texas, USA), one Reconyx Hyperfire 2 (Reconyx Inc., Wisconsin, USA) and one Browning BTC-5PXD (Browning North America, Missouri, USA). At beaver ponds, one camera was aimed at the pond to track pond activity, and one was aimed across the dam to capture travel on or around dams. At control sites, one camera was aimed upstream and one downstream to capture stream activity. For all camera traps, cameras were installed on nearby trees between 0.5-1 m above the ground, unless no trees were available to meet trap criteria. In these situations, either a PVC pipe or found piece of wood was sunk into the earth or dam structure and the camera was installed at least 60 cm above the water level. Vegetation was cleared around each camera whenever possible to reduce obstructions. Each camera was programmed to a setting of a three-photo burst and 30-second pause between triggers. Despite a lack of specific protocols for camera trap positioning and programming, the deployment methods and camera settings were within established parameters for capturing wildlife activity (mean deployment height: 80.3 cm, trigger delay range 0-60 min) (Burton et al, 2015).

Water Metrics

For all beaver ponded streams, samples were taken both in the pond and downstream of the dam, no more than 20 m below the dam, depending on access. At one site, Unnamed Creek 8-3, access to the stream 20 m below the dam was not possible, so the downstream samples were collected at the nearest access point, which was 986 m downstream. For all control streams, samples were taken at only one location, which was consistent across the study.

For all sites, turbidity was the first water sample collected, before any additional sediment disturbance via sampling activity or movement in the water could impact the readings. Turbidity was measured using a FieldMaster 120-cm turbidity tube (Science First, Florida, USA). At beaver ponded sites, samples were first collected at the downstream sample sites and then at the pond site. At all sites, the tube was placed into the water with the drainage tube locked, facing upstream, until the entirety of the tube was filled with water. The tube was then taken onto land where water was slowly released from the drainage tube until the Secchi disk at the bottom was clearly visualized when looking down through the long axis of the tube. This value was recorded in centimeters.

Both ponds and streams were measured at their deepest point. Thalwegs were identified for each stream and beaver ponds were surveyed for their deepest point through repeated measuring. One site, Fall Creek, experienced the rebuilding of the dam between September and October that was too deep to accurately measure with the available equipment. An estimation of at least 2 m of depth was made based on the height of the dam downstream and the water depth at the edge of the pond being well over the top of chest waders (approx. 1.2 m).

For all sites, water temperature was recorded at 10 cm below the water surface and at the bottom of the waterbody using a submersible Fishpond Riverkeeper digital thermometer (Fishpond, Colorado, USA). Both surface temperatures, measured at 10 cm below the water surface, and bottom temperatures were collected to determine if thermal gradients exist in deeper bodies of water. If a pond or stream depth was not deeper than 10 cm, the same temperature reading from 10 cm “surface” was also recorded for the “bottom” measurement.

For all sites, conductivity was measured at the water’s surface using Oakton Instruments ECTestr11 Dual Range Conductivity Meter (Environmental Express, South Carolina, USA). The probe was calibrated prior to the start of the sampling season. At each site, the probe was placed in an undisturbed portion of water and held in place, with the probe tip fully submerged, until readings stabilized. This value was recorded.

Data Storage

For audio files and camera trap data, all files were labeled by session, day, and site name. For acoustic recordings, files were only kept if there was a matching timestamp at both locations. This served to remove any bias from deployment or recovery intervals and provided a one-to-one comparison of total recording events per site pair. Audio files that required merging for analysis purposes were modified using Audacity software (Muse Group, Limassol, Cyprus). No audio files were modified or edited beyond being compiled, by day, into a single audio file.

Data Analysis

Ultrasonic recordings were analyzed using Kaleidoscope Pro software (Wildlife Acoustics, Massachusetts, USA). Kaleidoscope Pro is a paid software platform that specializes in pattern-matching ultrasonic bat calls. Automatic bat species identification analysis was completed using preset parameters for species present in Wisconsin, USA. One pair of ultrasonic recordings (Session 3, Fall and Coon Creeks) were limited by interfering and obscuring noise. The data from this session was run through various alternative parameters and analysis in an effort to render the files clear enough for species identification. Despite working directly with technical assistance from Wildlife Acoustics, this data was unusable and therefore removed from the study.

Acoustic recordings were analyzed for bird call identification using BirdNET v1.5.1 software (Center for Conservation Bioacoustics, Cornell Lab of Ornithology, Cornell University, New York, USA). BirdNET software is a free bird sound analyzer that utilizes pattern matching and deep learning to identify audio recordings of avian species. All audio files for a given day and location were merged into one .wav file for the purposes of BirdNET analysis. Preset parameters were used, except for analysis by location (which utilized site-specific GPS coordinates). Analysis was not sorted by date to eliminate climate-based variation in expected species arrival, migration timings, and vagrants. Confidence levels were set to a minimum of 50%, as recommended by multiple studies (Biffi et al., 2024; Pérez-Granados, 2023; Wood et al., 2021).

Camera trap images were analyzed manually by tallying identifiable species. Animals identified multiple times within a five-minute window from their first appearance were excluded from the count. Unidentifiable mammals and birds were placed in separate “unidentified” categories. Humans were tallied when present. Additionally, any species visually identified while working at a site was documented in the field and compiled with the camera trap data.

Data and statistical analysis were completed using both Excel (Microsoft Corporation, Washington, USA) and R Studio (Posit PBC, Massachusetts, USA) software. Species richness was calculated for all sites using avian species identification data. Paired t-tests were used to compare all beaver and control site data. Species accumulation curves were also calculated for each site, by calculating the running total of “new” species identified by day, over the course of the 21 days of sampling. A pairwise t-test was conducted on bat data to compare the frequency of bat call activity at beaver impounded sites versus free-flowing sites. Additive linear mixed effect models were used to analyze temperature and turbidity data. This model was chosen to address the fixed effects (date, sample location, pond depth, precipitation, land use) and random effects (site pairs) to determine if there is a statistically significant difference in these metrics between beaver and control sites.

Limitations

One of the biggest limitations of this study, and future studies, is access to beaver dams and safeguarding dam structures for the duration of the study period. Dams located on public land are subject to trapping, site interference, dam removal and/or damage. Private land sites are difficult to identify, require forming and maintaining landowner relationships, and can be subject to scheduling conflicts. Wisconsin beaver management regulations do not require landowner permission if there is perceived damage to adjoining properties, as such, this limits the security of dam sites that cross or share property boundaries. Trout streams in Wisconsin are also managed to remove beaver dams through Wisconsin DNR partnerships with the USDA, both on public and private lands. Lastly, it is legal for members of the public to remove or damage beaver dams on public land. At least one beaver site in this study was negatively impacted by human interference. The Fall Creek dam was notched by an unknown party in April and remained in that state, despite visual confirmation of beaver activity, until September when the dam was rebuilt approximately 40 m downstream. This dam was again notched after the final sample collection in October.

Several external factors also limited or impacted sample collection. At three sites (Unnamed Creek 8-3, Unnamed Creek 7-12, and Wilson Creek) the location of beaver ponds and access points resulted in recording units being installed proximate to roads (minimum distance 22 m) which resulted in frequent recordings of road and vehicular noise. It is unclear how many bioacoustic calls were obscured or blocked by vehicle noise. One location, Dienhammer Creek, was located near frequently used hiking trails and a youth summer camp facility. This resulted in frequent human disturbance at the site, despite efforts to move equipment both upstream and downstream by at least 60 m. These frequent human incursions may have reduced animal utilization of this site and resulted in a much higher incidence of humans captures on both camera traps and ARU units. The small number of available recording units (2 ultrasonic, 2 acoustic) limited the ability to concurrently measure all sites within the study. Randomizing the sample collection dates by session was an attempt to minimize bias that could be amplified by a regular or repeated scheduling pattern. Finally, two acoustic ARUs failed to record any data during session 1 at the Little Waumandee and Waumandee sites. This failure was attributed to a programming problem and no avian call data was collected at either site for the entirety of session 1.

Chapter IV: Results

The purpose of this study was to better understand the physical and biological impacts of beaver dams on streams in northern Wisconsin. As such, data was collected for numerous water quality metrics including depth, temperature, turbidity, and conductivity. To address the biodiversity impacts of beaver dams, both ultrasonic and acoustic ARUs and camera trap devices were used to measure species richness and diversity at each site. Additional data was collected on stream morphology, including stream grade, watershed size, stream order, and WIDNR trout stream classification status. Land use, vegetation cover, and precipitation patterns were also tracked over the course of the study. Statistical analysis was completed in both Excel and R Studio.

Dam breaches or deterioration occurred at four of the six sites over the course of the season, potentially reducing water residence times and increasing connectivity between ponds and downstream stretches. Dam breaches are natural occurrences, especially in spring with large precipitation or flood events, and dams are not always repaired or rebuilt. Given that this is a natural part of beaver activity on streams, that breached or overtopped dams can still retain water on the landscape, and that effects of dam presence on the broader ecological community are likely to persist for some time after beaver maintenance has ceased, we did not remove sites from the study in response to changes in dam integrity.

Waterway Morphology

Beaver dams ranged in length from the smallest dam at 2.13 m (Beaver Creek) to the longest at 353 m (Unnamed Creek 8-3). Pond depths ranged from the shallowest measure of 24.13 cm (Little Waumandee Creek) to the deepest at over 160 cm (Fall Creek). Control stream depths ranged from 11 cm (Unnamed Creek 7-12) to 134 cm (Wilson Creek). Based on mean values to account for changes in morphology over the course of the study (See Table 3), dam length and pond depth were not correlated ($t = 1.047$, $df = 4$, $p = 0.354$). Although deeper ponds tended to have more shallow downstream depths, that relationship was also not statistically significant ($t = -2.483$, $df = 4$, $p = 0.068$).

Table 3

Mean Dam Length and Water Depth During the Study

Pair	Mean dam length (m)	Mean pond depth (cm)	Mean downstream depth (cm)	Mean control stream depth (cm)
AW	5.28	50.25	52.75	99.75
FC	8.37	74.00	54.75	41.63
GG	26.97	103.83	30.00	74.83
UU	353.00	92.38	31.25	30.00
BD	5.17	44.38	63.38	23.50
LW	8.26	71.91	26.74	44.29

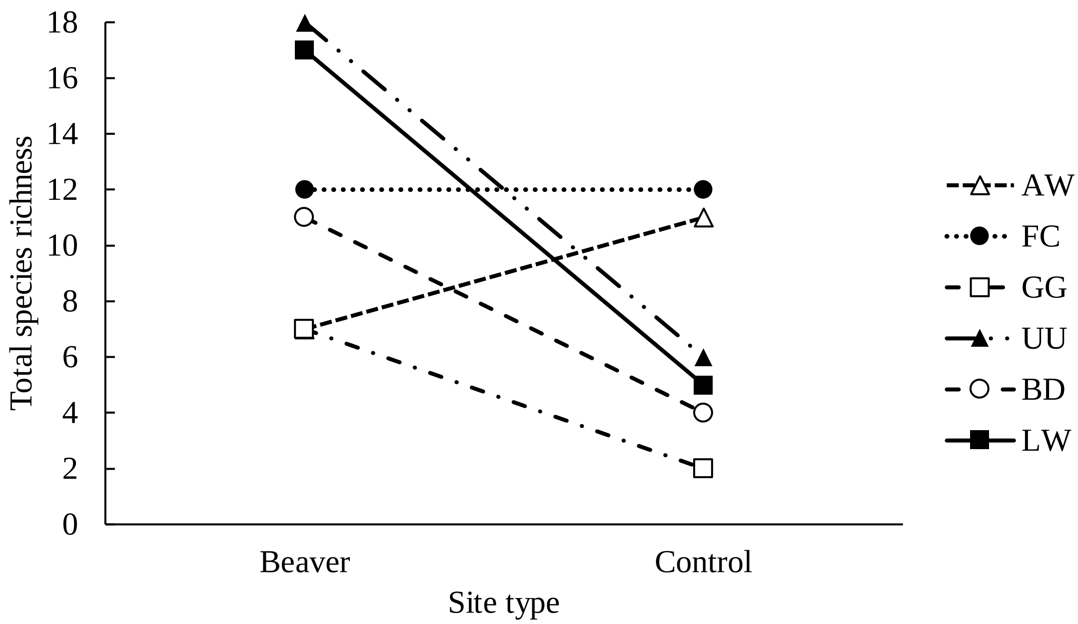
Biodiversity

Cumulatively, no differences in biodiversity were identified between beaver ponds and control streams. A total of 163 bird species were identified over the course of the study. Of those, 149 species were found across all beaver pond sites while 147 were identified across all control sites. Sixteen species were unique to beaver pond sites, and 14 species were found only at control sites. Camera traps captured 11 different species across beaver pond sites but only seven at control stream sites.

Species richness was calculated for all sites using only avian audio identification data. The mean richness was 3.66 (variance 0.036) at beaver sites and 3.48 (variance 0.168) at control sites. Using paired t-test, no statistically significant differences were found between beaver and control sites ($t = 0.908$, $df = 5$, $p = 0.202$). Camera traps recorded both terrestrial and avian species. The species richness via camera traps at beaver ponds was, on average, 5.3 (-0.316, 10.983) species greater than species richness at control sites, however, this difference was not statistically significant when corrected for multiple comparisons ($t = 2.029$, $df = 5$, $p = 0.49$; See Figure 4).

Figure 4

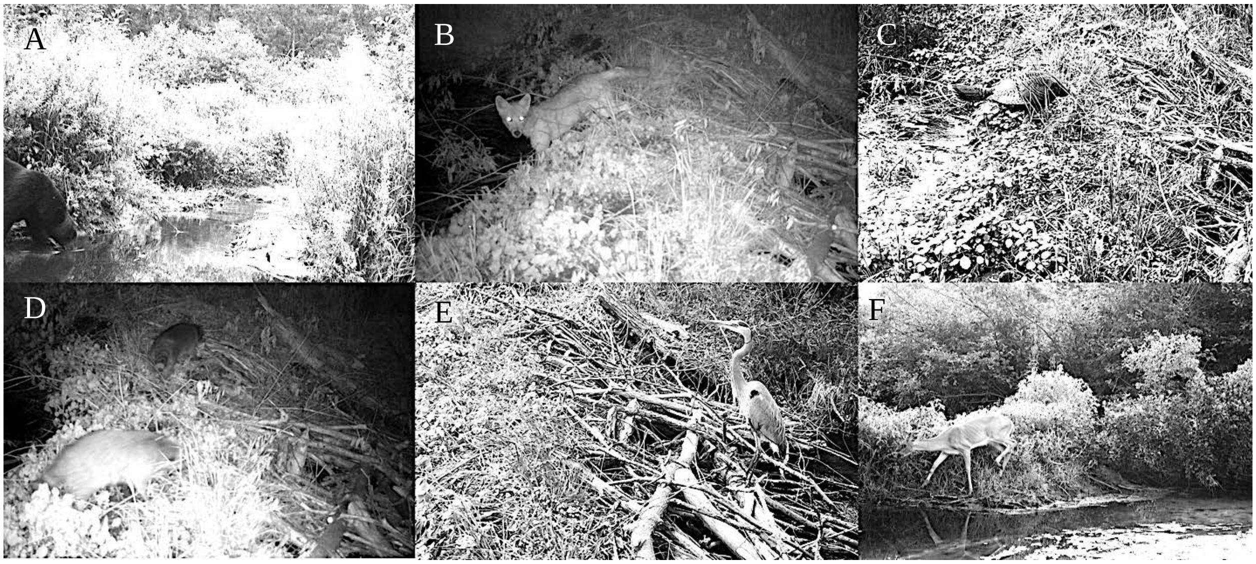
Camera Trap Species Richness by Pair and Site Type



An increase in species diversity at beaver ponds was noted, primarily due to terrestrial mammal use, such as white-tailed deer (*Odocoileus virginianus*), American black bear (*Ursus americanus*), red fox (*Vulpes vulpes*), raccoon (*Procyon lotor*), various squirrel species (*Sciurus spp.*), muskrat (*Ondatra zibethicus*) and Eastern wild turkey (*Meleagris gallopavo silvestris*) as well as increased waterfowl presence (See Figure 5). Of these species, bear, turkey, and fox were only identified at beaver sites. Squirrel species were only identified at control sites. Deer, muskrat, and raccoons were present at both sites at relatively equal frequency which is an expected finding given the generalist nature of these species.

Figure 5

Dams Used as Travel Corridors by Terrestrial Species



Note. Species documented included (A) black bear (B) red fox (C) wild, (D) raccoon (E) great blue heron, and (F) white-tailed deer.

Lastly, beaver ponds have been previously documented as preferred waterfowl habitat, particularly for dabbling duck species like mallard (*Anas platyrhynchos*), wood duck (*Aix sponsa*), green-winged teal (*Anas carolinensis*), and gadwall (*Maraca strepera*), due to the higher incidence of shallow, still water and increased food abundance leading to increased brood survival rates (Nummi & Hahtola, 2008). Of these four species, only the gadwall was not found at beaver ponded sites. The remaining three species were more frequently identified at beaver ponds than at control streams (mallard 6.25:1, wood duck 8.3:1, green-winged teal 92.0:1). These findings are in keeping with published literature suggesting beaver ponds create preferential habitat for some waterfowl species (Nummi & Hahtola, 2008). Evidence of this is supported by camera trap data exhibiting multiple instances of hen waterfowl with ducklings at beaver ponds, while none were documented at control sites (See Figure 6).

Figure 6

Beaver Ponds as Waterfowl Nursery Habitat

Note. Top: Mallard hen with ducklings at Unnamed Creek 8-3 beaver pond, Bottom: Wood duck hen with ducklings at Fall Creek beaver pond.

Birds

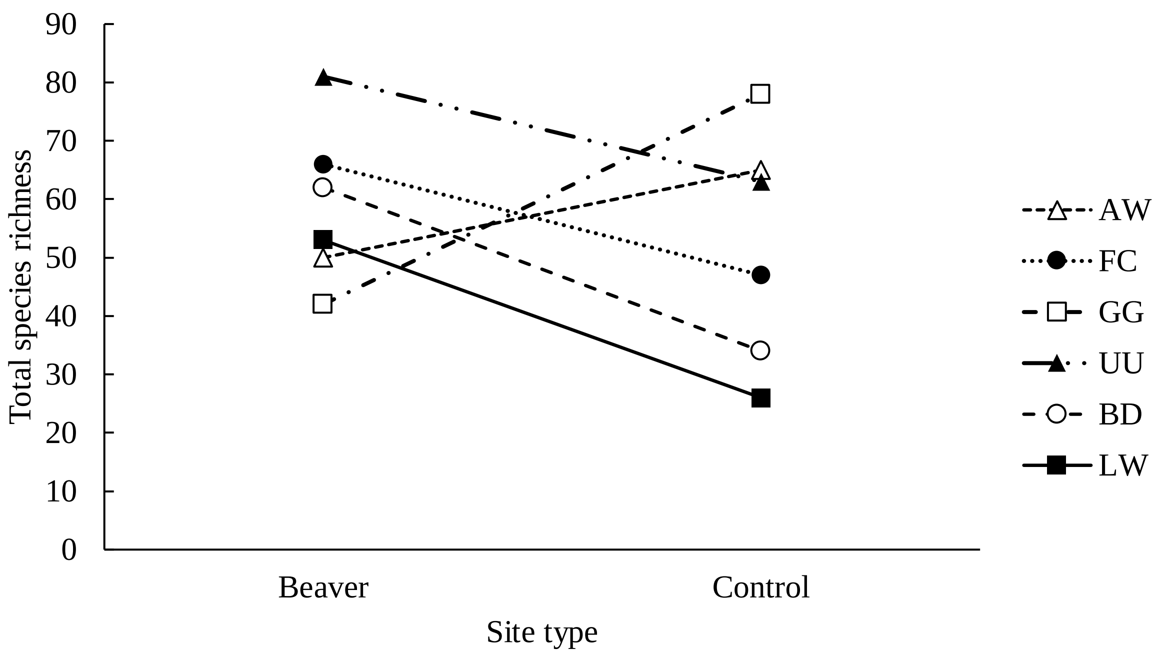
Approximately 443 hours of soundscape recordings were analyzed for bird songs and calls. Between 26 and 81 avian species were detected at each site, with a combined total of 163 unique bird species recorded during the study.

Avian Species Richness

Using a paired t-test, species richness for avian species was not found to be significantly different between beaver and control sites ($t = 0.638$, $df = 5$, $p = 0.276$). A general trend of greater diversity at beaver sites was noted but is not consistent across pairs (See Figure 7).

Figure 7

Bioacoustics Avian Species Richness by Pair and Site Type



A total of 163 avian species were identified across the study, 133 of which were recorded at both beaver and control sites. Analysis of the unique bird species identified at each site type yielded 31 species found only found at beaver impounded sites, as compared to 24 species only found at free-flowing sites. However, these counts included multiple species that were only recorded once during the entire sampling period. To limit the possibility of misidentifications, all single-call identifications with an identification confidence level less than 0.80 were removed. This resulted in 16 unique species at beaver ponds and 14 unique species at free-flowing streams. Bird species found only at beaver impounded sites tended to be insectivorous wetland species, whereas species found only at control streams were more likely to be omnivores and less likely to require or prefer wetland habitats (See Table 4).

Table 4

Characteristics of Avian Species Found at Only One Type of Site

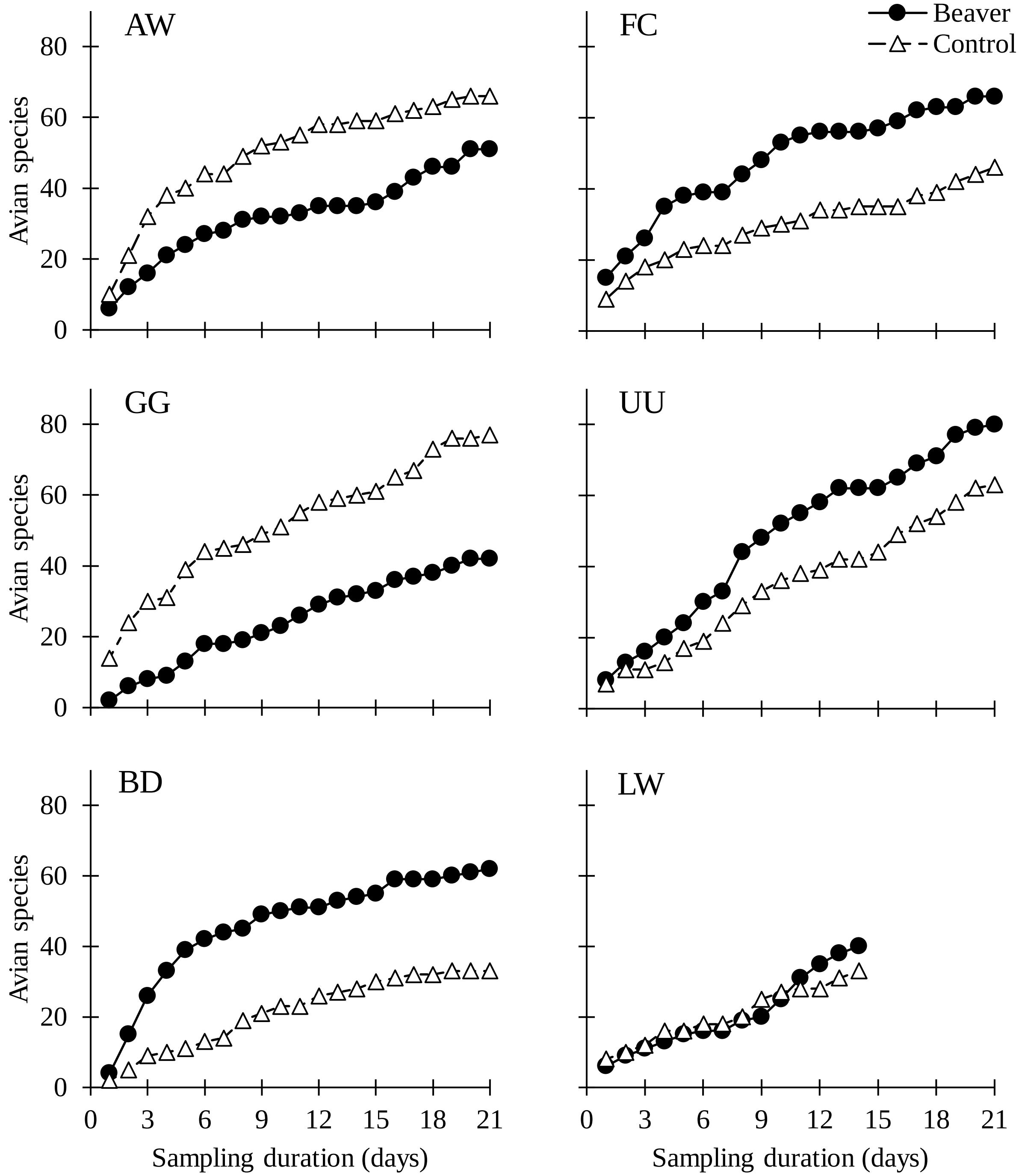
Characteristic	Category	Control-only species ($n = 14$)	Beaver-only species ($n = 16$)
Diet	Herbivore	1 (7.14%)	2 (12.50%)
	Omnivore	6 (42.86%)	1 (6.25%)
	Insectivore	4 (28.57%)	11 (68.75%)
	Carnivore	3 (21.43%)	2 (12.50%)
Preferred habitat	Wetland	4 (28.57%)	16 (100%)
	Other	10 (71.43%)	-
Nesting location	Burrow	-	1 (6.25%)
	Cavity	-	3 (18.75%)
	Ground	7 (50.00%)	7 (43.75%)
	Shrub	1 (7.14%)	-
	Tree	5 (35.71%)	5 (31.25%)
	Other	1 (7.14%)	-
Portion of range	Breeding	7 (50.00%)	6 (37.50%)
	Migratory	5 (35.71%)	6 (37.50%)
	Non-Breeding	1 (7.14%)	3 (18.75%)
	Year-Round	1 (7.14%)	-
	Invasive	-	1 (6.25%)

Species Accumulation Curves

No site, regardless of type, exhibited a plateau in avian species identification over the course of the study (See Figure 8). Four of the six paired sites showed higher accumulation curves at beaver ponds, three of which were higher for the duration of the study. Only the Waumandee paired sites showed a change in trends, with the control site starting out with a higher accumulation curve and the beaver site surpassing it nine days into sampling. Two sites, the Gilbert and AnWil pairs, showed a clear trend of the control sites exhibiting higher accumulation curves than their paired beaver pond sites.

Figure 8

Avian Species Accumulation Curves by Site Pair



Note. LW curves only cover 14 days due to an equipment malfunction during the first session.

Two sites were sampled during peak migration periods, the Waumandee pairs during peak spring migration, and B3 pairs during the fall migration (See Figure 2). However, acoustic recording units at the Waumandee pairs during this first session experienced programming errors that resulted in no avian acoustic data being recorded.

Bats

All seven bat species known to occur in the study area were detected over the course of the study. The endangered northern long-eared bat was excluded from analysis because fewer than 15 recordings of this species were documented in total, across all sites. On average, bat activity for the remaining six bat species combined was 72.9% (27.1%, 118.8%) higher at streams impounded by beavers than at paired control streams ($t = 4.09$, $df = 5$, $p = 0.005$). Taken separately, the average activity of each species was 44.1–351.9% higher at beaver sites (See Table 5), although none of these species-specific differences between beaver impounded sites and free flowing streams were statistically significant.

Table 5

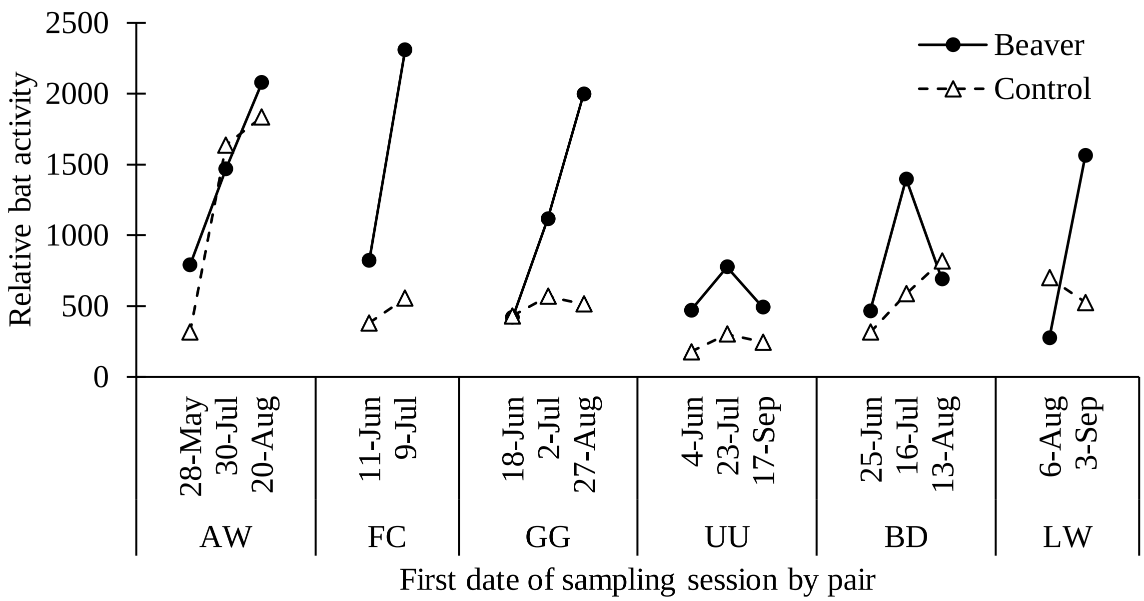
Percent Increase in Bat Activity by Species for Beaver Pond Locations

Bat species	Increase in mean activity (95% CI) at beaver sites relative to control sites
Big brown (*Eptesicus fuscus*)	55.7% (-57.4%, 168.8%)
Silver haired (*Lasionycteris noctivagans*)	63.3 (-44.6, 171.2)
Eastern red (*Lasiurus borealis*)	138.5 (-143.1, 420.2)
Hoary (*Lasiurus cinereus*)	90.7 (-77.0, 258.4)
Little brown (*Myotis lucifugus*)	44.1 (-169.0, 257.1)
Tricolor (*Perimyotis subflavus*)	351.9 (-29.8, 733.5)

The total number of bat calls recorded for beaver pond sites was 17,917 while control site totals were 9,927. Call frequency was calculated by site (See Figure 9). Bat call frequency increased at all sites from July through September, which corresponds with established volancy and pre-hibernation hyperphagia periods in Wisconsin (Bureau of Natural Heritage Conservation, n.d.). Call frequency was lowest for all sites between May and June, which corresponds with parturition and pre-volancy periods in the region (Bureau of Natural Heritage Conservation, n.d.).

Figure 9

Count of Bat Call Activity by Site



Species richness for bat species was not significantly different by site type ($t = 0.542$, $df = 5, p = 0.305$). Northern long eared bats, which are listed as federally endangered by the US Fish and Wildlife Service, were only identified at three of the 12 sites, Annis (beaver), Coon (control), and Little Waumandee (beaver) Creeks, while the remaining 6 species were identified at all sites, regardless of type.

Water

Conditions at beaver impoundments and free-flowing control sites were similar for all metrics studied. Across all sites and time periods, the average water temperature was 13.03°C, the average transparency tube reading (turbidity) was >80.9 cm, and the average conductivity was 386.4 μS/cm.

Temperature

Water temperature was expected to be warmer in beaver ponds than in free-flowing control streams, however water temperatures varied greatly across all sampling sites. Both the coldest water temperature recorded across the study was 8.3°C (Fall Creek) and the warmest temperature 20.3°C (Unnamed Creek 8-3) were recorded in beaver ponds. To determine if water temperature was linked to sample location type (beaver pond, downstream, or control) or pond depth a linear mixed effect model was used. Comparing water temperature to sampling location, water depth, and site pair, no statistically significant difference in water temperatures was found between either beaver ponds ($p = 0.210$) and control stream temperatures or downstream of beaver ponds ($p = 0.109$) and control stream temperatures (See Table 6). There was also no statistically significant link between water depth and water temperature ($p = 0.739$).

Table 6

Water Temperature by Location, Depth, and Site Pair

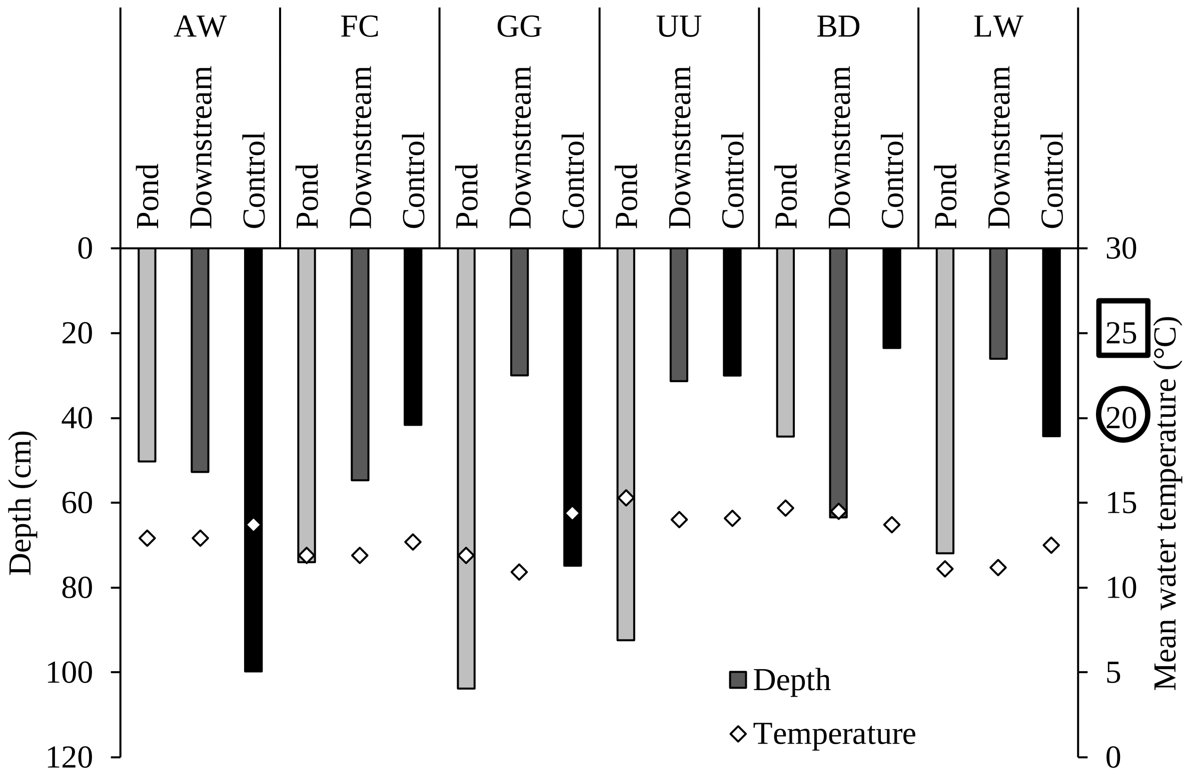
Variable	Estimate	Standard error	Test statistic	P value
(Intercept)	*12.9*	*0.877*	*14.7*	*<0.001*
Location downstream	-1.43	0.910	-1.57	0.109
Location pond	-1.22	0.964	-1.27	0.210
Depth	-0.004	0.012	-0.334	0.739
FC pair	-1.55	1.17	-1.32	0.190
GG pair	-1.54	1.17	-1.32	0.195
UU pair	1.30	1.21	1.08	0.286
BD pair	-2.70	1.22	-2.22	0.030
LW pair	-1.42	1.20	-1.18	0.241

Note. Greyed out rows are not of interest as they are random effects of pairs.

Across all study sites, water temperatures rarely rose above 16°C, accounting for less than 12% of water temperature measures. There were no links between higher water temperature readings and air temperature, collection date, or site type. While not statistically significant, the estimated water temperatures were colder in both beaver ponds (-1.22°C) and downstream sections (-1.43°C) than control streams.

Figure 10

Average Water Temperatures and Depths



Note. Circle indicates trout preferred maximum temperature (20°C), square indicates trout critical thermal maximum temperature (25°C)

No site averaged water temperatures higher than 15.1°C at any collection location (See Figure 10). Temperature trends appear to be independent of water depth or collection location. The two sample locations with the warmest average water temperature were both within the UU pair, the beaver pond site on Unnamed Creek 8-3 (average depth: 92.38 cm) averaging 15.13°C and the control site on Unnamed Creek 7-12 (average depth: 30 cm) averaging 14.1°C. The two sample locations with the coldest average water temperatures were both located on the South Branch of Gilbert Creek, with the beaver pond (average depth: 103.83 cm) averaging 10.53°C and the downstream location (average depth: 30 cm) averaging 10.93°C.

Turbidity

To determine if external variables like weather or land use were linked to turbidity levels, a mixed effect model was run. This model for turbidity included the total percentage of land use within each watershed classified as agricultural and the total precipitation from the seven days prior to sampling. Both variables were chosen for their hypothesized impacts to erosion and stream turbidity. Precipitation was the only statistically significant ($p = 0.009$) variable (See Table 7). Neither the percentage of agricultural land use ($p = 0.553$) nor sampling location (downstream $p = 0.816$, pond $p = 0.956$) were statistically significant.

Table 7

Turbidity by Location, Percent Agriculture, Prior Precipitation and Site Pair

	Estimate	Standard error	Test statistic	*P* value
(Intercept)	*90.4*	*24.6*	*3.86*	*<0.001*
Location downstream	-1.990	8.55	-0.233	0.816
Location pond	0.473	8.55	0.055	0.956
Percent agriculture	0.235	0.393	0.597	0.553
Previous precipitation	-10.1	3.77	-2.68	**0.009**
FC pair	-33.1	11.9	-2.79	0.007
GG pair	-4.0	12.7	-0.315	0.754
UU pair	-37.8	1639	-2.24	0.029
BD pair	22.1	16.6	1.33	0.189
LW pair	6.57	12.1	0.544	0.588

Note. Greyed out data is not biologically meaningful as it only comparing one paired site to another.

To better quantify the significant precipitation impact on turbidity readings, monthly precipitation data was collected for each study site. May, June, July, and August were all wetter than the 30-year NOAA averages, with the cumulative sites averaging 16.1 cm of extra precipitation across these 4 months (Community Collaborative Rain, Hail and Snow Network, n.d.). Meanwhile, the months of September and October were well below the 30-year NOAA average, with abnormally low precipitation at all sites during the month of October, which encompasses the fourth water sample collection period (See Table 8). Notably, large precipitation events prior to water sample collection date resulted in markedly altered turbidity readings for two locations (Session 1: North Branch, Gilbert Creek, Session 2: Coon Creek). Markedly lower than average precipitation during October resulted in all turbidity readings during the 4th sample session measuring at 100 cm or greater clarity, which was significantly different from turbidity readings across all other sampling sessions.

Table 8

2024 Difference From 30 Year NOAA Average Precipitation (cm)

Site Pair	May	June	July	August	Sept	October	Total
AW	2.16	9.04	9.65	2.31	-6.88	-6.78	9.50
FC	0.38	9.19	5.51	4.42	-7.77	-6.68	5.05
GG	2.21	9.47	-3.73	2.46	-7.85	-7.24	-4.67
UU	0.43	8.99	1.75	5.72	-6.50	-7.14	3.25
BD	2.21	9.47	-3.73	2.46	-7.85	-7.24	-4.67
LW	2.34	5.21	4.34	4.47	-7.21	-7.29	1.85
Average	1.62	8.56	2.30	3.64	-7.34	-7.06	1.72

Conductivity

Statistical analysis was not completed on this data as the conductivity values between beaver ponds and downstream locations and control sites were nearly identical in most instances (See Table 9). Both the Beaver Creek Reserve and Fall-Coon sites did show marked differences in their conductivity readings between beaver sites and control streams, but the fact that they show opposite patterns in the direction of the difference suggests that this is not linked to beaver presence or absence.

Table 9

Conductivity (μS/cm) by Session and Location

Pair	Session	Pond	Downstream	Control
AW	1	580	580	570
	2	590	540	590
	3	580	580	590
	4	590	590	570
FC	1	410	410	210
	2	410	410	170
	3	420	420	220
	4	410	410	230
GG	1	560	560	530
	2	550	550	550
	3	540	550	530
	4	-	-	-
UU	1	120	140	140
	2	150	170	180
	3	160	160	170
	4	170	160	120
BD	1	40	40	140
	2	50	50	140
	3	50	50	140
	4	60	60	130
LW	1	630	630	640
	2	560	560	640
	3	640	600	640
	4	630	600	620

Chapter V: Discussion, Conclusion and Recommendations

The results of this study have begun to document the physical and biological impacts of beaver activity on streams in northwestern Wisconsin. In doing so, these findings illustrate the conservation potential of beavers for species of conservation concern, specifically the declining and at-risk bat populations in the state. Water temperatures in beaver ponds were expected to be higher than control stream temperatures, however the results of this study indicate that this is not the case. This information can begin to inform future beaver management policies and research, particularly those relating to beaver-trout relationships and dam removal programs. This study did not find increased species richness at beaver ponds, but did note increased trends in waterfowl brooding activity, wetland obligate avian species, and terrestrial species utilization of beaver dams. While these general trends were identified, the results lack the statistical power to say with confidence that beaver activity is linked to increased habitat use by specific species or animal groups. In total, these findings undermine existing negative perceptions about beaver dams increasing water temperatures and illuminate previously undocumented linkages between beaver ponds and bat activity. The results of this study also serve to focus future studies on the utility of beavers and beaver activity for other species of conservation concern and establish bioacoustic methodologies for the region.

Waterway Morphology

There was no consistent pattern in pond depth, downstream depth, or relationship to control stream depth across sites. In two instances, Annis and Beaver Creeks, downstream water depths were deeper than beaver pond depth, illustrating the common, but not compulsory, plunge pool effect found immediately downstream of some beaver dams (Bouwes et al., 2016). At three pairs, the control streams were deeper than both the paired beaver ponds and downstream stretches. This is likely related to geography and restoration projects rather than the presence or absence of beaver activity. For the Gilbert Creek pairs, the differences in depth are likely resulting from the south branch (beaver) location being proximate to the headwaters of the stream while the north branch (control) location has been undergoing traditional stream restoration work since the early 2000s. The Annis-Wilson Creek pair differences are due to differences in stream order, with Annis Creek being a smaller, headwater-type third order stream and Wilson Creek being a medium-large fourth order stream. Lastly, the Little Waumandee-Waumandee pair differences are likely related to both stream condition and installation of riprap. The Little Waumandee site is only slightly incised, flows through a narrow valley bottom and does not contain riprap along its banks, unlike the Waumandee site which is deeply incised and features extensive riprap on both banks.

There was very little consistency in dam length across sites and there was no relationship between dam length and pond depth. Both dam and pond morphology, along with downstream depths, are site specific and likely related to dam construction materials and stream incision state. Dam construction materials, mud/vegetation versus primarily woody material, along with geographic features like the size of the watershed and stream grade likely all factor into dam size and pond volume. Furthermore, stream channel features, such as connection to the floodplain, stream bank elevations, bank erosion, and the presence of riprap or other bank stabilization materials dictate the overall size, depth, and heterogeneity of beaver ponds. This corroborates previous studies suggesting that beaver dam and pond morphology is highly site specific (Brazier et al., 2021).

Land Use

The similarities in land use across the three counties and 12 study sites indicate that, in this case, land use is unlikely to be a differentiating factor for stream water quality in the region for the purposes of this study. Exceptions would include sites more proximate to developed regions or located in watersheds with less forested cover, however, beaver activity is less likely in these locations due to the increased probability of beaver-human conflict resulting in beaver and dam removal, which is expected given Wisconsin's liberal beaver removal policies. This pattern may not hold true in instances where land use variations are more pronounced across study sites or beaver management policies impact urban beaver populations.

Sample site proximity to high-traffic roads did not appear to negatively impact habitat utilization or species richness. In fact, of the two sites most proximate to high-traffic roads recorded higher than average species richness values. No sites were proximate to highly developed areas, though a number were subject to frequent human activity. Agriculture, residential areas, and nature preserves were present across multiple study sites.

Biodiversity

There were no statistically significant differences in species richness measures between beaver and control streams, indicating that both beaver ponds and free flowing streams are important, diverse, and well-used habitats on the landscape for avian, bat, and terrestrial species. Increases in species diversity of the animals captured using camera traps were noted at beaver pond sites, though the results were not statistically significant. These trends likely occur because beaver dams may be used as travel passages across streams and represent a consistent source of both water and food on the landscape (See Figure 5; Wikar et al., 2024). Ground foraging species like turkey also may have higher foraging success rates in the consistently wet soils surrounding beaver ponds or may find preferred food sources in these damp and hydric soils. These are areas to be considered for future research, specifically regarding species of conservation concern.

Bats

While overall bat activity was significantly increased at beaver ponded sites by an average of 73%, species richness across sites was largely the same across the study, with most bat species identified at all study sites. This indicates that all Wisconsin bat species utilize rivers, riparian corridors, and beaver ponds as travel thoroughfares and hunting grounds. The increase in bat activity over beaver ponds indicates that these habitats create advantageous conditions for bats via flat water, ideal echolocation conditions, high concentrations of emergent and flying insects, and persistent food availability.

The flat, nearly still water of beaver ponds provides bats with smooth, high resolution and low disturbance reflected signals during foraging via echolocation. Compared to the often uneven and inconsistent water surface in streams, particularly within riffles, echolocation signals are more likely to be altered or unclear, resulting in lower hunting success rates and higher energy outputs. The increased volume of water stored behind beaver dams, particularly as compared to free-flowing control streams, likely provides an increase in available insect biomass. Beetle and fly species larvae can inhabit both terrestrial and aquatic environments, while moths and butterflies are mostly terrestrial in their larval phase. The ability of beaver ponds to provide suitable habitat for a wide variety of insect species across multiple niches makes them an invaluable, dense source of food on the landscape.

Both factors are biologically significant as bat populations in Wisconsin and across the United States are facing population declines due to WNS, habitat loss, domestic cat attacks, and wind turbine linked fatalities. With Wisconsin having already lost nearly 95% of its cave-dwelling bats due to WNS alone (Wisconsin DNR, n.d.-a), methods to increase survival rates are increasingly critical. The data collected in this study represents novel findings in both the United States and in Wisconsin and are consistent with expectations that beaver ponds provide increased foraging opportunities and ideal echolocation conditions (Ciechanowski et al., 2010; Hooker et al., 2024; Nummi et al., 2011). These results indicate that beaver ponds and beaver activity can be an important aspect of bat conservation efforts. Given this, beaver activity and pond creation can and should be strategically leveraged to support bat populations across the region.

Birds

Although bird species richness did not statistically significantly differ between beaver ponds and control sites, species accumulation curves indicate that the study's sampling effort was insufficient to completely capture species richness. Moreover, the composition of the avian community at beaver ponds likely differs meaningfully from the species using control streams.

Accumulation Curves. Bioacoustic analysis and species accumulation curves are an important component to this work as it helps demonstrate which species are utilizing study sites over time. Given the relatively new technology and application of ARUs for avian species composition and richness, these accumulation curves can help inform future ARU deployment techniques and timelines in similar habitats.

The lack of a well-defined plateau in species identification curves across all study sites suggests that the total number of days sampled (21) was insufficient to estimate overall avian species richness in these habitats (See Figure 8). This could, in part, be linked to migration and/or weather patterns bringing new species into study areas over time. The lack of plateaus could also be linked to the fragmented nature of sampling, with three discrete, randomly assigned weeks spread over five months, rather than at regular or more frequent intervals. Additional analysis on bioacoustic deployment frequency, spatial arrangement, and peak sampling periods would better inform ARU deployment methods. Nevertheless, the differences in both avian species richness and diversity appear to be idiosyncratic to the specific sites sampled, rather than a clear indication that beaver ponds and wetlands harbor higher avian diversity.

Community Composition. In analyzing the cohort of avian species identified only at beaver sites, the most common traits were obligate or facultative wetland habitat requirements and insectivorous diets. This suggests that beaver pond creation generates wetland-type features that are otherwise absent at control stream sites. In keeping with this study's findings regarding bats, beaver ponds appear to provide insect-rich habitats that benefit insectivorous species of birds.

Water

Arguably, the most important finding of this study is that beaver ponds do not increase water temperatures in this region. Current beaver and stream management policies are predicated upon the idea that beaver activity negatively impacts trout through increasing water temperatures. However, efforts to enhance trout habitat by removing beavers are likely to be ineffective, because beavers do not appear to be significantly impacting water temperatures.

Temperature. There were no statistically significant differences in water temperatures in beaver ponds compared to either downstream reaches or control streams. In fact, the data suggests that temperatures at paired sites are more similar to one another than sites sharing beaver or control status. This may indicate that watershed-level factors like overhead cover, geology, slope/grade, proximity to headwaters, hydrology, and terrain features have greater impacts on water temperatures than the presence or absence of beaver dams. This could also be an indicator that beaver ponds provide increased connectivity to groundwater supplies, resulting in lower-than-expected temperatures.

These findings are both biologically significant and important for informing state management policies related to both beaver and trout. Because trout are temperature sensitive species, with thermal maximums between 20-25°C, Wisconsin state trout management policies have prioritized beaver removal from trout streams based on the assumption that beaver dams increase water temperatures beyond trout thermal maximums both in ponds and downstream of dams (See Figure 10; Wisconsin DNR, 2015; Wisconsin DNR, 2019). This data undermines the claims that beaver activity negatively impacts water temperatures and should help inform beaver management policies to more accurately reflect the impact they have on streams.

Turbidity. The primary source of suspended sediments, or turbidity, in streams is erosion from the surrounding watershed and streambanks. This can be a natural process or one intensified by land use practices like agriculture and development. Sediments in waterbodies stay suspended when water velocity is high, resulting in higher turbidity readings. In slow or still waterbodies, sediments are expected to fall out of suspension due to low water velocity's inability to transport or suspend sediments. Beaver ponds are traditionally characterized by low-velocity conditions and deposition of sediments behind dam structures is expected.

We did not see the expected trend of decreased turbidity through sediment deposition in beaver ponds and downstream from beaver ponds. There was also no statistically significant link between turbidity and the percentage of agricultural land use surrounding each site, despite all study sites being classified as primarily agricultural and forested land types. This data does indicate that precipitation, or the lack thereof, has a marked impact on overall stream water turbidity, regardless of beaver damming activity. The late-season low-precipitation conditions likely reduced sediment entering streams in runoff and resulted in low water velocities across all study sites, rendering all streams within the study unable to keep sediments suspended within the water column.

Conductivity. Although pilot study data in 2023 indicated that conductivity values were significantly different between upstream ponds and downstream stretches (Dean & Beston, 2024), no statistically significant patterns were observed in the current study. Unlike turbidity, which is a function of particulate matter suspended in the water, conductivity encompasses compounds dissolved in water. Given that beaver dams are porous structures, with water moving through, over, and around them, it is perhaps not surprising that water downstream of a dam would carry the same dissolved compounds as the water behind the dam.

At the two pairs of sites that had a marked difference between the beaver and control streams, the control stream had higher conductivity in one case and lower conductivity in the other. This suggests that the differences between beaver pond and control stream values are likely a function of watershed-specific factors, including underlying geology and non-point source pollutants carried in runoff, such as road salt and fertilizer.

Management Implications

Beavers are managed as a nuisance species in Wisconsin and are actively removed from trout streams through WIDNR programs and regulations, but the results of this research indicate that current management practices may be inadvertently harming species of conservation concern, bats in particular. These results highlight the lack of research on the impacts of an ecosystem engineer like the beaver on other species. This study's findings also indicate that statewide beaver removal practices as a means to protect trout against rising water temperatures are not universally supported by the data.

Beaver

Species and habitat impact models could be created to identify specific streams or locations where beaver activity would be most beneficial, either to specific species of conservation concern or where in-stream complexity is lacking. State support and subsidizing of non-lethal beaver and water management tactics, like Beaver Deceivers and pond leveling devices, would serve to facilitate coexistence while promoting beaver-related ecosystem services. In these instances, beavers are allowed to stay on the landscape while modifications to their dams or pond levels mitigate potential damage or encroachment on key structures like culverts, driveways, roads, or buildings. Currently, there is only one certified installer of water control devices in Wisconsin, which limits the installation and scope of these devices. Consequently, Wisconsin landowners who may opt for coexistence are left without access to non-lethal management tools or support and therefore resort to lethal trapping as the only available option. Integrating awareness of these non-lethal techniques, along with training on installation across multiple government agencies and facilitating additional certified installers could provide viable options to landowners seeking coexistence. While conflict with infrastructure and landowners cannot be eliminated and is a very real concern, a beaver relocation program would serve to mediate conflict and apply beavers to targeted locations.

Given this study's evidence that beaver ponds do not increase water temperatures, a concerted effort must be given to redefine what criteria are necessary for beaver removal on trout streams and the role beaver activity has in healthy trout streams. Shifting trout and beaver management policies from their current adversarial nature towards a cooperative and collaborative one could serve to boost native brook trout populations and decrease funding spent on beaver removal practices and state-funded hatchery operation costs. Treating beavers as a valuable conservation tool and sources of fiscal savings would stretch conservation and restoration dollars to where they are more critically needed, reduce the burden of wetland and stream restoration projects on government agencies, increase wetland acres across the state and support species of conservation concern at little-to-no cost.

Bats

Given the critical condition of bat populations in Wisconsin, there is an urgent need to address habitat loss and factors that may promote WNS fatalities. While predation from domestic cats and fatalities linked to wind farms cannot be addressed through beaver management, habitat improvement, new habitat creation, and facilitating the availability of dense sources of preferred food can help support all bat species within the state. This study illustrated the positive impact of beaver activity on bat populations. Using beavers to create high-value habitats to benefit bat populations is a low-cost, low-maintenance conservation strategy that should be an area of future research in both Wisconsin and other locations facing bat population declines.

Known bat hibernacula sites near streams could be targeted sites for beaver relocation or reintroduction. Hibernacula with known lower temperatures could be prioritized to entice bats away from caves where higher air temperatures result in higher infection and mortality rates. Conversely, even where warm temperature roosts have been identified and continue to be selected by bats, increased densities of beaver ponds and wetlands in the area may provide enough nutritional support, at a low enough energy cost, to offset the increased risk of WNS fatalities. Supplemental bat roosting structures could also be constructed near protected beaver ponds or in established no-trapping areas to support both overall bat population growth and available, protected hibernacula.

Recommendations

Broadly speaking, the results of this research indicate that further analysis is required to fully understand the ways in which water, other species, and ecosystems are impacted by beaver activity. This additional research would serve to better inform management policies and practices while potentially creating pathways for beavers to be used as conservation and habitat restoration tools. Lastly, long term analysis of beaver impounded sites is logistically difficult and could benefit from protected status and increased landowner support.

Methods

Regarding data collection methods, my primary recommendations are focused on more frequent or continual sampling. Additional ARUs would allow for concurrent bioacoustic sampling across sites, potentially capturing more accurate species accumulation curves and allowing for one-to-one comparisons across all sites. For particularly large study sites, using additional ARU arrays would more accurately survey the site. Additional camera traps, deployed in an array around the perimeter of ponded sites and along stretches of streambank could better estimate terrestrial species utilization. Utilizing long-term monitoring equipment like temperature data loggers would allow for more accurate analysis of the thermodynamics of beaver ponds and better illustrate seasonal trends.

Future Research

The role of beaver ponds in creating food-dense habitats on the landscape, particularly those involving insectivorous species, warrants further study. Analysis of insect and invertebrate biomass production of beaver ponds versus free-flowing streams, particularly those critical to bat and other species of conservation concern, would be beneficial in quantifying the impact of beaver ponds on food webs and productivity. Zooplankton biomass analysis could further clarify food web linkages to species utilization of beaver ponds and illustrate what life stages of species, such as trout, most benefit from beaver ponds.

Damage to beaver dam structures that occurred over the course of the study may have reduced the magnitude of their effects, particularly on water quality metrics that are more responsive to short-term changes in flow. Increasing the number of sites monitored to increase the sample size of completely intact beaver dams would be useful in further clarifying the impact dams have.

Camera trap analysis indicated that there was increased biodiversity and habitat utilization by terrestrial animals near beaver ponded sites, particularly in areas of flooded forest. Additional research, utilizing a network of camera traps and ARUs, could better quantify habitat use patterns and species presence in these unique ecosystems. This could be of particular use in land management programs aimed at upland game species like ruffed grouse (*Bonasa umbellus*), eastern wild turkey (*Meleagris gallopavo silvestris*) and woodcock (*Scolopax minor*).

Lastly, any research that can monitor sites for changes across multiple years, and in varying settings would continue to improve local knowledge regarding the physical and biological impacts of beavers on ecosystems in Wisconsin. Expanding study parameters to include more counties, stream types, and beaver sites of differing ages would address land use variations and determine how ecosystem services provided by beaver ponds change over time.

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