Wisconsin Initiative on Climate Change Impacts

Coldwater Fish and Fisheries Working Group Report

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Coldwater Fish and Fisheries Working Group

Primary Authors

Matthew Mitro – WDNR, Science Services
John Lyons – WDNR, Science Services
Sapna Sharma – UW-Madison, Center for Limnology

Working Group Participants

Matthew Mitro – WDNR, Science Services – chair
Mike Bozek – UW-Stevens Point/Wisconsin Cooperative Fisheries Research Unit
Marty Engel – WDNR, West Central Region
Andy Fayram – WDNR, Central Office
Steve Greb – WDNR, Science Services
Laura Hewitt – Trout Unlimited
John Lyons – WDNR, Science Services
John Magnuson – UW-Madison, Center for Limnology
Frank Pratt Jr. – WDNR, Northern Region
Dave Seibel – WDNR, Northern Region
Sapna Sharma – UW-Madison, Center for Limnology
Brian Sloss – UW-Stevens Point/ Wisconsin Cooperative Fisheries Research Unit
Jana Stewart – USGS-Middleton
Jack Sullivan – WDNR, Science Services – sponsor
Gene Van Dyck WDNR, South Central Region
Jake Vander Zanden – UW-Madison, Center for Limnology
Dave Vetrano – WDNR, West Central Region
Jordan Weeks – WDNR, West Central Region
Kurt Welke – WDNR, South Central Region
Steve Westenbroek – USGS-Middleton

WICCI Science Council Reviewers

Barry Johnson

George Kraft

Phil Moy

Jack Sullivan

Additional Reviewers

Laura Hewitt – Trout Unlimited

Jana Stewart – USGS-Middleton

Brian Wiegel – WDNR, Science Services

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(Clockwise from top left)

Mount Vernon Creek, Dane County – Matthew Mitro

Male spawning brook trout – Matthew Mitro

Cisco – John Lyons

WDNR electrofishing Elk Creek, Vernon County – Matthew Mitro

Brown trout in Timber Coulee Creek, Vernon County – Matthew Mitro

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Executive Summary

Wisconsin is recognized for its abundance of coldwater streams, which includes over 10,000 miles of classified trout streams that provide fisheries for brook trout and brown trout. Expected climatic changes in air temperature and precipitation patterns across the state may threaten the viability of Wisconsin's inland trout resources. In this analysis, we use computer models to show how the distribution of some coldwater fishes may change in response to climate warming and we discuss adaptation strategies that can be employed to lessen the impacts of climate change on coldwater fishes in Wisconsin.

Wisconsin has rich and varied coldwater resources including streams, spring ponds, and thermally-stratified lakes. In addition to over 10,000 miles of managed trout streams, another 22,000 of Wisconsin's 54,000 stream miles may be suitable for coldwater species such as mottled sculpin. Wisconsin also has about 1,000 spring ponds that support coldwater fishes such as brook trout and nearly 3,000 stratified lakes of which about 170 contain self-sustaining populations of coldwater fishes such as cisco. Lake trout are indigenous to Wisconsin and are also present in some inland lakes.

Climatic changes in air temperature and precipitation will affect water temperature and flow in streams. Climate change will also affect water temperature and groundwater input to spring ponds. Many lakes in Wisconsin thermally stratify during summer, with the coldest layer occurring at the bottom. The suitability of this cold layer of water for coldwater fishes will be affected by climate change impacts on the duration of stratification and the consequent depletion of dissolved oxygen in this layer. An increase in the duration of lake stratification during the open water period will worsen the depletion of dissolved oxygen in the coldwater layer to levels stressful or lethal for coldwater fishes, resulting in the decline of populations of coldwater fishes.

Coldwater fishes native to Wisconsin are an integral part of our state's natural legacy, and coldwater fisheries are a core part of our culture and identity. The restoration of native fisheries to Wisconsin waters is a stated goal of the state agencies entrusted to manage these resources. Anglers also make a significant contribution to our local and state economies in their pursuit of trout and other coldwater fishes. In the face of changing climate conditions it is important to assess the potential impacts to coldwater fish and fisheries and to implement adaptive management strategies to ameliorate climate change impacts on Wisconsin's coldwater streams and inland lakes and their fisheries.

We used watershed-scale models to predict the changes in coldwater habitat and distributions of coldwater fishes that might occur under three different climate change scenarios. For streams, we considered three coldwater species: brown trout, brook trout, and mottled sculpin. For stratified lakes, we considered one species: cisco. We did not have enough information to model spring ponds.

For the coldwater streams and stratified lakes, we ran models for each stream reach or stratified lake in the state under current climate conditions and three climate warming scenarios projected for Wisconsin by the Climate Working Group: (1) a "best case" scenario, in which summer air temperature increased by slightly more than 1.8°F and water temperature by 1.4°F; (2) a "moderate case" scenario, in which air temperature increased by 5.4° F and water temperature by 4.3° F; and (3) a "worst case" scenario, in which air temperature increased by 9° F and water temperature by 7.2° F. For these models we assumed water temperature responds the same to air temperature in all streams, there was no change in precipitation across the climate change scenarios, and there was no change in land use over time from current conditions. These assumptions will be relaxed in future model development. Improvements to the stream models are in progress and include capabilities to incorporate variation in precipitation and groundwater inputs across the state for use in predicting stream water temperatures. For the stratified lakes model, the model did not appear to be strongly sensitive to lake productivity even though lake productivity is expected to affect dissolved oxygen in the bottom cold layer of water and hence lake suitability for cisco.

Climate change will likely cause reductions in all coldwater habitats and fish species in Wisconsin. Increases in air temperature will negatively affect thermal conditions required for the persistence of coldwater fishes. Changes in the amount and distribution of precipitation across the state may ameliorate or exacerbate the reductions in coldwater habitat and fishes. The magnitude of the reductions in coldwater fishes will therefore depend on the type and location of the habitat, the particular fish species that live there, and the nature and severity of the climate change that occurs.

Under current conditions, our models show mottled sculpin to be the most widespread coldwater fish species in Wisconsin streams, with brook trout the least widespread and brown trout intermediate. All three species declined in distribution under all three climate change scenarios. Brown trout declined least and brook trout the most. Under the worst-case climate change scenario, brook trout were predicted to be extirpated from Wisconsin streams, with mottled sculpin reduced in distribution by 95% and brown trout by 88%. Losses of habitat were expected to occur evenly across the state and were not noticeably concentrated in any particular geographic region. The models for stratified lakes indicated that climate change could also cause major declines in cisco populations.

Climate-induced changes in stream temperature and flow will not be uniform. Interactions between air temperature and precipitation and stream temperature and flow are mediated by stream channel, riparian, and watershed characteristics. It follows that the ability of streams to buffer change in water temperature and flow against change in climate will vary. Herein lays opportunity for managing climate impacts on inland trout and other coldwater resources. We suggest two types of adaptation strategies that can be used to lessen the impact of climate warming effects on trout. The first involves environmental management activities to offset the impacts of rising air temperatures and changes in precipitation. These activities include land, riparian, and water management and stream restoration. The second involves a triage approach to identifying potential impacts of climate change to coldwater resources and allocating management resources to those coldwater habitats most likely to realize success. Some streams, for example, may face inevitable losses of coldwater fishes, some may be resilient to climate impacts, and some may allow for persistence of coldwater fishes contingent on management approaches used to counteract climate impacts. Appropriate management actions may include environmental adaptation strategies as well as changes to angling regulations and fish stocking strategies. We expect that a proactive application of these adaptation strategies will help protect Wisconsin’s coldwater fishes and fisheries from the impacts of our changing climate.

Introduction

The purpose of the Coldwater Fish and Fisheries Working Group is to identify the potential impacts of climate change on coldwater fish and fisheries in Wisconsin streams and inland lakes and to develop management adaptation strategies in response to climate change impacts. The focus of the Group is to make use of existing information and to propose and implement new research where necessary to assess the vulnerabilities and sensitivity of coldwater resources to climate change, characterize uncertainties thereof, and advance science-based management of coldwater fish and fisheries by developing adaptation strategies to address climate change impacts on the resource.

Water temperature is a critical factor in determining where fish can live. Most fish are ectotherms, which exchange heat with and are generally the same temperature as their surrounding environment. Temperature affects biochemical and physiological processes in fish, and fish have adapted to different temperature regimes in which they can function efficiently. Each fish species has a thermal niche with lower and upper lethal limits. Within this range are optimal temperatures for body functions such as feeding and growth and life history events such as reproduction.

In temperate regions such as Wisconsin, freshwater fishes are usually found at temperatures in the range of 0–30°C. Summer maximum water temperature can be used to classify streams across a spectrum from coldwater to warmwater (Table 1). Coldwater streams maintain relatively cold summer maximum water temperatures and are usually dominated by a small number of "coldwater" fish species in the families Salmonidae and Cottidae. Brook trout *Salvelinus fontinalis* and brown trout *Salmo trutta* are the most common salmonids and mottled sculpin *Cottus bairdii* the most common cottid found in Wisconsin's coldwater streams (Figure 1a, b, and c). Warmwater streams have relatively warm summer maximum water temperatures and usually contain a more diverse assemblage of "warmwater" species in the families Cyprinidae (minnows), Catastomidae (suckers), Ictaluridae (catfish), Centrarchidae (sunfish), and Percidae (darters). Warmwater species, while able to survive as individuals at colder temperatures, require warmer temperatures to complete their life cycle and persist as populations.

Coldwater and warmwater represent endpoints on a thermal continuum. Streams with temperatures intermediate between coldwater and warmwater have commonly been referred to as coolwater streams. Coolwater streams may have temperatures suitable for both coldwater and warmwater fishes and therefore have no clear representative species. Lyons et al. (2009) recently defined subclasses of coolwater streams as "cold transition" and "warm transition" streams and presented temperature ranges characteristic of each of four classes of streams (Table 1).

Wisconsin's streams currently comprise 7.9% coldwater, 45.9% cold transition, 28.6% warm transition, and 17.6% warmwater stream kilometers (86,958 total stream km; 1:100,000-scale national hydrography data) (Lyons et al. 2009). Both coldwater and cold transition streams can support high abundances of coldwater fishes such as trout, with brown trout abundance often highest in cold transition streams. Coldwater fishes are less abundant in warm-transition streams and essentially absent in warmwater streams during summer. Warmwater streams may support coldwater fishes at times of the year other than summer, when temperatures are colder.

Coldwater fishes, such as Wisconsin's native brook trout, are sensitive to changes in environmental conditions, particularly water such as temperature. As such, they may be particularly susceptible to the effects of climate change on Wisconsin's coldwater streams as well as spring ponds and inland lakes. Native coldwater fishes are an integral part of Wisconsin's natural legacy, and coldwater fisheries are a core part of our culture, and identity, and economy. The restoration of native fisheries to Wisconsin waters is a stated goal of the Department of Natural Resources Water Division and Bureau of Fisheries Management. Anglers also make a significant contribution to local and state economies in their pursuit of coldwater fishes. A report commissioned by Trout Unlimited and published in 2008 identified trout angling to have an economic impact in excess of $1.1 billion each year in the Driftless Area of Wisconsin, Minnesota, Iowa, and Illinois (Trout Unlimited 2008). In the face of changing climate conditions it is important to assess the potential impacts to coldwater fish and fisheries and implement adaptive management plans to ameliorate climate change impacts to the maximum extent practicable on Wisconsin's coldwater streams and inland lakes and their fisheries.

Future Climate Impacts

Climate change may impact coldwater streams and lakes in at least two ways. Increases in air temperature may affect water temperature directly. Changes in air temperature and precipitation may affect the recharge of groundwater (i.e., precipitation less evapotranspiration), which then affects discharge in streams and stage in streams and lakes. Changes in discharge and stage in turn affect water temperature and the availability of coldwater habitat.

Streams

Climatic changes in air temperature and precipitation will affect water temperature and flow in streams. Stream temperature models for Wisconsin streams indicated air temperature was an important climate variable driving water temperature. We developed an artificial neural network model to predict daily mean temperature time series for the June-August summer period for Wisconsin streams (Stewart et al. 2006). Model input variables included categorical site stream segment and watershed attributes and dynamic climate signals from the summer period in 1990-2002. We evaluated five climate variables (air pressure, air temperature, dew point temperature, precipitation, and solar radiation) and found that air temperature was the climate variable that best explained temporal variation in stream temperature. These modeling results suggest that increases in air temperature will in general lead to increases in stream temperatures in Wisconsin.

Long-term (decadal or greater) stream temperature data sets for Wisconsin are rare, but those that are available suggest a warming trend in stream temperatures. We analyzed 1992-2009 stream temperature data from four coldwater stream sites on the Kinnickinnic River and a tributary stream in Pierce and St. Croix counties (Kent Johnson and Kiap-TU-Wish Chapter of Trout Unlimited, personal communication), which showed increasing trends in the moving average of maximum daily mean temperatures as the length of exposure period to the daily temperature regime increased from 1 to 63 days (Table 2 and Figure 2). We calculated the daily mean temperature for each date from 15 May to 15 September for each year, the maximum daily mean temperature for each year, and a moving average of the maximum daily mean temperature for exposure periods durations of 3, 7, 14, 21, 28, 35, 42, 49, 56, and 63 days. Each stream site has remained thermally suitable for trout (Wehrly et al. 2007). There was generally no change, or a decrease in the case of the tributary stream, in the maximum daily mean temperature by year. However, as the duration of exposure period to the daily temperature regimes increased from 7 to 63 days, the maximum daily mean temperature increased with year (slope $b_1 > 0$ and correlation coefficient $r > 0$) (Table 2 and Figure 2). These observed trends in stream temperature are consistent with the observed warming trend in Wisconsin air temperature for the same time period (Kucharik and Serbin 2008). These data suggest that to date the warming in stream temperature has not necessarily occurred in short term peaks but rather as temperature increases measured over broader lengths of exposure periods during summer.

Although air temperature is an important factor in determining stream temperature, stream temperatures are highly heterogeneous across the landscape as compared to air temperature. Coldwater, coolwater, and warmwater reaches in streams occur in close proximity and under the same climate conditions because of local variation in geology and groundwater contributions to streams. Coldwater streams depend on the input of cold groundwater. Groundwater within about 100 feet of the land surface is about the same temperature as the regional mean air temperature, which in Wisconsin ranges from about 4°C in the north to 10°C in the south. Warmer air temperatures as a result of climate change will lead to a warming of groundwater, which will lead to relatively warmer stream temperatures. However, local variations in stream temperatures are expected to remain.

Climatic changes in precipitation will affect stream temperature both through effects of surface water runoff and groundwater recharge. Precipitation events are predicted to become more intense and may lead to large, short-term inputs of water into streams. Such runoff in more urbanized areas may lead to short-term increases in water temperature. When runoff exceeds the capacity of stream channels to carry water, flooding may occur. Such large-scale flooding events may increase erosion, sedimentation, and nutrients and ultimately degrade stream habitat, particularly in streams that are already degradedin poor condition. Restored tTrout streams with some level of restoration, however, were largely undamaged by the heavy precipitation and flooding events that occurred in Driftless Area streams of Wisconsin such as Timber Coulee Creek in August 2007 and June 2008 (Figure 3). These restored streams had previously high, eroded banks sloped back in order to dissipate energy from flood waters in the stream channel to the flood plain.

Large-scale runoff events may negatively affect trout recruitment should such events occur during the critical and vulnerable time period following trout emergence from spawning redds in early spring. Recently emerged trout fry typically occupy slower water near the margins of streams and are vulnerable to being swept away by stronger currents. Climate change that leads to more frequent or more intense precipitation events will exacerbate these such surface water runoff effects on streams and their fish populationstrout early life stages and recruitment.

Changes in precipitation associated with climate change may lead to positive or negative effects on groundwater recharge. More frequent precipitation events will may have the beneficial effect of recharging groundwater and augmenting baseflow in streams where land use is conducive to precipitation infiltrating the ground. Increases in precipitation frequency or intensity can lead to increases in groundwater recharge when the precipitation increases are in excess of evaporation, evapotranspiration, and surface runoff. Increases in cold groundwater input to streams resulting from improved groundwater recharge will buffer help moderate streams from the effects of increasing air temperature and may create more useable habitat in streams for coldwater fishes.

Less frequent precipitation events associated with climate change, including drought conditions, will may result in less groundwater recharge and lower baseflows in streams should there be decreases in excess precipitation after losses to evaporation, evapotranspiration, and surface runoff. Lower baseflows reduce available habitat for fish, and streams with lower baseflow will be less buffered protected from the effects of air temperature on water temperature. Groundwater withdraws are increasing and could increase more in the future to make up for moisture deficits on farmland, thereby exacerbating the effects of decreases in precipitation.

Lakes

Climate change will affect spring ponds and stratified lakes differently. In spring ponds, coldwater fishes persist because “spring” or groundwater inputs maintain refuge areas of cold water in which the species can survive the summer. Warmer air temperatures as a result of climate change will lead to a warming of groundwater that will result in the coldwater habitats within spring ponds becoming warmer and less extensive. Consequently summer habitat for coldwater species will decline in quality and quantity, presumably reducing populations of coldwater fishes. If climate change also results in lower amounts of precipitation, then groundwater recharge and subsequent input to lakesinputs will may decline, further reducing the extent of coldwater refuges within spring ponds and accelerating declines of coldwater fishes. However, if precipitation increases, then groundwater recharge and subsequent inputs to lakes inputs may also increase and the amount of coldwater habitat may expand, perhaps partially offsetting the impacts from warmer groundwater. Longer periods of warm temperatures as a result of climate change will also extend the time during which coldwater fishes are restricted to coldwater refuges within spring ponds, which may also reduce their populations.

In stratified lakes, coldwater species are restricted during summer to the cold water at the bottom layer of the lake in the hypolimnion layer during the summer. Climate change will affect the suitability of the hypolimnionthis layer for coldwater fish through effects on the duration of lake stratification and consequent depletion of hypolimnetic dissolved oxygen. Coldwater fishes generally are stressed when dissolved oxygen levels go below 5-6 mg/l and die when dissolved oxygen drops below 2-3 mg/l. Because the hypolimnion is isolated from wind mixing at the surface of the lake and is usually too deep and dark for significant oxygen production from photosynthesis, hypolimnetic dissolved oxygen content cannot be replenished as long as the lake remains stratified, and dissolved oxygen concentrations will gradually decline over the course of the stratification period. With a warming climate, the duration of lake stratification during the open water period is expected to increase. With longer stratification, depletion of hypolimnetic dissolved oxygen to levels stressful or lethal for coldwater fishes will become more likely and will last longer, and populations of coldwater fishes will probably decline as a result.

Lake stage is controlled by groundwater levels. Reductions in groundwater levels may therefore decrease the size of the hypolimnion and also make depletion of hypolimnetic oxygen to stressful or lethal levels more likely. Rises in summer air temperature may also increase evaporation rates, contributing to declines in lake levels and depth.In some lakes, rises in summer air temperature may increase evaporation rates enough that lake levels and depths decline, which will decrease the size of the hypolimnion and also make depletion of hypolimnetic oxygen to stressful or lethal levels more likely. Small headwater lakes that get all or most of their water from precipitation are most likely to be affected, and they may decrease in depth by more than a meter. Precipitation patterns will influence the amount of water loss from these lakes, but even under scenarios of increased snow and rainfall, lake levels are still predicted to decline. Larger lakes located lower in the a drainage network that receive much of their water from groundwater or surface streams will likely see much less change in their water levels compared to lakes higher in a drainage network as a function of groundwater hydraulics.

Vulnerability Assessment

Wisconsin has a rich and varied coldwater fish resource. There are about 87,000 km of streams and rivers in the state of which nearly 16,700 km (19%) are formally classified as trout streams. Field surveys and water temperature modeling results indicate that another 40,000 km (46%) may be suitable for certain coldwater species such as mottled sculpin. Most coldwater streams are small headwaters, but some small to medium-sized coldwater rivers (up to 5th order) exist in the northern half of the state. The estimated number of lakes and ponds in Wisconsin exceeds 15,000. Spring pond numbers are unknown, but probably total more than 1,000 statewide. They are most common in northern Wisconsin, particularly in and around Langlade County, which has over 200 identified spring ponds capable of supporting trout. Most spring ponds are small, with the largest having a surface area of about 10-15 ha and the vast majority having surface areas well under 1 ha.

Nearly 3,000 stratified lakes occur in Wisconsin, but only about 170 contain self-sustaining populations of coldwater fishes dependent on the hypolimnion, primarily cisco *Coregonus artedi* (Figure 1d). Lake trout *Salvelinus namaycush* are indigenous to Wisconsin and are present in some inland lakes. Approximately another 100 stratified lakes are stocked with trout to support fisheries, but no reproduction occurs. Stratified lakes with coldwater fishes tend to be relatively deep, usually greater than 15 m, and range widely in surface area from about 10 ha to nearly 4,000 ha.

Sensitivity Analysis and Uncertainties

Climate change is likely to cause reductions in all coldwater habitats and species, although the extent and magnitude of the decline will depend on the type and location of the habitat and the species and the particular nature of the climate change that occurs. Generally, increasing air temperatures and longer periods of warm weather will cause coldwater species to disappear, and changes in precipitation amount and pattern may ameliorate or exacerbate these reductions. Human lLand-use changes associated in conjunction with climate change also have the potential to dampen or amplify losses of coldwater species populations. Generally, more intensive human land usesalterations to the landscape, such as increasing urban sprawl or expanded row-crop agriculture, degrade coldwater resources and will worsen climate change impacts, whereas the implementation of best-management practices to minimize environmental impacts of agriculture and urban development or the conversion of disturbed lands to natural vegetation will usually benefit coldwater resources and may partially offset climate change impacts.

We conducted ecological modeling exercises to predict the changes in coldwater habitat that might occur under various climate change scenarios. For streams, we considered three coldwater species: brown trout, brook trout, and mottled sculpin. For stratified lakes, we considered one species: cisco. We did not have enough information to model spring ponds. For the coldwater streams and stratified lakes, we ran models for each stream reach or stratified lake in the state under current climate conditions and three climate warming scenarios projected over the next 50 years. Specific Wisconsin climate warming scenarios were obtained from downscaled climate model projections obtained from the Climate Working Group of the Wisconsin Initiative on Climate Change Impacts (Available on the web at http://www.wicci.wisc.edu/climate-change.php; accessed December 2010). We addressed the following three scenarios (Lyons et al. 2010): (1) a "best case" scenario, in which summer air temperature increased by slightly more than 1°C and water temperature by 0.8°C (Global Circulation Model CSIRO-M3K-0 under optimistic projections of future greenhouse gas emissions); (2) a "moderate case" scenario, in which air temperature increased by 3°C and water temperature by 2.4°C (Global Circulation Model GISS-AOM with "business as usual" projections of future greenhouse gas emissions); and (3) a "worst case" scenario, in which air temperature increased by 5°C and water temperature by 4°C (Global Circulation Model MIROC3-HIRES with "business as usual" projections of future greenhouse gas emissions). We did not consider any changes in precipitation across the climate scenarios because the stream models cannot account for effects of precipitation on groundwater recharge and input to streams, and hence water temperatures. Precipitation was assumed to remain unchanged across the climate change scenarios, but this was a moot point as the stream and lake models were generally insensitive to increases or decreases in precipitation. Land use was also held constant at current conditions across all modeling runs. Model outputs included predictions of the presence or absence of each considered fish species in every stream reach or stratified lake in Wisconsin.

Climate Change Modeling - Streams

For streams, we estimated statewide habitat suitability for individual fish species was estimated withusing GIS-based, watershed-scale regression tree species models developed for the entire state (Lyons et al. 2010). These models used information on topography, watershed position, watershed size, surficial and bedrock geology, potential groundwater inputs, air temperature, precipitation, and various categories of land cover in the riparian zone and watershed to estimate stream water temperature and flows and suitability for fish species. In validation tests with independent data, accuracy at predicting current presence or absence in stream reaches was 64.3% for brown trout, 67% for brook trout, and 73.74% for mottled sculpin.

Modeling results indicated that climate change could lead to major declines in the occurrence and distribution of coldwater fish species in streams. Under current conditions, mottled sculpin were predicted to be the most widespread species and brook trout the least, with brown trout intermediate (Table 3 and Figures 4-6). For all three climate-change scenarios all three species declined, brown trout the least and brook trout the most. Under the worst-case climate-change scenario, brook trout were predicted to be extirpated from Wisconsin streams and mottled sculpin reduced in distribution by 95% and brown trout by 88%. Losses of habitat were expected to occur evenly across the state and were not noticeably concentrated in any particular geographic region.

The model results clearly indicate that climate change has the potential to cause major declines in coldwater fishes in streams, including the possible extirpation of species. However, model predictions must be qualified with three caveats. First, the models assume that water temperatures will increase the same amount in all streams across the state in response to a given rise in air temperature. This assumption is an oversimplification but is required to allow the scenarios to be run given the large number of stream reaches (35,748) and the complexity of the stream temperature model. In reality, for any given climate change scenario, water temperature responses will vary depending on geographic location and stream reach attributes characteristics (e.g., relative ground water inputs, channel morphology, shading, riparian and watershed land uses). Consequently, some reaches predicted to become unsuitable for coldwater fishes may in fact remain suitable and the total loss of coldwater may be somewhat overestimated by the models. We are in the process of developing improved versions of the models that allow for geographic and reach-specific changes in water temperature.

A second caveat is that the stream models cannot account for effects of precipitation changes on groundwater recharge and inputs to streams, and hence water temperatures. Consequently, changes in precipitation amount and pattern were not included in the three climate change scenarios that we explored. More realistic future climate scenarios for Wisconsin differ in how precipitation is expected to change, some projecting increases and others decreases, but few predict that precipitation patterns will remain unchanged. Increases in precipitation could enhance groundwater inputs and moderate potential dampen water temperature rises increases caused by warmer air temperatures and thus reduce declines in coldwater fishes. Decreases in precipitation could have the opposite effect. Many climate change scenarios predict that precipitation effects such as flooding and drought are likely to become more common in the future, and such events can potentially harm coldwater species. Improvements to the models are in progress and include capabilities The improved versions of the models we are working on will be able to incorporate variation in precipitation and groundwater inputs across the state for use in predicting stream water temperatures.

A final caveat is that the models were run under the unrealistic assumption that land use will remain unchanged over the next 50 years. Land use is constantly changing, and several land-use trends of recent decades are expected to continue into the future. These trends could have several important consequences for coldwater streams that were not incorporated into the model predictions. First, urban areas will probably continue to expand (“urban sprawl”), with negative effects on coldwater streams and fish species. Second, in some areas of the state such as southwestern Wisconsin, agricultural lands may continue to be converted into less intensive uses, such as fallow fields or woodlands, generally to the benefit of coldwater species. In other areas, such as east-central and north-central Wisconsin, agricultural land use may intensify, generally to the detriment of coldwater species. About 39% of current groundwater withdrawal is used for irrigation, and such use of groundwater may increase with agricultural land use. Finally, given that many coldwater streams support popular and valuable sport fisheries, riparian and watershed land management activities designed specifically to benefit coldwater species are widespread and likely to continue and perhaps expand in an effort to lessen impacts of warmer air temperatures on coldwater streams. In future modeling runs, we will explore the relative effects of these land-use trends in combination with climate change on coldwater streams and fishes.

Climate Change Modeling – Stratified Lakes

For stratified lakes, we estimated habitat suitability for cisco with a logistic regression equation that considered information on lake surface area and depth and morphology, water chemistry, climate, and location in the state (S. Sharma, Center for Limnology, University of Wisconsin-Madison, unpublished data). The best model was:

$$\text{Cisco occurrence} = -14.04 + 0.99 \times (\log +1)\ \text{Conductivity} + 1.9 \times (\log)\ \text{Surface area} + 7.7 \times (\log)\ \text{Maximum depth} - 0.36\ \text{Mean annual air temperature}$$

This model was 93% accurate in predicting cisco occurrence in a validation step with independent data.

Modeling results indicated that climate change could cause major declines in cisco populations. Cisco losses occurred in 44 of 170 (25.926%) cisco lakes under the best-case climate-warming scenario, in 58 lakes (34.1%) under the moderate-case scenario, and in 81 lakes (47.68%) under the worst-case scenario (Figure 7). Losses occurred most often in the smallest and shallowest cisco lakes and were more likely in southern Wisconsin. However, cisco disappearance did not have any obvious relation with measures of relative lake productivity.

As was the case for coldwater streams, the stratified lakes model indicated that there may be significant declines in cisco populations with even just minor climate warming. However, one caveat should be considered when examining modeling results. The model does not appear to be strongly sensitive to lake productivity, but certainly changes in lake productivity will have effects on hypolimnetic dissolved oxygen and thus lake suitability for cisco. In recent years there has been a trend for greater shoreline development and urbanization of lake riparian areas, which has boosted nutrient inputs and lake productivity in many instances. This trend of increasing productivity in many lakes will likely exacerbate climate change impacts on cisco, and perhaps make cisco loss more likely than the model predicts. Conversely, if an aggressive policy of land-use management that reduces nutrient inputs were to be adopted, then perhaps cisco habitat suitability could be improved.

Adaptation Strategies

We recognize two types of adaptation to climate change that are relevant to coldwater habitats and fish populations in Wisconsin. The first type relates to implementing environmental management activities that could perhaps at least partially offset the negative impacts of climate change on coldwater resources. This would include in-water habitat modifications and riparian and watershed land-use practices that result in continued support of conditions for adequate maintenance of adequate groundwater inputs, cold water temperatures, and good water quality despite in spite of warmer air temperatures, while minimizing the negative impacts of possible increased magnitude and frequency of floods and droughts. The second type relates to directing management efforts and resources to locations where they will provide the greatest benefit. This involves a "triage" process for examining potential impacts of climate change: identifying locations where loss of coldwater fishes would likely be inevitable even with intensive management, locations where coldwater fishes would likely continue to occur even in the absence of management, and locations where the persistence of coldwater fishes would likely depend on the type and amount of management. It would be most effective to direct appropriate management efforts to the latter group of locations where persistence depends on management. Such efforts could include various environmental management activities (see below) as well as fisheries management actions such as more protective harvest regulations and supplemental stocking to maintain populations and fisheries.

Streams

The Wisconsin DNR currently manages trout fisheries in over 16,700 km of coldwater streams using a combination of stream habitat protection and improvement, fishing regulations, and stocking of hatchery-reared trout. Here we suggest adaptation strategies for managing coldwater streams threatened by climate change. These adaptation strategies fit within the current framework of trout stream management as well as more broad-scale efforts aimed at management at the watershed scale.

Trout stream management in Wisconsin utilizes a classification system that indicates the quality of the stream and its ability to support trout. Class I streams (includes 40% based onof total stream lengthkilometers) support natural reproduction sufficient for theto maintenance maintainof wild trout fisheries, but fisheries in Class II streams (45%) require supplementation by stocking and in Class III streams (15%) are wholly dependent on stocking. This system is used to allocate management resources based on stream quality. For example, trout stamp revenues are used for habitat restoration projects on degraded streams and have been successful in increasing the quality of trout fisheries therein. While trout stream management has been successful at increasing the amount of Class I and Class II waters in Wisconsin, we anticipate that climate change may act to reverse this trend. Here we present adaptation strategies, from broad watershed-scale efforts to more site-specific stream-focused efforts, adaptation strategies thatwhich can be used to protect coldwater fisheries in streams impacted by climate change.

Land Management.—Land use and management have in recent years been widely acknowledged as critical to the protection and restoration of coldwater streams. Urbanization, measured as the percent connected impervious area in a watershed, is known to have a positive influence onincrease stream temperature (Wang et al. 2003; Stewart et al. 2006) and a negative influence onreduce stream baseflow and coldwater fish communities (Wang et al. 2003).

Wang et al. (2003) showed that in watersheds with levels of connected imperviousness in the threshold region of 6-11%, minor changes in urbanization can lead to major changes in coldwater fish communities. For agricultural regions, Wang et al. (2002) found that upland best management practices were critical for the restoration of cold water in Wisconsin streams. Best management practices refer to state and federal programs designed to reduce agricultural nonpoint source pollution by targeting both riparian and upland areas of watersheds.

Marshall et al. (2008) documented positive effects of changes in agricultural land use in southwest Wisconsin on coldwater fish communities in streams. They investigated the effect of implementing the Conservation Reserve Program (CRP), a federal program that supported planting cool- or warm-season grasses on highly erodible cropland and along stream corridors, resulting in watershed-scale protection efforts focused on environmentally sensitive agricultural land. A comparison of fish community metrics in streams located in areas of relatively high (21.3% land area) versus low (12.1% land area) CRP participation, surveyed both before (1970's) and after (2000's) the start of the CRP, showed significant increases in scores of the coldwater index of biotic integrity (IBI) scores for streams in areas of high versus low CRP participation. Higher coldwater IBI scores were consistent with shifts in community structure from species tolerant of warmer stream temperatures and overall reduced water quality to coolwater and coldwater species intolerant of degraded stream environments. Improvements in fish community metrics were correlated with reduced phosphorus loading, reductions of which were predicted to be higher in high-CRP grassland areasresult from CRP participation. Higher levels of CRP land result in lower levels of surface runoff and increased groundwater infiltration. Also, of note was that instream habitat improvements in low-CRP streams did not lead to improvements in coldwater fish community metrics, which highlights the importance of watershed-scale land management.

While Wisconsin streams have been subject to watershed-scale changes in land use and management, these changes have occurred simultaneously with regional-scale changes in climate. Juckem et al. (2008), in a study of Driftless Area streams in Wisconsin, showed that both changes in land management and climate have influenced the hydrologic response of streams. An evaluation of streamflow and climate data for 1941-2000 indicated that the timing of an abrupt increase in baseflow around 1970 was related to changes in precipitation (i.e., climate), while the magnitude of the changes in baseflow and stormflow were likely amplified by changes in land management that allowed for an increase in infiltration versus overland runoff.

These studies highlight the importance of both climate change, and land use, and management to the condition of coldwater streams in Wisconsin and how they may change in the future. Long-term climatic trends in precipitation are playing an important role in driving the timing and direction of hydrologic changes in Wisconsin. And land management is playing an important role in increasing hydrologic changes beyond that which is driven by climate.

We suggest that the following land use and management practices may act as important adaptation strategies for protecting coldwater fisheries threatened by climate change:

- Reduce existing or limit creation of additional impervious surfaces in critical watersheds containing coldwater streams, and utilize use best management practices in urban areas.
- Protect environmentally sensitive agricultural land by enrollment in the Conservation Reserve Program or other similar federal or state programs.
- Utilize Use best management practices on agricultural lands by, for example, implementing conservation tillage approaches to limit surface runoff and favoring intensive rotational grazing over continuous grazing, both in riparian and upland areas of watersheds.

The stream temperature model and the regression tree stream fishes models can be used to identify watersheds with coldwater streams and land use attributes characteristics suitable for further protection or restoration efforts.

Riparian Management.—Management of riparian areas also plays an integral role in stream management and protection. The riparian area is the interface between a stream and the land in its watershed and includes the stream bank and land adjacent to the stream. Riparian areas are critical to stream functioning, and when functioning properly in undisturbed or restored areas, may help lessen soil erosion and dissipate the energy of a stream, particularly during flooding by opening the stream to the floodplain. Riparian areas that are not functioning properly may contribute to the further degradation of streams. For example, flood energy improperly confined to a stream channel may erode banks, widen streams, and increase instream sedimentation. Riparian areas also act as buffers between upland areas and streams, helping to mitigated the impacts of urban and agricultural land use on streams by preventing or limiting nonpoint source pollutants from entering streams.

Many studies have documented the benefits of sound riparian management to trout streams. For example, Wang et al. (2002) found that while upland best management practices led to improvements in the thermal regime of trout streams, the addition of riparian best management practices led to additional improvements in stream habitat and trout abundance. Lyons et al. (2000b) found for trout streams in southwestern Wisconsin that intensive rotational grazing and grassy buffers led to less bank erosion as compared to continuous grazing and led to less fine substrate in the stream channel as compared to continuous grazing in areas with woody buffers.

Riparian vegetation plays an important role in maintaining water temperatures in coldwater streams, but different forms of riparian vegetation may be more appropriate in different regions of Wisconsin. Lyons et al. (2000a) discuss the effects of woody versus grassy riparian areas and stream banks on streams in central North America. They conclude that for grassland/savannah regions, such as in southern Wisconsin, grassy riparian vegetation was more effective than woody vegetation in reducing bank erosion and trapping suspended sediments. Grassy vegetation contributes to bank stability, helps to narrow and deepen stream channels, and may provide shade on small streams, all of which contribute to maintaining lower water temperatures in coldwater streams.

Forested riparian areas also contribute to lower water temperatures on some coldwater streams and may be more appropriate in the north central hardwoods and northern forested regions of Wisconsin. Cross (2009) used a combination of empirical stream temperature data and a stream temperature model to show that shading from forested riparian areas could be used to create thermally suitable stream reaches for brook trout in central Wisconsin.

We suggest that riparian management can play an important role in protecting coldwater streams from climate change impacts. Management of appropriate riparian vegetation can be used to promote stream bank and channel stability, to reduce erosion and siltation in streams, to protect streams from damage attributable to high flow events, and to provide shading during summer to maintain the lower temperatures of groundwater input over longer lengths of coldwater streams.

Water Management.—Wisconsin trout streams are protected by laws designed to limit withdrawals of surface and ground water. Surface and groundwater are often drawn for use in irrigating croplands and groundwater is also used by municipalities and industry to provide water for household and commercial use. Trout streams and other special water resources are protected by laws that limit withdrawal of surface water directly from streams or groundwater near streams. Despite these protections, water use has led to detrimental effects on trout streams. In an extreme case, the Little Plover River dried up in August 2005 and again in subsequent years (Clark 2005).

Groundwater resources will be critical to maintaining coldwater streams threatened by a warming climate, and the direction of climatic changes in precipitation will play a central role in water availability. Increases in precipitation may improve groundwater recharge and provide adequate water for continued multiple uses.

Prolonged drought conditions, however, will cause added stress to many already over-utilized groundwater sources and may compound the effects of climatic warming on streams. We recommend that continued enforcement ofstrengthening the laws and the enforcement thereof governing groundwater use will be critical to protecting coldwater streams and trout fisheries impacted by climate change.

Stream Restoration.—Stream restoration is an integral part of trout stream management in Wisconsin. Stream restoration generally involves the re-establishment of aquatic functions and related biological, chemical, and physical characteristics of streams that would have occurred prior to disturbance. Trout anglers fishing inland waters in Wisconsin are required to purchase a trout stamp, from which the proceeds are directed towards stream habitat restoration work. Hunt (1988) and Avery (2004) have documented a half century (1953-2000) of evaluations of trout stream habitat development projects in Wisconsin and have shown how restoration has been successful at improving trout populations in terms of trout number and size.

Restoration is generally targeted at Class I or Class II trout streams. Restoration may take different forms, many of which may protect streams from impacts of climate change. For example, degraded streams may exhibit wide and shallow channels. Restoration efforts may narrow and deepen stream channels, which may act to help maintain or further cool stream temperatures during summer. Eroded stream banks may be sloped back to open the stream channel to the flood plain, which helps dissipate energy from floods out to the flood plain rather than eroding into stream banks. Instream structures may be installed providing overhead cover and shade, particularly structures that mimic undercut banks and are placed on the south side of a stream away from direct sunlight.

Beaver dam removal is another instream restoration tool that has been critical to the maintenance of many trout streams in Wisconsin. Beaver dams constructed on low- to moderate-gradient streams, often in excess of one per mile, may adversely affect trout populations by raising summer water temperatures and reducing stream connectivity and access to spawning sites. Avery (1991, 2002) documented reductions in water temperature and increases in trout populations in an 18-year study following the removal of beaver dams to maintain free-flowing conditions in Wisconsin coldwater streams. McRae and Edwards (1994), however, noted that the thermal effect of beaver impoundments was highly site dependent because of variation in groundwater inflow. Depending on the response of beaver to changes in climate, beaver dam removal may continue to be critical to maintaining coldwater stream habitat and trout fisheries in many Wisconsin streams impacted by climate change.

We expect stream restoration to continue to play a major role in trout stream management and to help lessen the effects of climate warming and flooding, related to changes in precipitation patterns, on coldwater streams. We recommend using restoration techniques that promote colder water temperatures (e.g., narrowing and deepening stream channels) and targeting restoration efforts to streams most likely to realize these benefits under a changing climate. Here again, the stream temperature and stream fishes models can be used to aid in site selection for future restoration projects.

Triage.—Recognizing that resources for stream management and restoration are limited, we recommend utilizing a triage approach to protecting coldwater streams from the impacts of climate change. A triage approach would involve a process setting realistic management expectations for success by evaluating possible climate change impacts on different coldwater streams. The loss of coldwater fishes may be inevitable, even under intensive management, in some streams. The triage approach would dictate that limited resource not be allocated to such streams. Other streams may be resilient to climate impacts and may continue to support coldwater fishes in the absence of intensive management. The triage approach would also dictate that limited resources not be allocated to such streams. A third group of coldwater streams may allow for the persistence of coldwater fishes depending on the type and amount of management used to counteract the impacts of climate change. The triage approach would dictate that while certain minimum protections should continue to apply to all coldwater streams, limited management resources should be allocated to this groupstreams for which active management is most critical to the persistence of coldwater fishes, with the and apportionment of management resourcesed based on the likelihood of realizing success.

Management efforts to protect coldwater streams, and fishes, and fisheries from the impacts of climate change many include any approaches to land, riparian, and water management and stream restoration outlined above. Additional approaches may involve the use of angling regulations or stocking of hatchery-reared fish. Angling regulations can be imposed on trout streams to restrict angling at times of the day or year when warm water temperatures are most stressful to coldwater fish. Stocking strategies will need to be evaluated to maximize return on investment. For example, we may need to cease stocking some streams with fingerling trout for “put, grow, and take” fisheries if the targeted stream can no longer support the year-to-year survival and growth of trout to a size that can be harvested by anglers. The need for stocking catchable trout for “put and take” fisheries will increase when the success of “put, grow, and take” and wild fisheries decline.

We recommend the use of the stream temperature and stream fishes models for holistically evaluating streams and their watersheds to identify coldwater resources for protection and restoration. These models will allow for evaluating potential responses to climate change scenarios so that managers can make informed decisions when allocating management resources.

Lakes

Groundwater inputs are critical to the continuing suitability of spring ponds for coldwater fishes, as they are similarly critical for coldwater streams, so many of the environmental adaptation strategies for spring ponds are also similar to those for streams. Overall, riparian and watershed land-use practices that promote infiltration of precipitation and recharge of groundwater can maintain or perhaps enhance groundwater inputs to spring ponds, possibly offsetting some of the effects of a warmer climate. Protection from groundwater pumping that reduces the water table is also essential. In terms of direct habitat management, spring pond hydraulic dredging is likely to be beneficial. This dredging removes accumulated sediments, deepening the pond and improving contact with the water table and increasing groundwater inputs, which can help offset warmer air temperatures.

Environmental management options for addressing climate-change effects on coldwater fishes in stratified lakes are limited and mainly concern modifying lake productivity. Depletion of dissolved oxygen in the hypolimnion during the summer is inevitable, with the rate of depletion a function of the overall productivity of the lake. Higher productivity results in a larger and faster decline in dissolved oxygen and a greater likelihood that dissolved oxygen will reach levels stressful or lethal to coldwater fishes. Productivity is in part determined by external inputs of nutrients, especially phosphorus, from the surrounding landscape, particularly riparian areas. Efforts to reduce nutrient inputs from riparian areas and the overall lake watershed through improved land-use management may thus help preserve coldwater fish populations as the duration of lake stratification increases under a warming climate.

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Table 1.—Stream water temperature (°C) criteria for classifying Wisconsin streams into thermal classes and transition subclasses (from Lyons et al. 2009).

Class and subclass	June-August mean	July mean	Maximum daily mean
Coldwater	<17.0	<17.5	<20.7
Coolwater	17.0–20.5	17.5–21.0	20.7–24.6
Cold transition	17.0–18.7	17.5–19.5	20.7–22.6
Warm transition	18.7–20.5	19.5–21.0	22.6–24.6
Warmwater	>20.5	>21.0	>24.6

Table 2.—Slope (b_1), coefficient of determination (r^2), and correlation coefficient (r) for linear relationships between year and maximum daily mean temperature for five exposure periods (1, 7, 21, 42, and 63 days) at four stream sites in Pierce and St. Croix counties, Wisconsin (Quarry Road, Upper Glen Park, and Lower Glean Park in the Kinnickinnic River and Rocky Branch Creek, a tributary entering the Kinnickinnic River downstream of the Upper Glen Park site).

Exposure period (d)	b_1	r^2	r
Quarry Road			
1	-0.002	0.000	0.000
7	0.05	0.08	0.28
21	0.08	0.27	0.52
42	0.07	0.26	0.51
63	0.08	0.31	0.56
Upper Glen Park			
1	0.05	0.06	0.24
7	0.07	0.11	0.33
21	0.12	0.30	0.55
42	0.10	0.27	0.52
63	0.10	0.30	0.55

Table 2.—Continued.

Exposure period (d)	b_1	r^2	r
		Rock Branch Creek	
1	-0.78	0.05	0.22
7	-0.03	0.02	0.16
21	0.002	0	0.02
42	0.02	0.03	0.18
63	0.04	0.12	0.35
		Lower Glen Park	
1	-0.008	0.002	0.05
7	0.02	0.01	0.12
21	0.06	0.10	0.32
42	0.05	0.12	0.34
63	0.07	0.20	0.44

Table 3.—Predictions from statistical models of the stream length in kilometers and as a percentage of the total stream length in Wisconsin (86,958 km) that would be suitable for three coldwater fish species under current air and water temperatures, and predictions of the lengths of suitable stream and the percent change from current climate conditions under three climate warming scenarios (see text).

			Climate warming scenarios					
	Current climate		Best case		Moderate case		Worst case	
Fish species	Length (km)	Percent of total	Length (km)	Percent of total	Length (km)	Percent of total	Length (km)	Percent of total
Brown trout	37,241	42.9	34,296	-7.9	24,908	-33.1	4,378	-88.2
Brook trout	28,802	33.1	16,245	-43.6	1,618	-94.4	0	-100
Mottled sculpin	59,599	68.6	46,547	-21.9	20,936	-64.9	2,755	-95.4

Figure 1.—a. Brook trout *Salvelinus fontinalis*. b. Brown trout *Salmo trutta*. c. Mottled sculpin *Cottus bairdii*. d. Cisco *Coregonus artedi*. (Photo credits: a, b – Matthew Mitro; c, d – John Lyons)

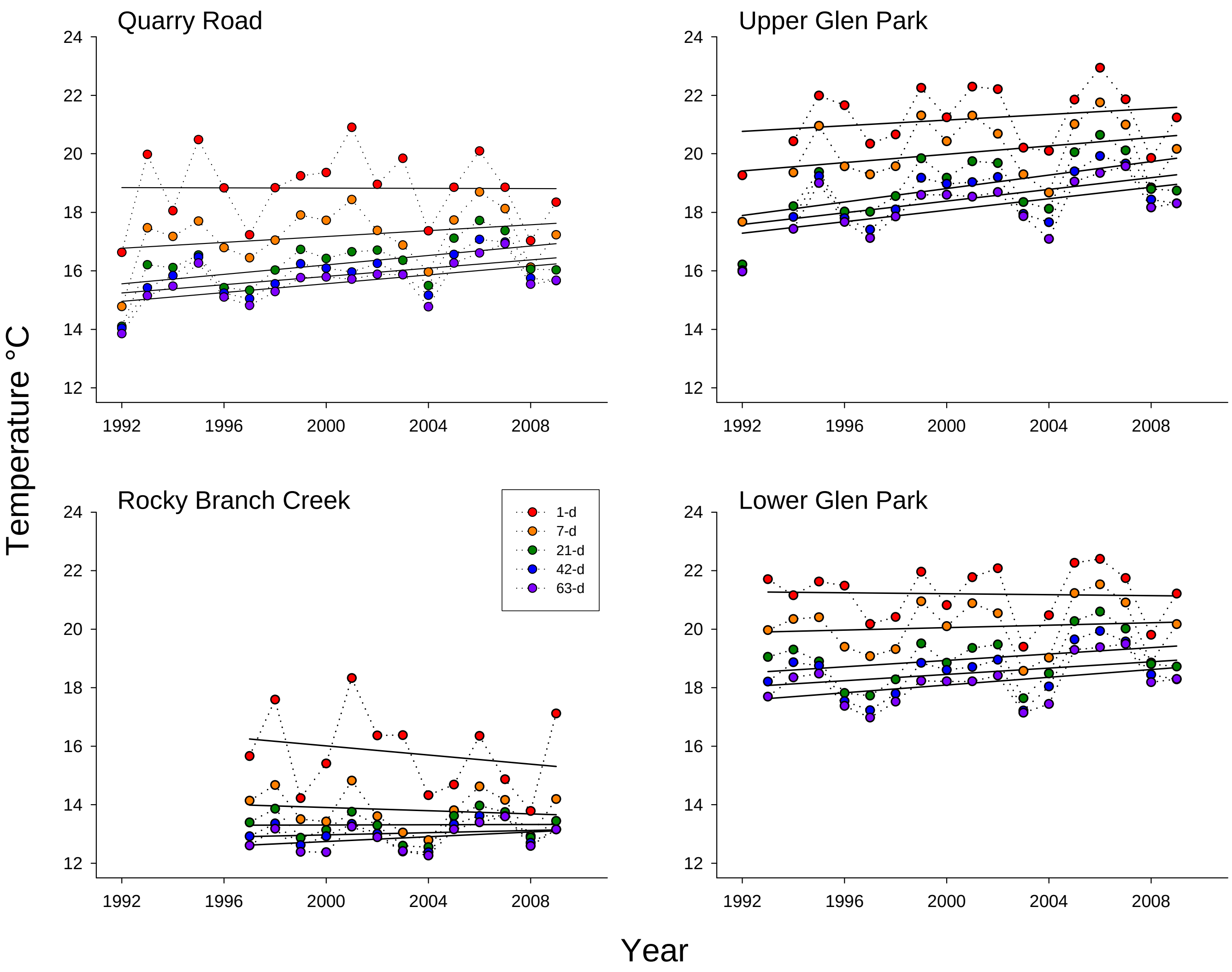


Figure 2.—Maximum daily mean temperature for five exposure periods (1, 7, 21, 42, and 63 days) by year at four stream sites in Pierce and St. Croix counties, Wisconsin (Quarry Road, Upper Glen Park, and Lower Glean Park on the Kinnickinnic River and Rocky Branch Creek, a tributary entering the Kinnickinnic River downstream of the Upper Glen Park site). Regression lines (solid lines) are shown for each exposure period at each site.

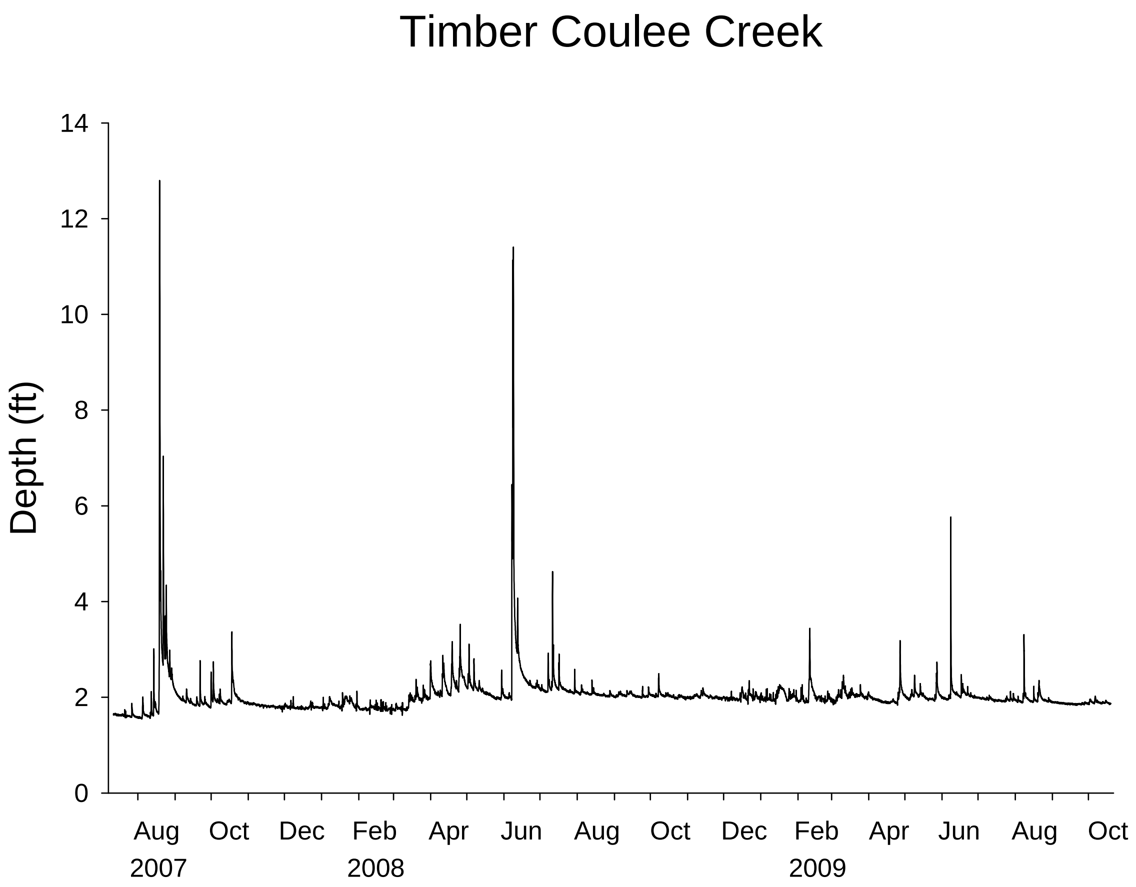
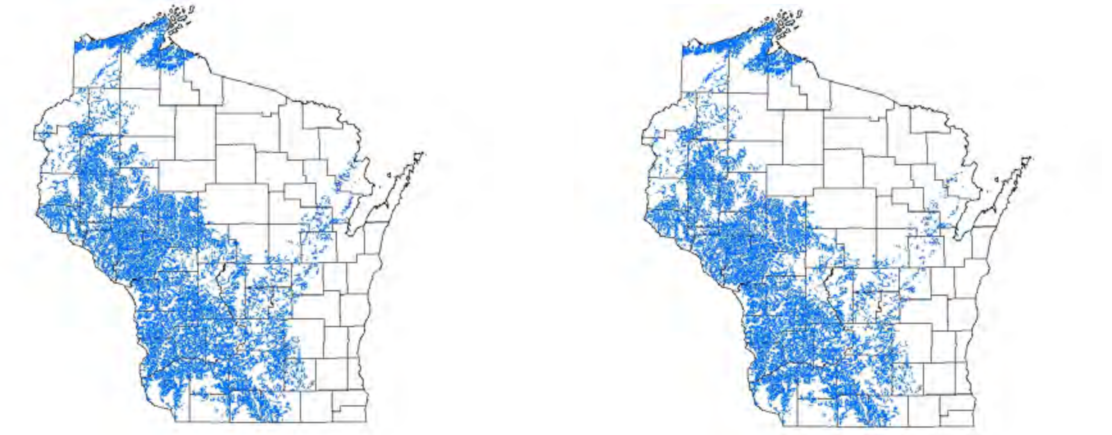


Figure 3.—Water level (depth, measured in ft) in Timber Coulee Creek, Wisconsin, measured hourly from July 2007 to October 2009.

Brown Trout

Current climate

Best case (-7.9%)



Moderate case (-33.1%)

Worst case (-88.2%)

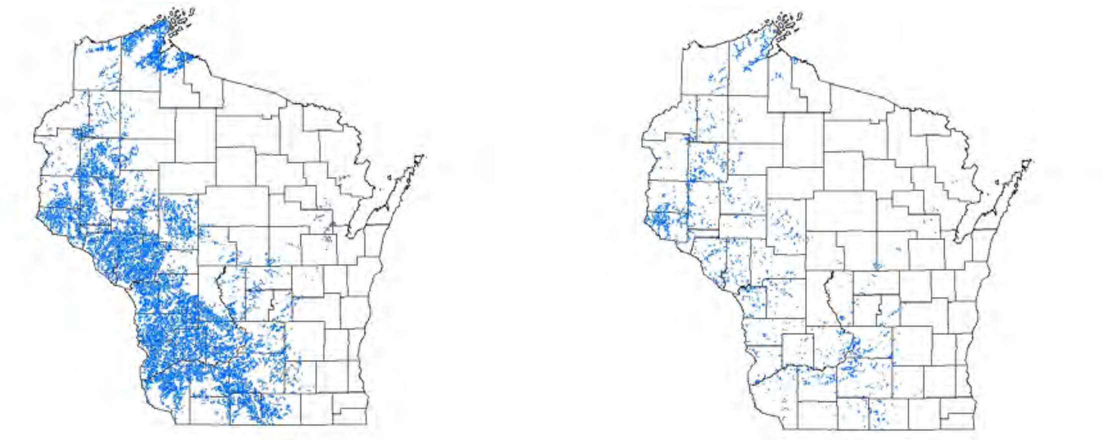
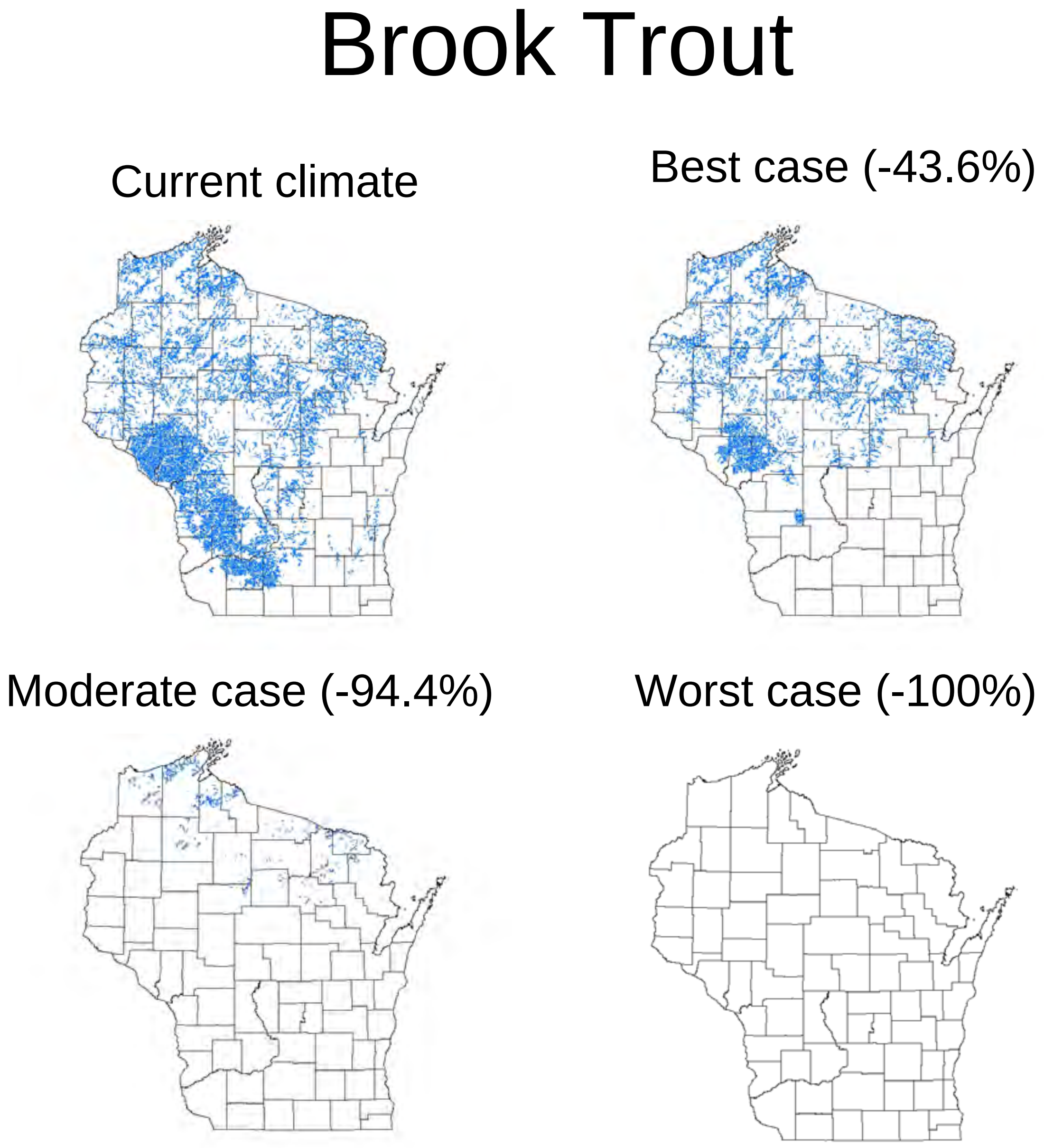


Figure 4.—Predicted distribution of brown trout in Wisconsin streams under current climate conditions and three climate-warming scenarios (see text).



Brook Trout

Current climate

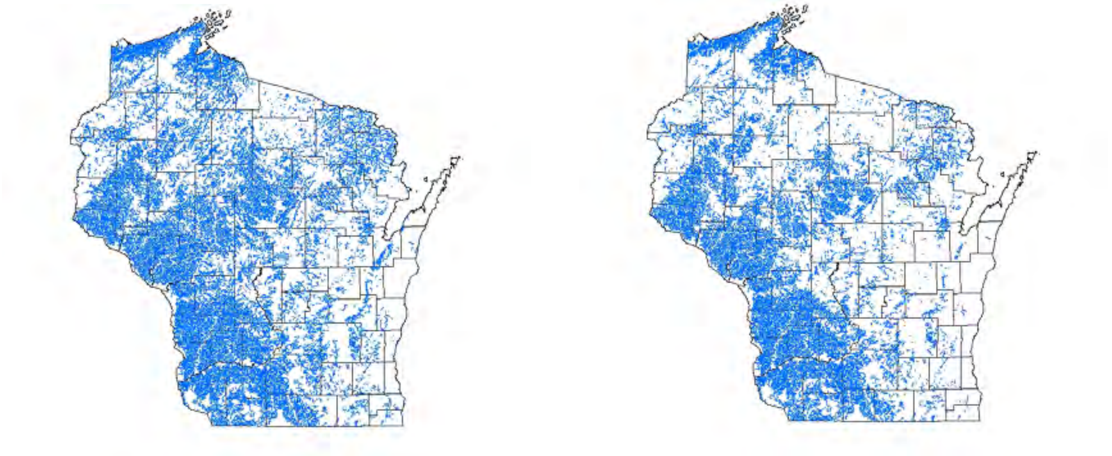
Best case (-43.6%)

Moderate case (-94.4%)

Worst case (-100%)

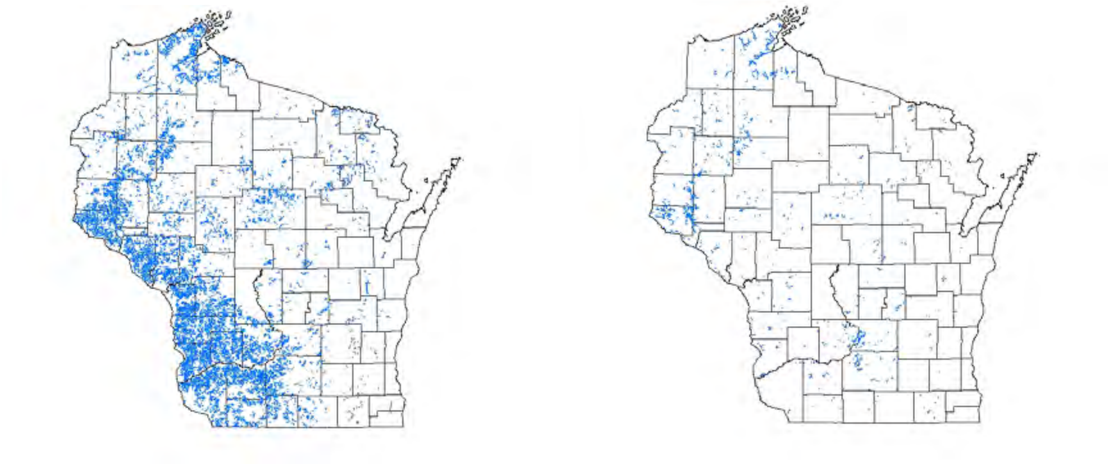
Figure 5.—Predicted distribution of brook trout in Wisconsin streams under current climate conditions and three climate-warming scenarios (see text).

Mottled Sculpin



Current climate

Best case (-21.9%)

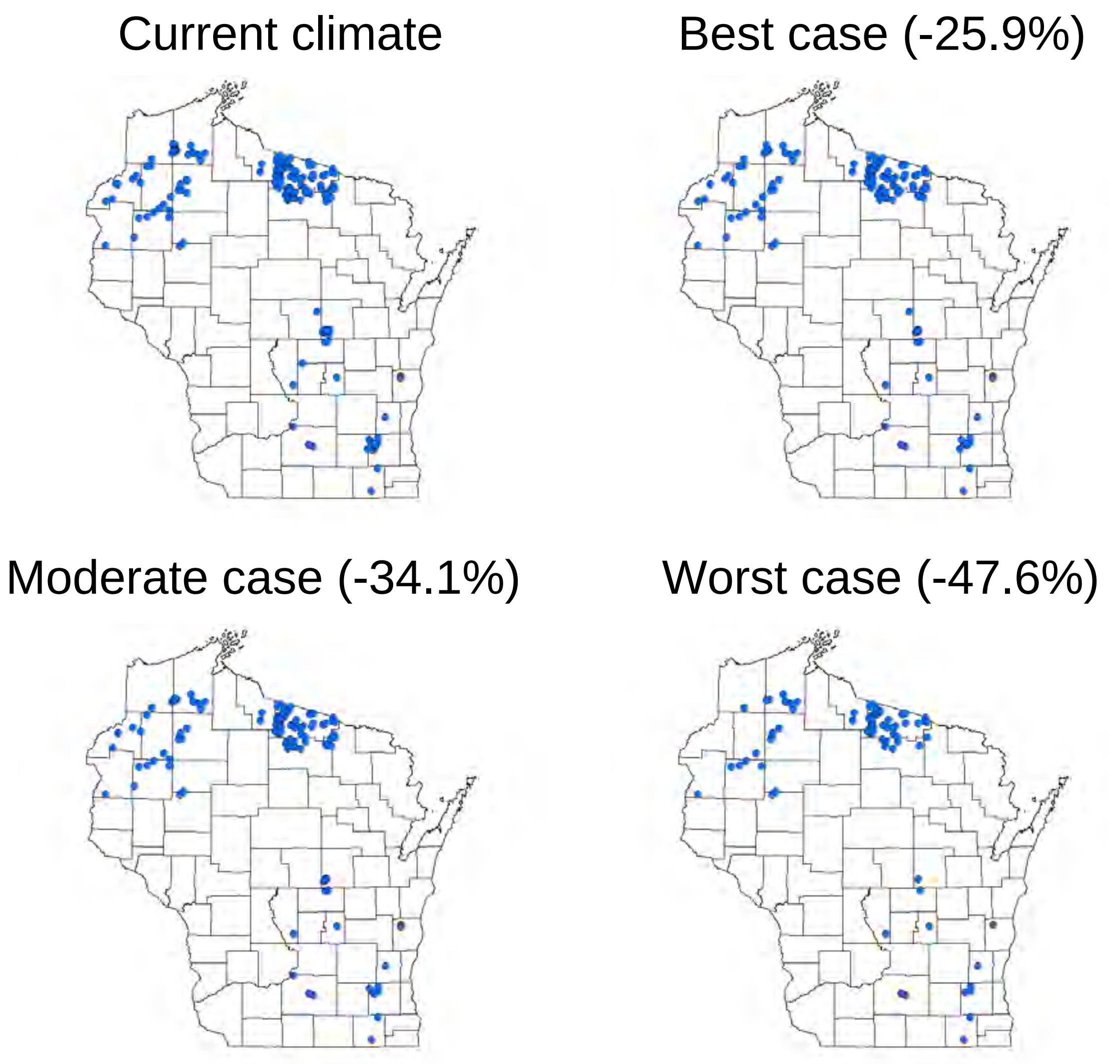


Moderate case (-64.9%)

Worst case (-95.4%)

Figure 6.—Predicted distribution of mottled sculpin in Wisconsin streams under current climate conditions and three climate-warming scenarios (see text).

Cisco



Current climate

Best case (-25.9%)

Moderate case (-34.1%)

Worst case (-47.6%)

Figure 7.—Predicted distribution of cisco in Wisconsin lakes under current climate conditions and three climate-warming scenarios (see text).