Evaluating Trout Stream Restoration Benefits: A Case Study at Pine Creek, Wisconsin

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ABSTRACT: In 2007-2011, the Wisconsin Department of Natural Resources and the Kiap-TU-Wish Chapter of Trout Unlimited conducted an extensive stream restoration project at Pine Creek, a native brook trout stream in the Driftless Area of Wisconsin. Primary project objectives were to remedy severe stream bank erosion and increase brook trout abundance by 40-50%. The project restored 2.11 stream miles at a cost of $270,000. In 2009, the Pine Creek Restoration Project was recognized by the National Fish Habitat Action Plan as one of 10 national "Waters to Watch". Key elements of a monitoring program to evaluate project success included physical and biological attributes measured pre- and post-restoration. Physical attributes included stream temperature and habitat (stream width, water depth, water velocity, canopy cover, stream bank height and cover, and stream bed substrate). Biological attributes included macrophytes, macroinvertebrates, and trout. Beneficial project outcomes included: a decrease in stream temperature, a reduction in stream width, greatly reduced stream bank heights and erosion potential, and increases in water depth, stream bank cover, presence of coarse stream bed substrate, and macrophyte presence. Unanticipated project outcomes included: no change in canopy cover, a decrease in water velocity, no significant improvement in macroinvertebrate metrics, and a significant increase in brown trout abundance and decrease in brook trout abundance. Within eight years post-restoration, numbers of brook trout per mile decreased by 70% (3,800 to 1,200), while numbers of brown trout per mile increased by 3,200% (175 to 5,600). A continuation of this trend may lead to the loss of the brook trout fishery. With brook trout being the only native trout species in the Driftless Area, this project highlights the need for appropriate restoration techniques that can protect and enhance brook trout in streams that could be subject to brown trout co-habitation.

INTRODUCTION

Pine Creek is a third-order, cold-water stream located in Maiden Rock Township, Pierce County, Wisconsin, at the northwestern end of the Upper Midwest's Driftless Area (Figure 1). Pine Creek emanates from a series of large springs and flows westerly into the Mississippi River at Lake Pepin (Figure 2). Consisting primarily of heavily forested coulees and upland agricultural areas, the Pine Creek watershed is part of the karst landscape of the Driftless Area ecoregion, which is characterized by thin loess soils underlain by fractured limestone. The Wisconsin Department of Natural Resources (WDNR) lists Pine Creek as a Class I trout stream that has historically sustained a naturally-reproducing population of brook trout. Approximately 1.8 miles of Pine Creek and 1.1 miles of classified tributaries are protected in the Pine Creek Fishery Area. The lower two miles of Pine Creek are separated from the headwaters by approximately 0.5 mile of subterranean flow (WDNR 2017).

As is characteristic of many streams in the Driftless Area, Pine Creek has good water quality but has suffered from severe stream bank erosion. In the early 20th century, poor agricultural practices and runoff from the watershed mobilized the thin loess soils at the tops of the surrounding bluffs and deposited them in the valley floor. Before a stream restoration project began in 2007, Pine Creek was still moving these deposits, resulting in steeply eroded and raw banks with massive deposition of fine sediment in the streambed. Overgrazing on adjoining pasture lands compounded the erosion and sedimentation problem, which severely limited habitat and brook trout reproduction in Pine Creek.

In 2002 and 2003, the West Wisconsin Land Trust (WWLT) purchased two agricultural properties (a combined 220 acres) that encompass the majority of the Pine Creek Fishery Area, thus conserving these properties forever. With much of the stream corridor in WWLT ownership and open to the public, WWLT, three Trout Unlimited (TU) chapters, and WDNR began planning a stream restoration project in 2006. The goal of the Pine Creek Restoration Project was to enhance and conserve the native brook trout population in Pine Creek by stabilizing severely eroding banks, providing in-stream cover, and improving aquatic habitat in the stream. Measurable project objectives included:

1. Improve stream temperature regime and armor for climate change.
2. Reduce stream bank erosion to 10% of pre-existing conditions.
3. Increase coarse stream bottom substrate by 50%.
4. Increase numbers of brook trout by 40-50%.
5. Increase numbers of brook trout 10 inches and larger by 50-100%.
6. Increase aquatic macrophyte growth by 25%.

During the 2007-2011 period, 2.1 miles of Pine Creek and two major spring tributaries were restored by WDNR, in partnership with TU (Kiap-TU-Wish, Clear Waters, and Twin Cities Chapters), WWLT, Fairmount Santrol, the National Fish Habitat Action Plan (NFHAP), the U.S. Fish and Wildlife Service, the Trout and Salmon Foundation, and Patagonia (Sours, 2011). The total cost of the Pine Creek Restoration Project was $270,000 ($24 per lineal foot of stream). In 2009, the success of the project was recognized by the NFHAP, which listed Pine Creek as one of 10 national "Waters to Watch".

Stream restoration is an integral part of trout stream management in Wisconsin, with the restoration work generally targeting Class I or Class II trout streams. Although stream restoration may take different forms, it 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 toward stream habitat restoration work. Hunt (1988) and Avery (2004) have documented a half century (1953-2000) of evaluations of trout stream habitat restoration projects in Wisconsin, and have shown how restoration has been successful at improving trout populations in terms of trout number and size (Mitro, Lyons, and Sharma, 2011).

The Pine Creek Restoration Project was accomplished using techniques developed by WDNR fisheries managers across the Driftless Area (White and Brynildson, 1967; Hunt, 1993). Steep eroding banks were sloped back (typically at a 3:1 slope) to open the stream channel to the flood plain, thereby dissipating flood energy. As a result, stream bank erosion and sedimentation are greatly diminished, water can infiltrate in the riparian area, and water pollutants can be removed and processed. Where suitable, "LUNKER" structures were added to provide trout cover from predators and refuge during floodwaters (Vetrano, 1988). These structures were covered with rock and soil and then reseeded to stabilize the stream banks. Boulder clusters and root wads were installed to enhance midstream cover. In addition, plunge pools were excavated to create deep water and over-wintering habitat. The installation of bank cover narrows the stream, which results in bottom scouring that exposes gravel substrate favorable for aquatic insects and successful trout reproduction. Bank stabilization results in a decrease in suspended sediment during runoff events, thus improving water quality in the stream. An improvement in the temperature regime of the stream may also occur, due to a narrower, deeper channel, increased current velocity, and bank shading.

With degraded cold-water streams present throughout the Driftless Area, and with global climate change posing an increasing threat to these sensitive systems, stream restoration is a critical tool for enhancing and protecting aquatic ecology, and upland restoration is an effective means of improving water quality and sequestering carbon. With limited resources available, it is imperative that restoration practices produce the best long-term outcomes with the most efficient use of funding, for public use and enjoyment.

METHODS

Stream restoration monitoring can be defined as the systematic collection and analysis of data that provides information useful for measuring project performance, determining when modification of efforts is necessary, and building long-term public support for habitat protection and restoration (Thayer et al. 2005). All parties involved with stream restoration projects, from grantor to practitioner to land manager, are vested in the outcomes of these projects and therefore benefit from feedback on project successes and failures. Such feedback is critical in expanding the collective knowledge of the relatively young science of stream and watershed restoration, fine tuning techniques, and enhancing maintenance regimes. Also, by directing the maintenance of existing projects and improving the design of future projects, such evaluation may increase the credibility of restoration efforts in the eyes of participating landowners and the public. More formally, grant administrators are requiring an increased level of accountability from grantees, including documentation that financial resources were used for the purposes requested and that they produced the desired results (Reeve et al. 2006).

Ecological success in a restoration project cannot be declared in the absence of clear project objectives from the start and subsequent evaluation of their achievement (Dahm et al. 1995). Monitoring objectives are directly connected to the goals and objectives of the restoration project and the two should be integrated starting from the project design stage (Kondolf and Micheli 1995). Understanding this connection and integration of the project's expected outcomes with monitoring will increase the ability to use monitoring effectively as a management tool.

Because of the cost and visibility of the Pine Creek Restoration Project, it was very important to document the achievement of the project objectives, as presented above. This was accomplished by measuring pre- and post-restoration temperature and habitat conditions, trout densities and size distribution, and macrophyte and macroinvertebrate community health. Evaluation of the project objectives was conducted jointly by local WDNR fisheries staff and Trout Unlimited (Kiap-TU-Wish Chapter) volunteers, via collection of pre- and post-restoration temperature, habitat, and biotic data.

Temperature Monitoring:

To determine whether the Pine Creek Restoration Project improved the stream temperature regime (Objective 1), continuous pre- and post-restoration monitoring of Pine Creek stream temperatures has been conducted at six sites since April 2007 (Figure 3), using methods described in Hastings, et al. (2011).

Air temperature is the climate variable that best explains spatial and temporal variation in stream temperature (Mitro, Lyons, and Sharma 2010). Because of the impact of air temperature on water temperature, it is important to monitor air temperature in the locale where stream temperature monitoring sites have been established. Since 2007, continuous monitoring of ambient air temperature, relative humidity, and dew point has been conducted at a weather station established in the Pine Creek Restoration Project area (Figure 3), using methods described in Hastings, et al. (2011).

Habitat Assessment:

Pre- and post-restoration assessments of Pine Creek habitat conditions were conducted at 18 locations within the project restoration area (Figure 4), using methods described in Hastings, et al. (2011). Measurements within the stream channel included channel width, water depth, flow velocity, stream bed composition, embeddedness, and canopy cover. Measurements of the stream banks included stream bank height, depth, slope, soil composition, and vegetative cover. Pre-restoration habitat assessment work was conducted in May 2007, June 2007, and May 2008. Post-restoration habitat assessment work was conducted in June 2015, September 2015, and July 2016. Habitat assessment data were used in part to determine whether project Objectives 2 and 3 were met. Data were also used to better understand if changes in stream channel morphology may have contributed to any observed improvements in the Pine Creek temperature regime (Objective 1).

Biological Monitoring:

Trout:

Hunt (1971) has emphasized the critical need to document quantitative changes in trout populations and their environment as a result of stream restoration. At Pine Creek, WDNR fisheries staff have been conducting trout surveys at two sites within the restoration project area (Figure 5), using WDNR monitoring protocols for coldwater wadeable streams (WDNR 2001 and 2007; Lyons et al. 1996). To conduct the survey work, WDNR staff use a stream barge electrofishing unit with 3 electrodes. The generator runs DC at 100-200V and 4A. The survey crew consists of the three electrode handlers/netters and a boat operator/puller. The survey station length is 35 times the mean stream width, which was calculated pre-restoration and continues to be used post-restoration. Surveys are conducted on a catch per unit effort basis, using one pass in an upstream direction. Effort time is recorded but trout numbers are generally compared by distance (number per mile). Air and water temperatures and weather conditions are also recorded on the day of the survey. Any extenuating circumstances (flooding, turbidity, excessive plant growth, etc.) which may have an effect on the catch rate are also noted. All trout surveys are conducted between June 15 and September 15, to allow capture of young-of-year fish.

Trout surveys in the upper part of the restoration area (Station 2A) were conducted in 2000, then annually during the 2005-2017 period. Pre-restoration survey years at Station 2A include 2000 and 2005-2008. Post-restoration survey years at Station 2A include 2009-2017. The stream length surveyed at Station 2A was 200 meters. Trout surveys in the lower part of the restoration area (Station 2B) were conducted during the 2005-2010 period. Pre-restoration survey years at Station 2B include 2005-2007, while post-restoration survey years at Station 2B include 2008-2010. The stream length surveyed at Station 2B was 172 meters. Electrofishing gear was used to collect trout at each station, according to WDNR protocols Survey data included brook and brown trout numbers and lengths. Based on the stream distance surveyed at each station, numbers of brook and brown trout per mile were estimated for young-of-year fish, adult fish in multiple size categories (typically one- two-inch length increments), and all size categories combined (total trout per mile). The WDNR trout survey data were used to determine whether project Objectives 4 and 5 were met.

Macrophytes:

At the 18 habitat assessment sites within the project restoration area (Figure 4), pre- and post-restoration macrophtye presence was estimated within each transect to the nearest 5%, by visual inspection. The observations of macrophyte presence were made as a part of the habitat assessment work described above. The macrophyte data were used to determine whether project Objective 6 was met.

Macroinvertebrates:

Pre- and post-restoration monitoring of the Pine Creek macroinvertebrate community was conducted at 8 locations within the project restoration area (Figure 6), using the single-habitat kick-sampling method described by Hilsenhoff (1987 and 1988) and Plafkin, et al. (1989). Pre-restoration macroinvertebrate samples were obtained in June 2009, while post-restoration macroinvertebrate samples were obtained in June 2013. With the exception of oligochaetes, all macroinvertebrates in these samples were identified to the genus level. The taxonomic analysis was conducted by Dr. Leonard Ferrington, Professor in the Department of Entomology at the University of Minnesota. Multiple metrics were used to compare the pre- and post-restoration macroinvertebrate communities (Barbour, et al. 1999). These metrics included richness measures (total number of taxa, number of EPT taxa, number of chironomidae taxa), composition measures (% EPT taxa, % chironomidae taxa), and tolerance/intolerance measures (% dominant taxon and the Hilsenhoff Biotic Index (HBI) (Hilsenhoff (1987 and 1988)). Although no project objective was established for macroinvertebrates, monitoring was helpful to determine whether restoration benefits were evident for this critical component of the coldwater community.

RESULTS

Stream Temperature:

The pre- and post-restoration stream temperature regimes in Pine Creek were compared using annual stream temperature data from 2008 (pre-restoration) and 2012 (post-restoration).

Pine Creek emanates from a large spring upstream from the restoration project reach (Figure 3). Continuous temperature monitoring has been conducted at the Pine Creek Spring (PC-Spring) since May 2011. The 2012 data for PC-Spring indicate that Pine Creek groundwater temperatures vary annually within a very small range (8.1-9.1^{o}C), with the coolest spring temperatures (8.1-8.3^{o}C) evident in a period from early April to early July, and the warmest temperatures (8.9-9.1^{o}C) evident in a period from late September to early January. These data suggest that the aquifer providing groundwater for Pine Creek experiences a delayed temporal response to air temperature. This pattern seems particularly advantageous to cold-water biota, providing the coldest groundwater entering the warmest summer month (July), and the warmest groundwater during the late fall and winter months, when air temperatures are coldest. Luhmann et al. (2011) have noted the same phase-shifted seasonal temperature signal in some Minnesota springs, and they suggest that these seasonally varying temperatures reflect groundwater discharges from shallow aquifers. On average, however, the annual PC-Spring temperature (8.6^{o}C) was nearly identical to the annual air temperature at

Pine Creek (8.7° C), supporting the observation that groundwater temperatures are near mean annual air temperatures (O'Driscoll and DeWalle, 2004; Krider, et al., 2013). This circumstance suggests that groundwater temperature, like stream temperature, is vulnerable to air temperature and climate change, especially in shallow aquifers (Taylor and Stefan, 2009).

Pre- and post-restoration mean summer (June-August) temperatures at Pine Creek monitoring sites were nearly identical (Figure 7), ranging from 9.2° C at PC-U1 to 11.6° C at PC-L3. According to Cunningham et al. (2014), the optimum temperature range for brook trout is 13-16° C. Combining all temperature data for the monitoring sites in the restoration project reach, 99.6% of pre- and post-restoration summer temperatures were less than 16° C (top of optimum temperature range for brook trout). Both pre- and post-restoration temperature data indicate a strong groundwater influence and an exceptional temperature regime for brook trout in Pine Creek.

In spite of a strong groundwater influence and an exceptional temperature regime for brook trout, reach-scale impacts of air temperature on water temperature are still very significant in Pine Creek, as shown in Figure 8. Post-restoration (2012) temperatures increased markedly from upstream (PC-U1) to downstream (PC-L3) through the 2,665-meter (1.7-mile) restoration reach, as the stream moved away from headwater groundwater sources and became increasingly susceptible to air temperature. The pre- and post-restoration influence of air temperature on stream temperature is also noted in the downstream increase in mean summer temperatures through the restoration reach (Figure 7).

Vulnerability of stream temperature to air temperature and long-term climate change has been noted as a critical concern for Wisconsin's coldwater resources (Mitro et al., 2011). Mitro et al. (2011) conducted ecological modeling exercises to predict the changes in coldwater habitat that might occur under three climate change scenarios. The three scenarios included (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; (2) a "moderate case" scenario, in which air temperature increased by 3°C and water temperature by 2.4°; and (3) a "worst case" scenario, in which air temperature increased by 5°C and water temperature by 4°C. Modeling results indicated that climate change could lead to major declines in the occurrence and distribution of brook trout in Wisconsin streams (Figure 9).

Mitro et al. (2011) note that stream restoration benefits include protecting streams from the impacts of climate change. Gaffield et al. (2005) suggest that the most important factors controlling summer stream temperatures include the inflow of coldwater, shade provided by canopy cover and riparian vegetation, stream channel width, water depth, and water velocity, all of which should be key considerations for stream restoration projects. Mitro et al. (2011) 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.

One of the key objectives of the Pine Creek Restoration Project was to improve the stream temperature regime and armor the stream for climate change (Objective 1). Krider (2012) and Krider, et al. (2013) used a simple linear regression model to examine the air-water temperature relationships for 40 groundwater-fed streams in southeastern Minnesota. This regression model of line slope versus intercept can be used to identify streams for which water temperatures are more meteorologically-controlled than hydrologically-controlled, and thus more vulnerable to climate change. In this instance, the model worked well for comparing the pre- and post-restoration temperature regimes at each of the Pine Creek monitoring locations. An example of the application of Krider's model to pre- and post-restoration stream temperatures at PC-L1 is provided in Figure 10. A post-restoration improvement in stream temperature at this location is evident by the reduced slope of the post-restoration regression line (0.1471), compared to the slope of the pre-restoration regression line (0.1838), indicating a reduced susceptibility of stream temperature to air temperature post-restoration. At upstream locations in the restoration reach (PC-U1 and PC-U2), those closest to groundwater sources and hydrologically-dominated, no post-restoration temperature improvements were noted. However, post-restoration temperature improvements were evident at all downstream locations in the restoration reach (PC-L1, PC-L2, and PC-L3), those more distant from groundwater sources and more subject to air temperature influence. Due to reach-scale impacts of air temperature (Figures 7 and 8), these temperature improvements became less apparent at PC-L2 and PC-L3. Although subtle, this shift in the air-water temperature relationship through the lower restoration reach provides a buffer against future climate change impacts on Pine Creek.

<u>Habitat Assessment:</u>

A comparative summary of the pre- and post-restoration habitat metrics measured at 18 survey locations along the Pine Creek project reach is presented in Table 1. The data represent the mean pre- and post-restoration condition for each metric, based on survey measurements from all 18 locations.

Pine Creek Habitat Assessment Summary

Habitat Metric	Pre-Restoration	Post-Restoration	Difference	% Change
Stream Channel:				
Channel Width (m)	5.5	3.3	-2.2	-40
Water Depth (m)	0.24	0.42	0.18	75
Flow Velocity (m/s)	0.19	0.16	-0.03	-16
Coarse Substrate (%)	40	65	25	62
Embeddedness (%)	60	35	25	-42
Canopy Cover (%)	20	16	4	-20
Macrophyte Presence (%)	15	35	20	133
Stream Banks:				
Bank Height (m)	1.07	0.41	0.66	-62
Bank Depth (m)	1.70	0.66	1.04	-61
Bank Slope (%)	33	33	0	0
Vegetative Cover (%)	75	95	20	27

Table 1. A summary of pre-restoration vs. post-restoration habitat conditions in Pine Creek

Within the Pine Creek stream channel, the restoration project produced some notable improvements, including a 40% reduction in channel width, a 75% increase in water depth, a 62 % increase in the presence of coarse stream bed substrate (gravel, rubble, and boulders), a 42% reduction in embeddedness, and a 133% increase in macrophyte presence. Based on these data, Project Objectives 3 and 6, related to increases in the presence of coarse stream bottom substrate (50%) and aquatic macrophyte growth (25%), were readily met. The 40% reduction in channel width and the 75% increase in water depth may have been important factors contributing to the improved stream temperature regime in the lower restoration reach.

Conversely, improvements in flow velocity and canopy cover, two additional key factors controlling summer stream temperatures (Gaffield, et al., 2005), were not achieved by the project work. The slight reduction in flow velocity (16%) was likely influenced by the increased presence of macrophytes (133%) in the post-restoration project reach. These macrophytes consisted primarily of watercress and several varieties of aquatic grasses. The slight reduction in canopy cover (20%) was not unexpected, as brushing of the stream banks occurred prior to the restoration work, largely to remove undesirable boxelder trees. As a caveat, evaluation of canopy cover for this project was conducted using a spherical densitometer, which primarily measures forest overstory. As such, the canopy cover estimates did not fully capture any benefits of the streamside shading provided by post-restoration riparian vegetation.

A reduction in stream bank erosion is a primary objective of all WDNR trout stream restoration projects, and is noted as Project Objective 2 for the Pine Creek Restoration Project. Pre- and post-restoration stream bank erosion potential was not directly measured as a part of the project monitoring program, making it difficult to determine whether this objective was met. However, substantial reductions in bank height (62%) and bank depth (61%) were achieved, and stream banks were stabilized with rock and re-vegetated. As a result of project re-vegetation, a 27% increase in stream bank vegetative cover was evident post-restoration. All of these restoration benefits resulted in a considerable reduction in stream bank erosion potential within the Pine Creek restoration reach.

Biological Monitoring:

Trout:

Improvement of the native brook trout fishery was a primary focus of the Pine Creek Restoration Project, as noted in project objectives 4 and 5. Since WDNR Station 2A in the upper part of the restoration area has the best record of annual trout survey data, this station can be used to compare the pre- and post restoration trout populations. A caveat of the survey data at Station 2A is the assumption that this station is representative of trout abundance and size in the remainder of the restoration reach.

A comparison of the pre- and post-restoration abundance of brook trout in Pine Creek (expressed as total trout/mile) is shown in Figure 11. The pre-restoration abundance of brook trout in Pine Creek was already robust, ranging from 1,905-5,609 trout/mile and averaging 3,817 trout/mile during the five-year pre-restoration survey period. The brook trout population immediately benefited from the restoration work, with post-restoration abundance increasing dramatically to 7,787-7,964 trout/mile in 2009-2010. In subsequent years, however, brook trout abundance in Pine Creek has experienced a steep decline, reaching a minimum of 1,213 trout/mile in 2016. As of 2016, brook trout abundance has decreased by 68%, compared to mean pre-restoration abundance. Project objective 4 targeted a 40-50% increase in brook trout numbers.

A comparison of the pre- and post-restoration abundance of 10-inch plus brook trout in Pine Creek shows a similar trend (Figure 12). Annual pre-restoration abundance of these larger brook trout varied widely, ranging from 0-72 trout/mile and averaging 31 trout/mile during the five-year pre-restoration survey period. After a rapid post-restoration increase that peaked at 104 trout/mile in 2011, the abundance of 10-inch plus brook trout has declined dramatically, reaching a minimum of 0 trout/mile in 2015. As of 2016, the abundance of 10-inch plus brook trout in Pine Creek has decreased by 74%, compared to mean pre-restoration abundance. Project objective 5 targeted a 50-100% increase in 10-inch plus brook trout numbers.

While the post-restoration abundance of brook trout in Pine Creek has been rapidly decreasing, the post-restoration abundance of brown trout has increased markedly (Figure 13). Small numbers of brown trout were present in annual pre-restoration surveys at Station 2A, but the brown trout proportion of total trout abundance never exceeded 7%, with the stream dominated by brook trout. The post-restoration abundance of brown trout in 2009-2010 remained similar to the pre-restoration abundance. However, a steep increase in brown trout abundance began in 2011, with the greatest increase occurring between 2013 and 2014. In 2016, brown trout abundance in Pine Creek reached 5,633 trout/mile, representing a 3,137% increase, compared to mean pre-restoration abundance. The pre- and post-restoration abundance of both brook trout and brown trout in the Pine Creek restoration reach is shown in Figure 14. On average, pre-restoration trout abundance in Pine Creek was 3,991 trout/mile, with brook and brown trout present in a 96%:4% proportion. In comparison, post-restoration trout abundance has averaged 6,299 trout/mile, with brook and brown trout present in a 62%:38% proportion. However, with rapidly-increasing numbers of brown trout in Pine Creek since 2011, the proportion of brook trout has decreased to 18% in 2016.

Macrophytes:

A comparison of pre- and post-restoration macrophyte presence in the Pine Creek restoration reach is presented in Table 1 and discussed in the **Habitat Assessment** results, above.

Macroinvertebrates:

A comparative summary of the pre- and post-restoration macroinvertebrate metrics for the Pine Creek project reach is presented in Table 2. Values for total taxa, EPT taxa, and Chironomidae taxa represent the sum of all unique taxa present in these categories at the eight macroinvertebrate monitoring locations. Each HBI value represents a mean of the eight individual HBI values calculated for each monitoring location.

Summary of Pine Creek Macroinvertebrate Metrics

	Pre-Restoration	**Post-Restoration**	**% Change**
Total Taxa	57	39	-32
EPT Taxa	9	7	-22
% EPT Taxa	16%	18%	
Chironomidae Taxa	25	16	-36
% Chironomidae Taxa	44%	41%	
HBI Value	4.36	4.42	1

Table 2. A summary of pre-restoration vs. post-restoration macroinvertebrate metrics in Pine Creek

A post-restoration reduction in macroinvertebrate diversity was evident in Pine Creek, including a 32% reduction in total taxa, a 22% reduction in EPT taxa, and a 36% reduction in Chironomidae taxa. Chironomidae taxa represented the predominant share of total taxa, comprising 44% of the pre-restoration taxa and 41% of the post-restoration taxa. EPT taxa accounted for relatively small proportions of the pre- and post-restoration macroinvertebrate taxa, at 9% and 7%, respectively. Pre-restoration, the three most common genera at all monitoring locations were *Baetis* (mayfly), *Simulium* (blackfly), and *Gammarus* (amphipod). Post-restoration, the three most common genera at all monitoring locations were *Baetis*, *Orthocladius/Cricotopus* (midge), and *Gammarus*. On a site-by-site basis, the post-restoration diversity of total taxa, EPT taxa, and Chironomidae taxa generally decreased at the three sites in lower Pine Creek and increased at the three sites in Upper Pine Creek and the two tributary sites. Pre- and post-restoration HBI values were nearly identical and representative of very good water quality (possible slight organic pollution) (Hilsenhoff, 1987).

DISCUSSION

Pre- and post-restoration monitoring of stream temperature, habitat, and biota was an integral part of the Pine Creek Restoration Project, providing a wealth of information on project outcomes, including benefits, unintended consequences, and opportunities for improvement. Monitoring also enabled a determination of whether the six key project objectives were met (see **INTRODUCTION** and **RESULTS**).

Stream Temperature Improvement:

Of the factors affecting the presence and distribution of brook trout in the Upper Midwest's Driftless Area, stream temperature is key (Cunningham et al., 2014). Furthermore, climate change poses a critical threat to Driftless Area brook trout, with projected impacts in Wisconsin described by Mitro et al. (2011). As such, stream temperature improvement should be a primary stream restoration objective.

The Pine Creek Restoration Project demonstrated that improvements in the stream temperature regime are possible by reducing stream channel width and increasing water depth, as suggested by Mitro et al. (2011) and Gaffield et al. (2005). However, increases in flow velocity and canopy cover, two additional key factors controlling summer stream temperatures (Gaffield, et al., 2005), were not achieved by the project, representing a lost opportunity to further enhance the stream temperature regime in Pine Creek. The slight reduction in flow velocity (16%) was likely influenced by the desired increased presence of macrophytes (133%) in the post-restoration project reach. The slight reduction in canopy cover (20%) was not unexpected, as brushing of the stream banks occurred prior to the restoration work, largely to remove undesirable boxelder trees and prepare the restoration reach for stream bank modifications. However, the project plan did not include post-restoration reforestation as an opportunity to enhance future canopy cover and provide increased shading along the restoration reach. A 27% post-restoration increase in riparian vegetative cover was evident at Pine Creek, and re-establishment of riparian grasses and non-woody vegetation along the restoration reach may provide some shading and temperature benefits. However, Cross et al. (2013) note that riparian reforestation will strengthen thermal resistance in trout streams. Riparian forests are important for maintaining thermal conditions suitable for brook trout in central Wisconsin streams and can be managed to increase the amount of stream habitat thermally suitable for brook trout. Riparian tree-vegetated stream segments had a significantly lower mean change in stream temperature per kilometer of stream compared with grass-vegetated stream segments during periods of maximum daily and weekly average temperatures. Blann et al. (2002) also note the importance of riparian vegetation restoration as one of the most effective management activities for improving stream temperature and mitigating the effects of climate change. Wooded buffers provided a greater stream temperature benefit than successional buffers (grasses and forbs) when stream width exceeded 2.5 meters, which reflects the post-restoration condition (3.3 meters) at Pine Creek. Cunningham et al. (2014) suggest that riparian reforestation will likely be required to sustain brook trout in “at-risk” watersheds.

Erosion Reduction and Floodplain Access:

Watersheds of the coldwater streams in the unglaciated Driftless Area are characterized by steep topography and valleys (Figure 1) that are highly susceptible to human-induced erosion and floodplain sedimentation (Booth 2012).

Booth (2012) notes that the combination of increased erosion from cropland, pasture, and gullies and increased surface runoff has resulted in substantial sediment delivery to streams and valleys throughout the Driftless Area during flood events. The sediment supply increased more than stream transport capacity and as a consequence, a majority of this sediment is now stored within local drainage systems, mostly in floodplains as overbank deposition (Knox 2006). These deposits, known as post-settlement alluvium, can exceed several meters in thickness in some larger tributary valleys. It has been estimated that over 75% of the post-settlement alluvium is still stored within many of the small tributary watersheds of the Driftless Area (Trimble 1999). Stream channel and valley morphologies have subsequently changed with this influx of sediment from the uplands (Booth 2012). Increased sediment supply and water discharge have increased stream power, creating wider and shallower channels in headwater tributaries (Knox 1977). These stream channels typically migrate within the floodplain alluvium, and the channels often become deeply incised, with high banks subject to erosion and sediment delivery to the stream. Soil conservation practices, implemented beginning in the 1930s, have substantially reduced upland sediment sources (Trimble and Lund 1982). However, much more sediment moves through tributary channels now than before settlement, due to re-mobilization of historical floodplain deposits through lateral channel erosion and continued upland erosion, primarily from croplands (Booth 2012).

This history of human-induced sediment deposition in the floodplains of Driftless Area streams creates a high potential for stream channel and stream bank erosion. As such, a reduction in stream bank erosion is a primary objective of all WDNR trout stream restoration projects, and is noted as Project Objective 2 for the Pine Creek Restoration Project. With a wide stream channel (5.5 m), a relatively shallow water depth (0.24 m), a high width:depth ratio (22.9), and high stream banks (1.07 m), pre-restoration habitat conditions in Pine Creek were typical of unrestored Driftless Area coldwater streams. The Pine Creek Restoration Project substantially reduced the width:depth ratio (7.9) and stream bank height (0.41 m). Stream banks were also stabilized with rock and re-vegetated, with a 27% increase in stream bank vegetative cover evident after restoration. All of these restoration benefits resulted in a considerable reduction in stream bank erosion potential within the Pine Creek restoration reach.

With greatly reduced stream bank heights after restoration, Pine Creek has re-connected to its floodplain, with benefits including reduced flood energy and erosion potential, water storage in the floodplain, capture and processing of water quality pollutants such as suspended sediment and nutrients, and groundwater recharge. Mitro et al. (2011) note that precipitation events are expected to become more frequent and intense with climate change, leading to large, short-term inputs of water into streams. In these circumstances, floodplain connectivity via stream restoration will be an important factor for mitigating climate change impacts.

Changes in Trout Dynamics:

The main impetus for the Pine Creek Restoration Project and the primary project goal was to enhance and conserve the native brook trout population in Pine Creek. However, within five years post-restoration, Pine Creek had become dominated by brown trout (Figure 14), a significant unanticipated consequence of the restoration project. By 2013, brook trout abundance in Pine Creek was lower than that during any of the five pre-restoration years surveyed, and abundance has continued to decline through 2016. This outcome represents a dramatic reversal of brook trout presence in Pine Creek, falling far short of Project Objective 4, a 40-50% increase in brook trout numbers.

Brown trout were already present in Pine Creek before the restoration project began (Marty Engel, personal communication, 2017). However, brown trout abundance was very low, ranging from 233-321 trout/mile during the pre-restoration period of 2006-2008 (Figure 14). In comparison, brook trout abundance ranged from 4,195-5,609 trout/mile during the same period, with brook trout comprising 94% of the Pine Creek trout population.

WDNR lists Pine Creek as a Class I trout stream that has historically sustained a naturally-reproducing population of brook trout. Although the pre-restoration abundance of brown trout in Pine Creek was very low (6%), WDNR was concerned about their presence in a naturally-reproducing brook trout stream. As a result, WDNR trout survey crews attempted to purge Pine Creek of brown trout via shocking and removal in 2007 and 2008. However, trout surveys in 2009 and 2010 showed that this effort was unsuccessful, and brown trout removal was no longer a viable management option as post-restoration brown trout abundance increased rapidly (Engel, personal communication, 2017).

The Pine Creek Restoration Project resulted in a major expansion of the Pine Creek trout population, with mean post-restoration trout abundance (6,299 trout/mile) representing a 58% increase over mean pre-restoration trout abundance (3,991 trout/mile) (Figure 14). Brook trout experienced an immediate but short-lived benefit of the restoration project, with abundance peaking at 7,787-7,964 trout/mile in 2009-2010. Since 2011, however, brown trout abundance has increased rapidly at the expense of brook trout abundance, which reached a low point in 2016 (1,213 trout/mile and 18% of the total trout population). Although the mean post-restoration abundance of brook trout in Pine Creek increased by 2%, compared to mean pre-restoration abundance, brook trout abundance had decreased by 68% as of 2016. Hence, the 58% increase in mean post-restoration trout abundance is due to the substantial expansion of brown trout presence in Pine Creek.

Engel (personal communication, 2017) notes that the post-restoration success of brown trout in Pine Creek may be due in part to their ability to out-compete brook trout for occupation of the best available habitat, which the restoration project created via installation of LUNKER structures, boulder clusters, and root wads. Fausch and White (1981) note that brown trout exclude brook trout from preferred resting positions, a critical and scarce resource. The combined effects of such interspecific competition, an increased susceptibility of brook trout to angling, differential response to environmental factors, and predation of brown trout on juvenile brook trout may account for declines of brook trout populations while brown trout populations expand in many streams where the two species co-exist. Hitt et al. (2017) note that the distribution of native brook trout in eastern North America is often limited by brown trout, in part via interference competition for access to thermal refugia and forage habitats.

The post-restoration increase in overhead cover and shade provided by LUNKER structures and root wads may also favor the presence of brown trout in Pine Creek. Cover is recognized as one of the basic and essential components of trout streams, as noted by Boussu (1954), Lewis (1969), and Raleigh (1982). In a study to determine the amount of shade utilized by brook, rainbow, and brown trout, Butler and Hawthorne (1968) reported that rainbow trout showed the lowest preference for shade produced by artificial surface cover. Brown trout showed the highest use of shade, while brook trout were intermediate between brown and rainbow trout.

Engel (personal communication, 2017) believes that habitat restoration in brook trout streams will result in improved brook trout populations and size structure. However, if brown trout have access to these streams, brown trout will prevail but not totally eliminate brook trout. The dramatic post-restoration change in trout dynamics in Pine Creek suggests that trout stream restoration in the Driftless Area should not be a "one size fits all" exercise. An exceptionally cold temperature regime in Pine Creek did not provide a competitive advantage for brook trout, and brown trout removal was unsuccessful, even when abundance was low. Resource managers hoping to protect and enhance native brook trout streams, especially those vulnerable to brown trout co-habitation, should consider an adaptive management approach that creates habitat favorable for brook trout. This consideration will become even more critical as climate change creates stream temperature regimes that are more suitable for brown trout, at the expense of brook trout.

FIGURES

TABLES

ACKNOWLEDGMENTS

The WDNR trout restoration team (John Sours and Nate Anderson) deserves credit for transforming Pine Creek. Trout Unlimited volunteers from the Kiap-TU-Wish, Clear Waters, and Twin Cities Chapters and Fairmount Santrol staff provided outstanding support for the restoration work. WDNR fisheries staff (Marty Engel and Barb Scott) conducted trout surveys and provided valuable data and interpretation for understanding trout dynamics. The Kiap-TU-Wish monitoring team (Andy Lamberson, John Kaplan, Dave Cumming, and Scott Wagner) provided excellent support for temperature, habitat, macroinvertebrate, and macrophyte monitoring. Kiap-TU-Wish project manager Greg Dietl deserves special recognition for his project role, serving as the liaison with the WDNR trout restoration team, coordinating the volunteer project support, and writing grants for project funding. The financial support provided by the National Fish Habitat Action Plan (NFHAP), the U.S. Fish and Wildlife Service, the Trout and Salmon Foundation, and Patagonia helped to make this project possible. Finally, the West Wisconsin Land Trust (WWLT) deserves recognition for purchasing two properties that encompass the majority of the Pine Creek Fishery Area, thus conserving these properties forever and making the restoration project possible.

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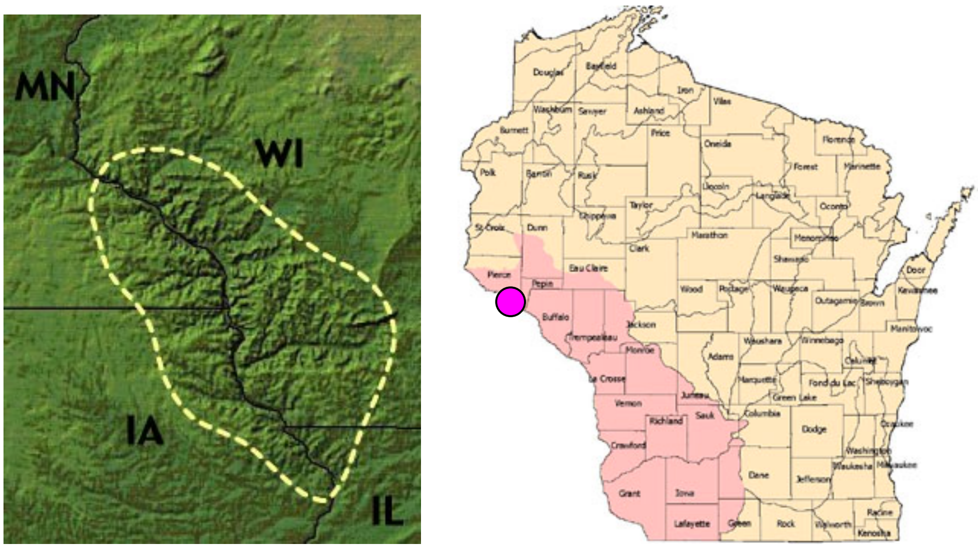


Figure 1. Location of Pine Creek in the Upper Midwest's Driftless Area

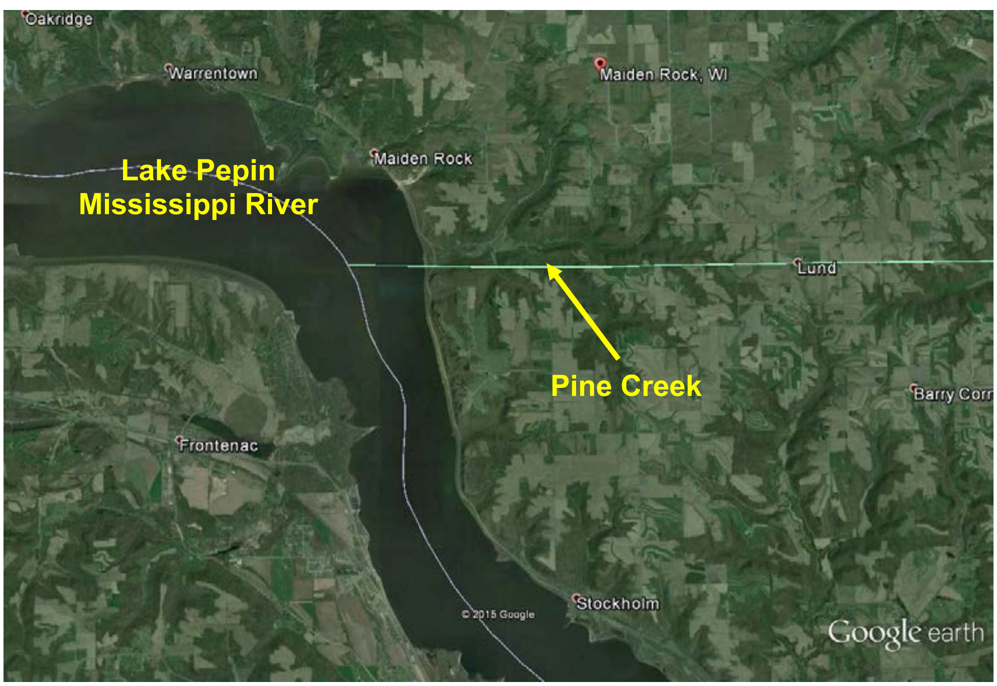


Figure 2. Pine Creek and watershed, near Maiden Rock, Wisconsin

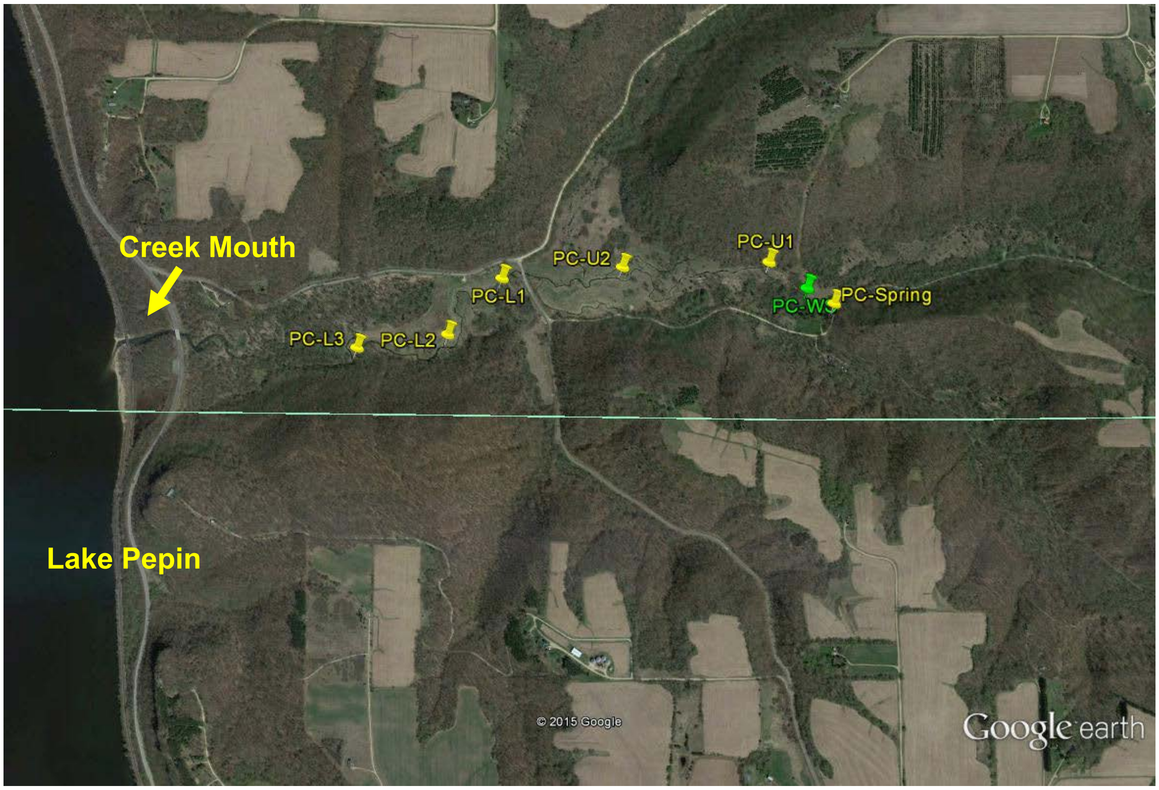


Figure 3. Pine Creek stream and air temperature monitoring sites

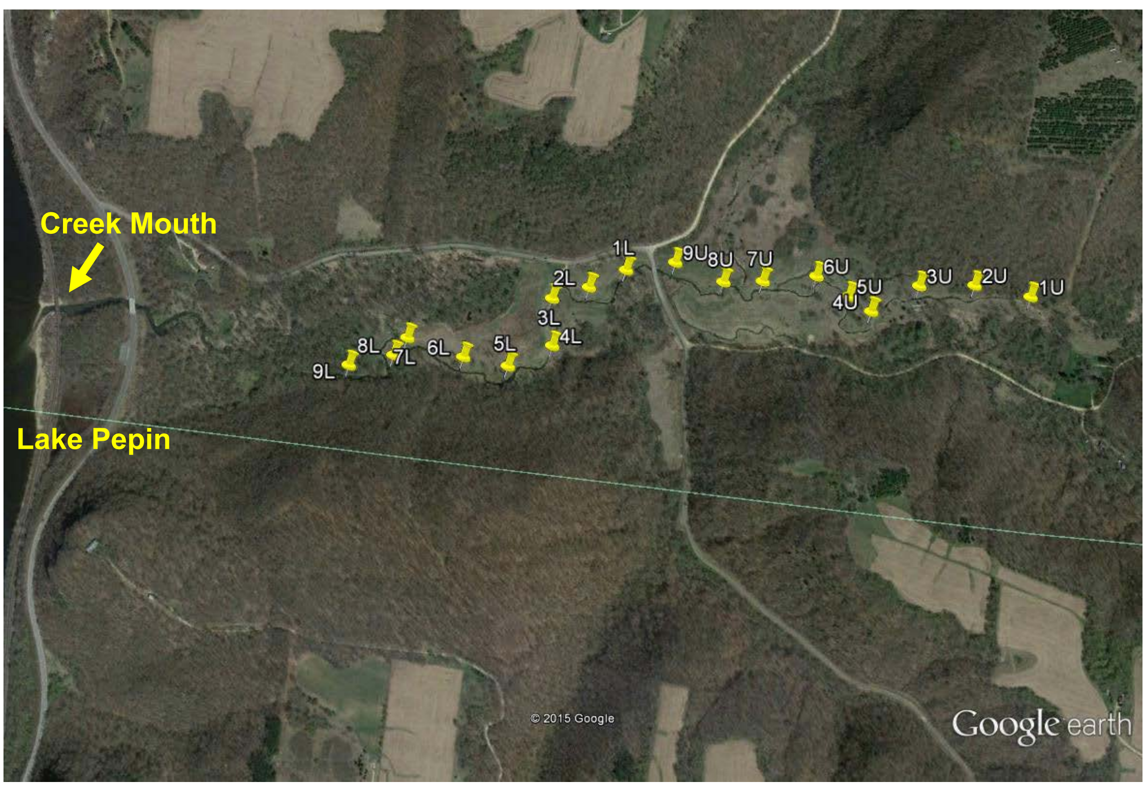
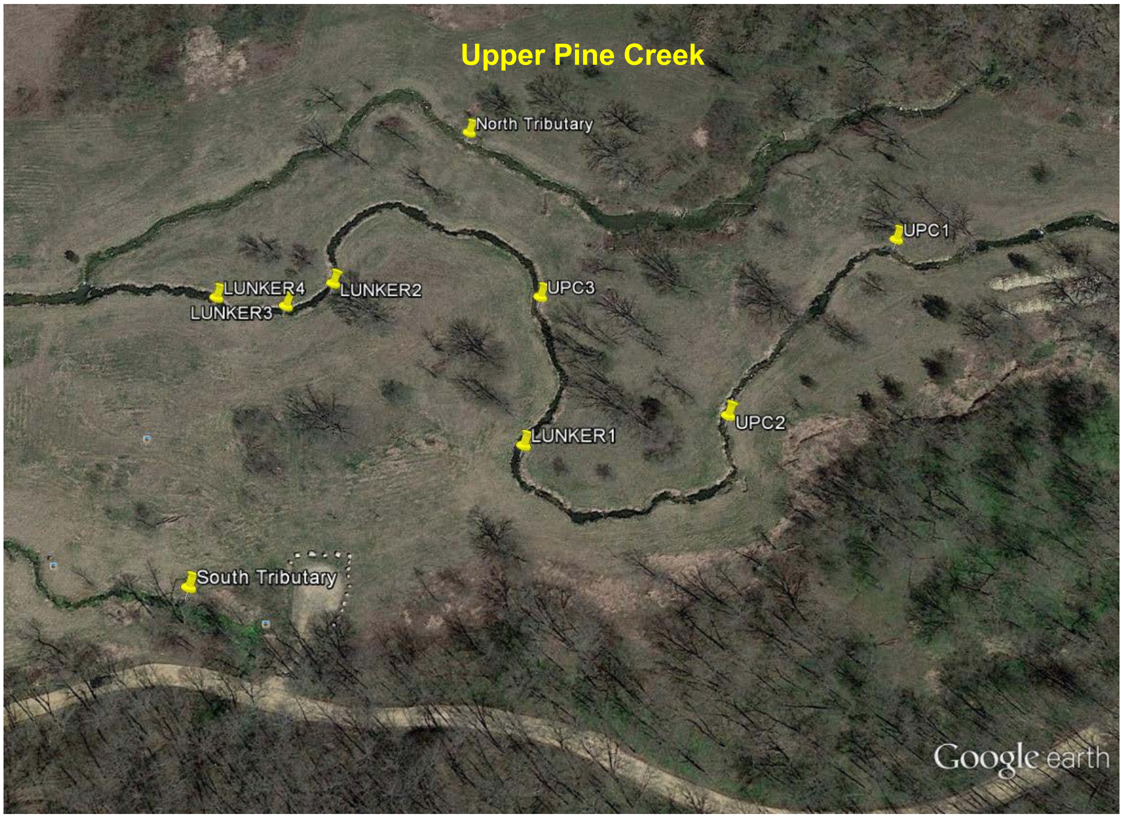


Figure 4. Pine Creek habitat assessment sites

Figure 5. WDNR's Pine Creek trout survey sites


Upper Pine Creek
North Tributary
UPC1
LUNKER4
LUNKER2
UPC3
LUNKER3
UPC2
LUNKER1
South Tributary
Google earth


Lower Pine Creek
LPC1
LPC3
LPC2
© 2015 Google
Google earth

Figure 6. Pine Creek macroinvertebrate monitoring sites

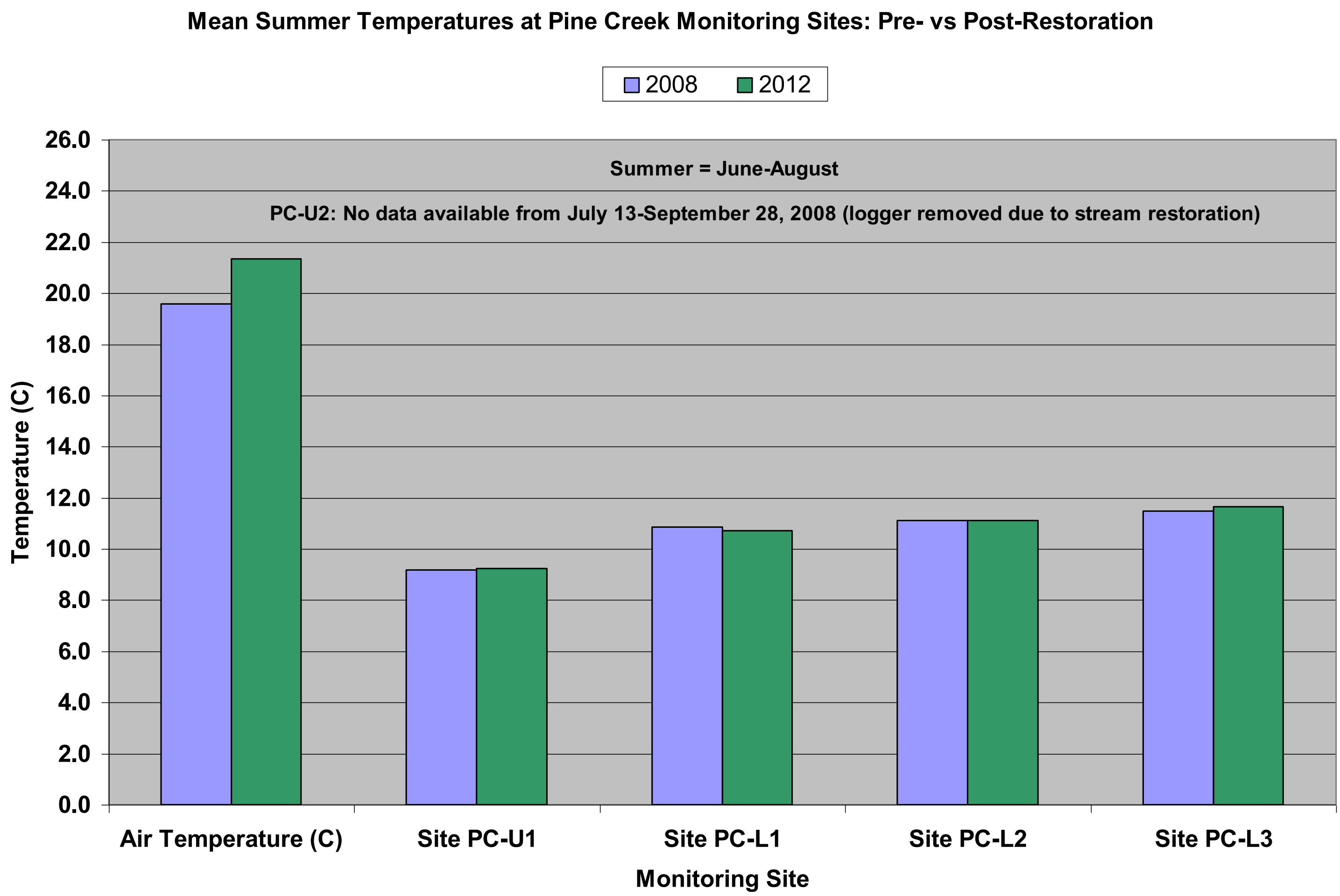


Figure 7. Mean summer temperatures at Pine Creek monitoring sites: Pre- restoration vs. post-restoration

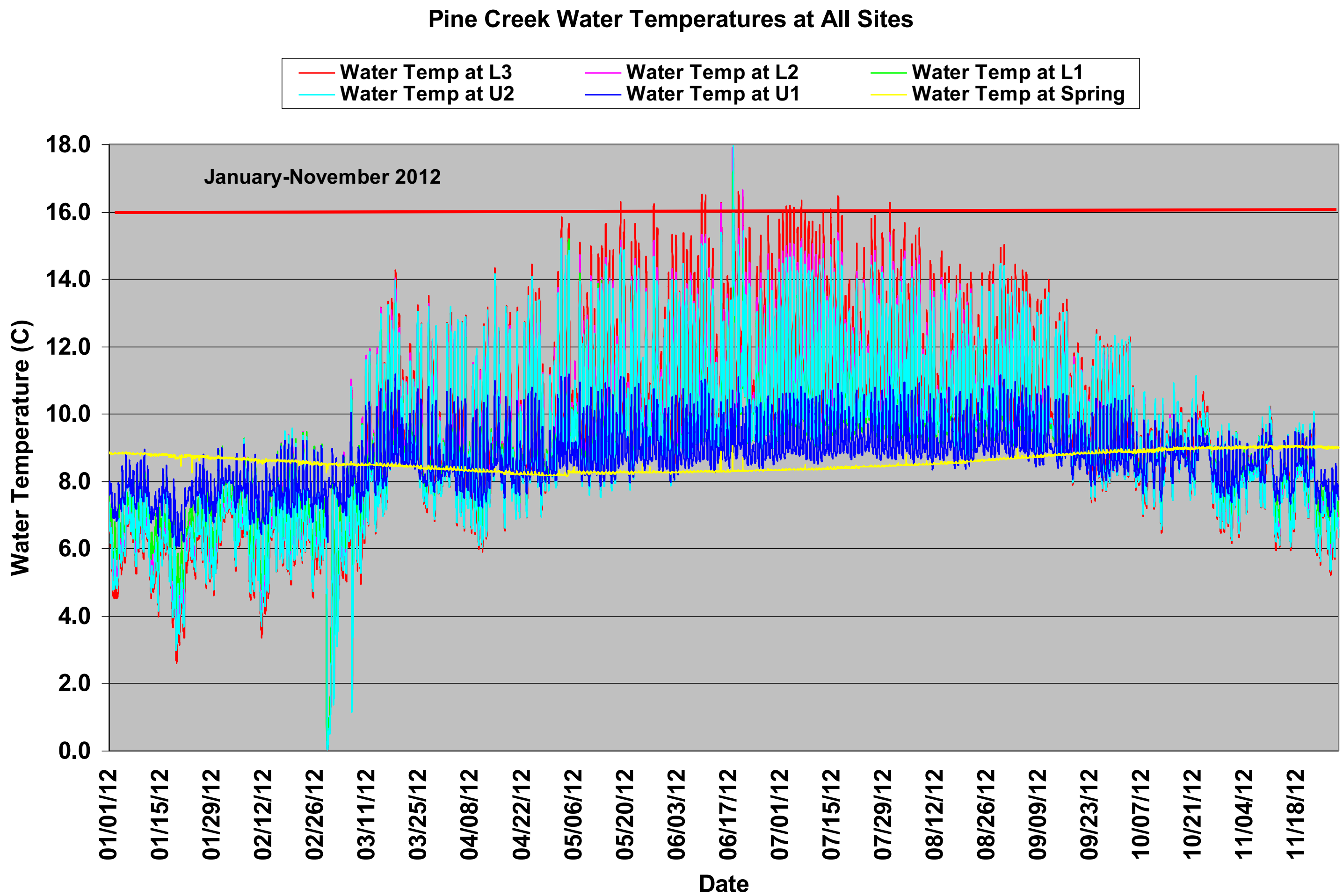


Figure 8. Reach-scale influence of air temperature on Pine Creek water temperature

Brook Trout

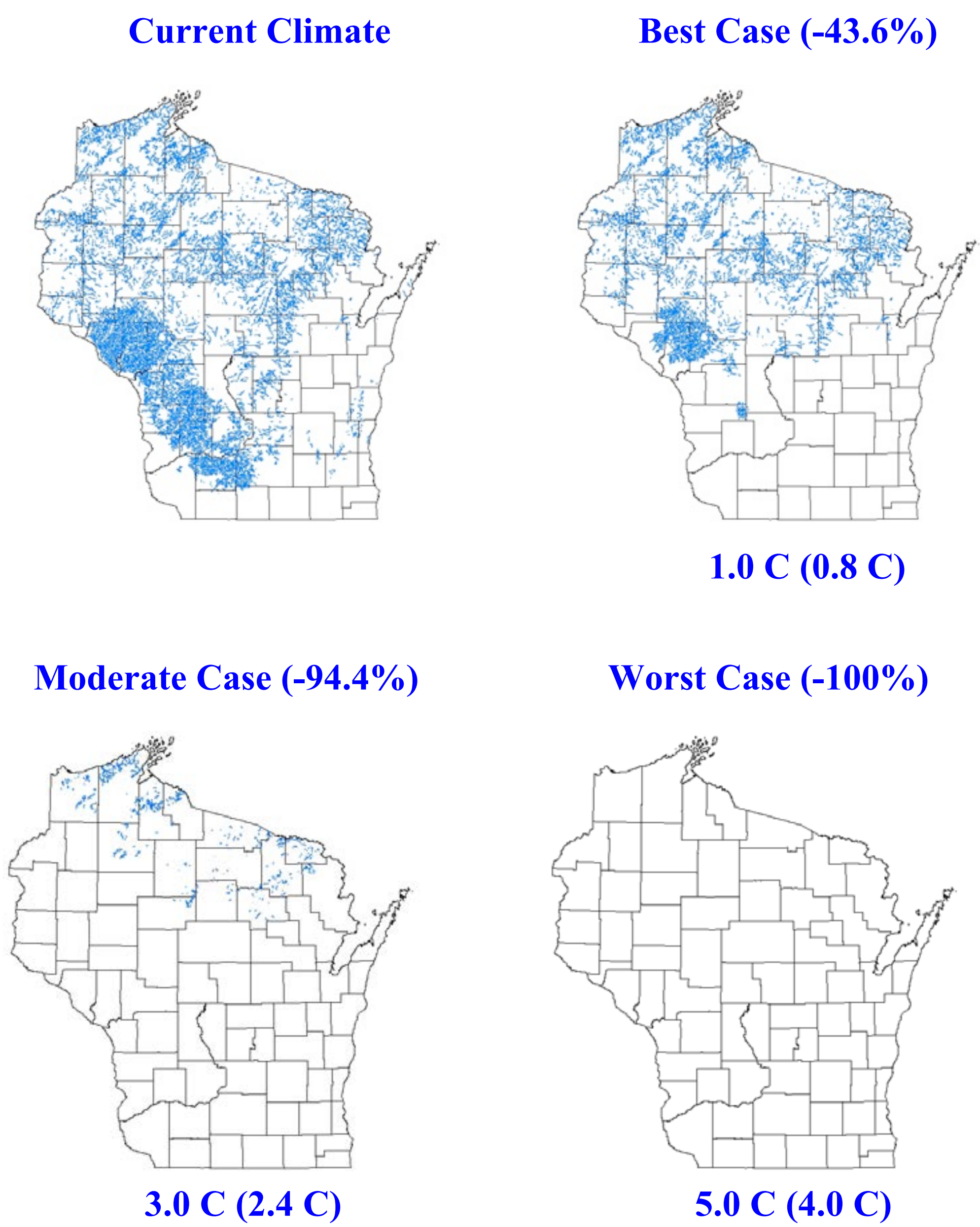


Figure 9. Occurrence and distribution of brook trout in Wisconsin streams under various climate change scenarios

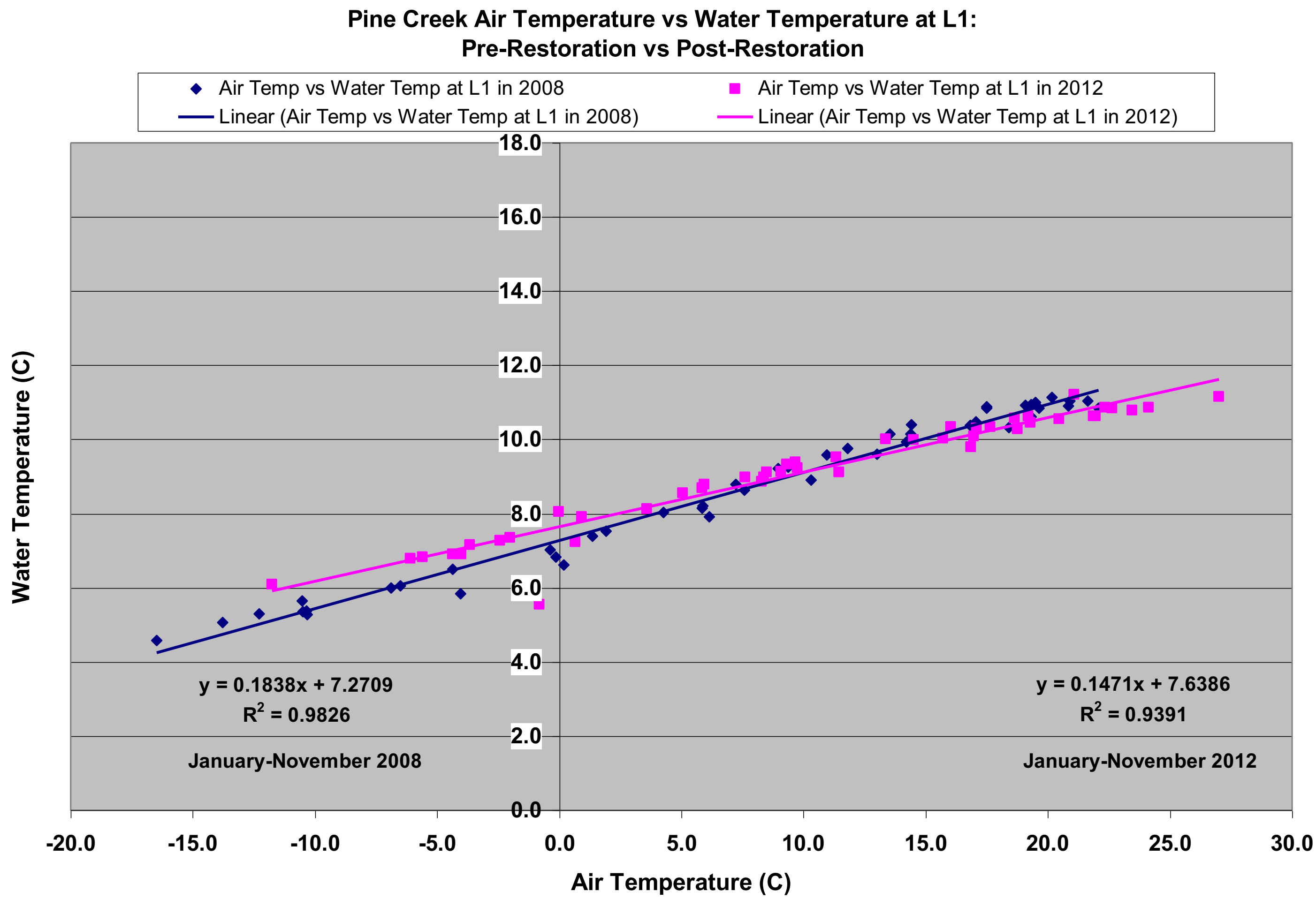


Figure 10. Pine Creek air temperature vs. water temperature at PC-L1: Pre-restoration vs. post-restoration

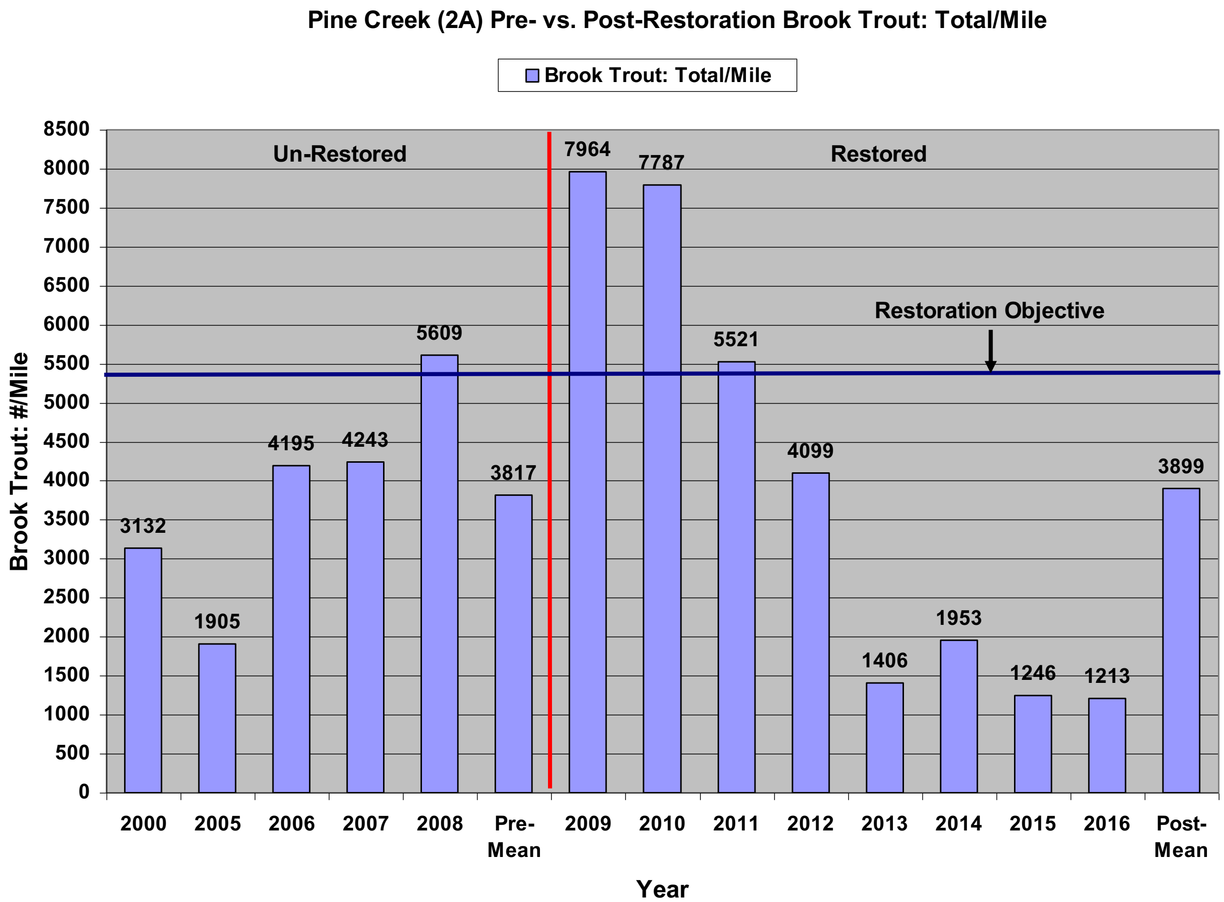


Figure 11. Pre- and post-restoration abundance of brook trout in Pine Creek

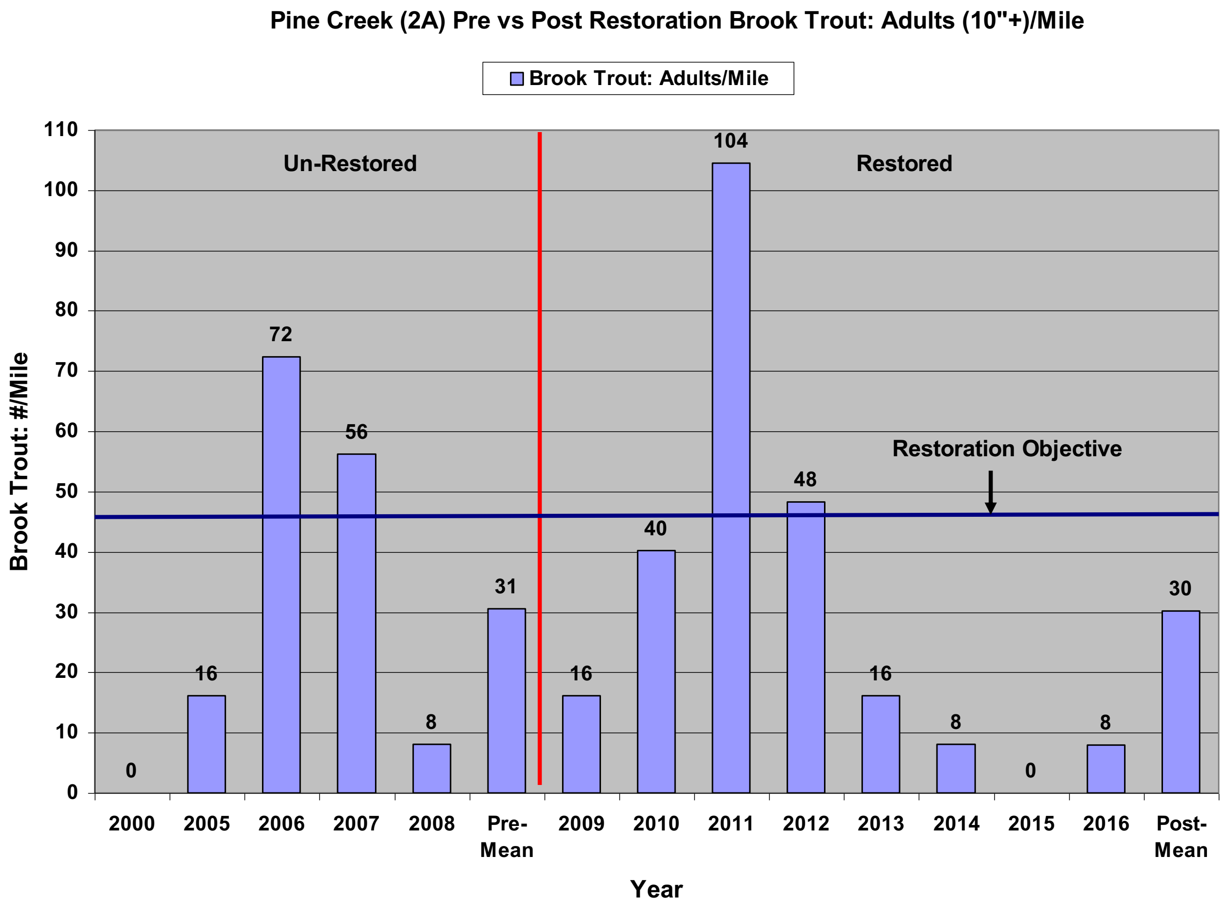


Figure 12. Pre- and post-restoration abundance of 10-inch plus brook trout in Pine Creek

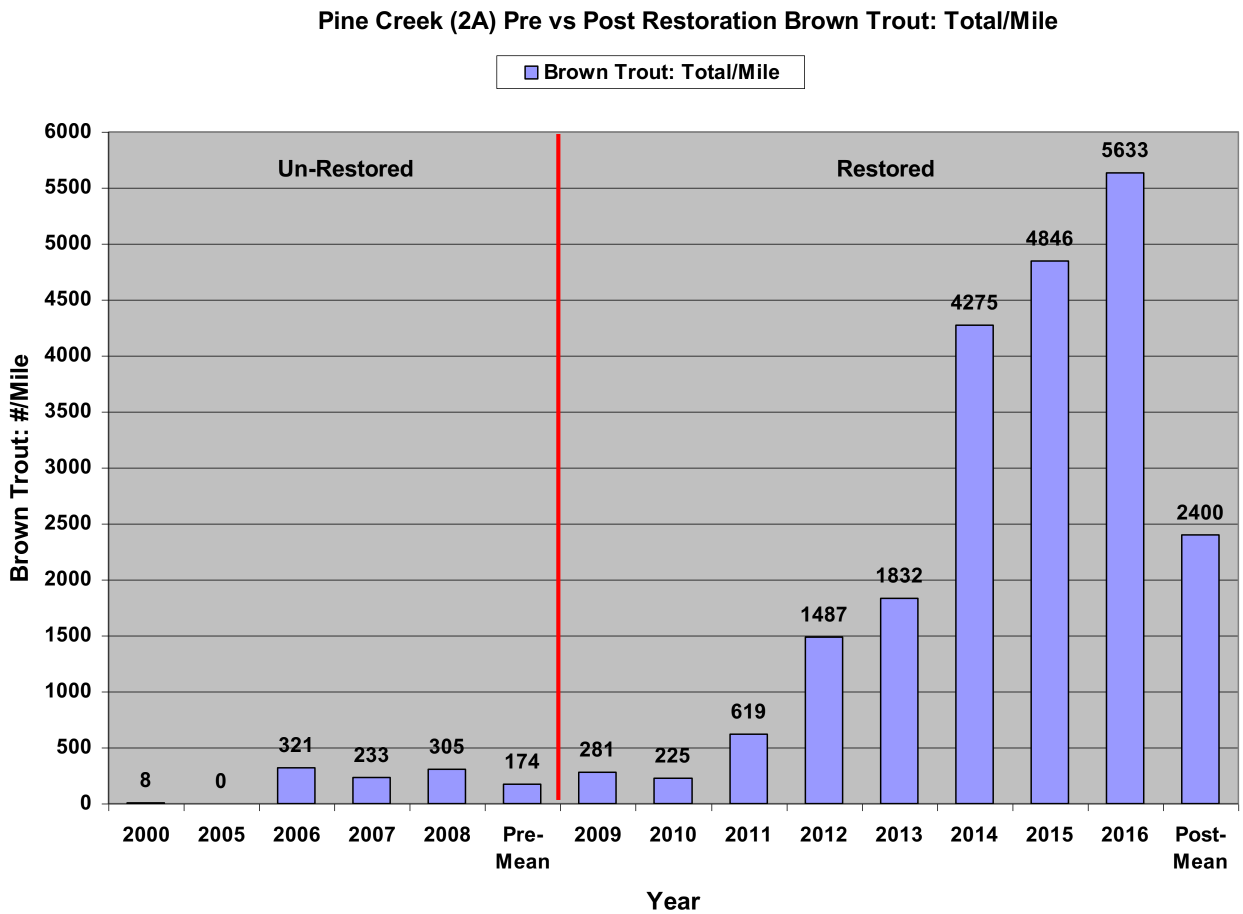


Figure 13. Pre- and post-restoration abundance of brown trout in Pine Creek

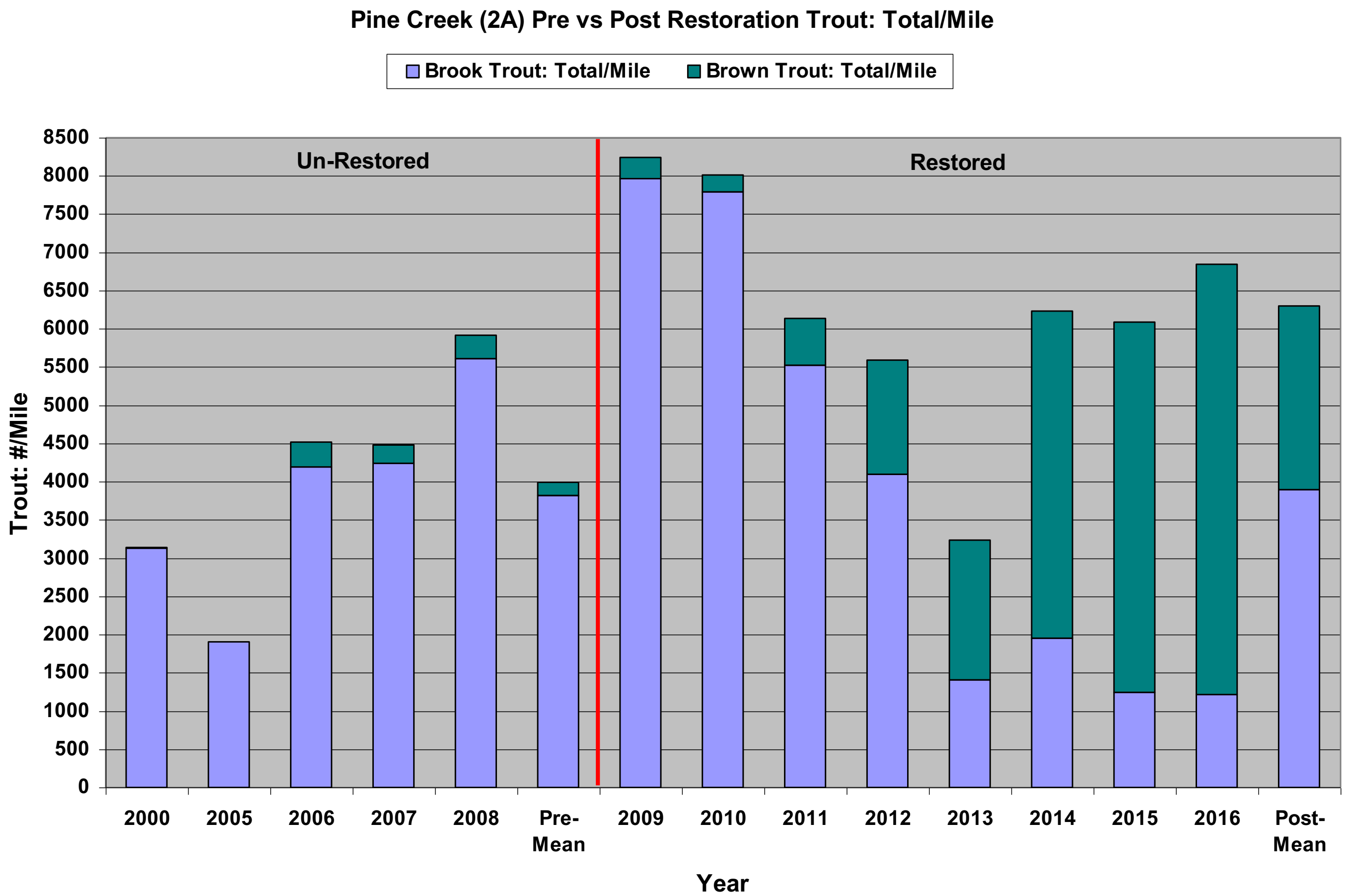


Figure 14. Pre- and post-restoration abundance of brook trout and brown trout in Pine Creek