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Identification of Predictive Habitat Attributes for Minnesota Streams to Support Tiered Aquatic Life Uses

Midwest Biodiversity Institute

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Identification of Predictive Habitat Attributes for Minnesota Streams to Support Tiered Aquatic Life Uses

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Appendix 5. List of MSHA metrics, attributes and weighted attributes for MIBIs in Minnesota.

Note: This document was updated in June of 2016 to correct some minor errors in text and tables. This document established a methodology for exploring MSHA habitat attributes associated with higher FIBI or MIBI scores ("good" habitat attributes) or lower FIBI or MIBI scores ("poor" habitat attributes) that can be used as an aid in determining whether habitat may be limiting to aquatic life when conducting stressor analyses and determining likely aquatic life use potential for Use Attainability Analyses. The State of Minnesota conducted further analyses with additional, newer data and derived logistic regression models to predict limiting effects of habitat on FIBI and MIBI (MPCA 2015) and that report supersedes the analyses in this report for conducting UAAs and stressor identification in Minnesota.

Introduction

Physical habitat characteristics are fundamental to the distribution and occurrence of aquatic assemblages in streams and rivers (Gorman and Karr 1978, Schlosser 1982, Maddock 1999). These physical features include the substrate and stream bottom attributes, stream channel features such as riffles, runs and pools, and in-stream structures such as boulders, logs, rootwads, aquatic plants, and undercut banks. Perhaps the most important physical feature in the formation of the aforementioned habitat characteristics is flow which has been termed the “master variable” (Poff et al. 2009). Historically, most streams and rivers had diverse habitat features related to the undisturbed interaction between landscapes and their geologic context, river bottom forests, swamps, oxbows and the natural hydrology. The settlement of Europeans who brought their culture and technology of intensive agriculture and agricultural drainage practices substantially altered stream habitat conditions compared to “as naturally occurred” conditions, especially in the Midwest.

The Clean Water Act (CWA) directs states to protect and restore the chemical, physical and biological integrity of streams and provides a water quality standards (WQS) framework that includes “designated aquatic life uses” and the development of stressor criteria to protect these uses. The development of tiered aquatic life uses (TALUs) necessitates an understanding and quantification of human alterations to the landscape that have substantially altered the biological potential of rivers. In the Midwest the influence of landscape and land use changes are particularly in evidence in the habitat features characteristic of streams and rivers. Instream habitat features are the product of both upstream changes to hydrology, geomorphology, sediment supply, etc., and direct alterations to habitat that include channelization, removal of riparian habitat and loss of wetland features once integral to the functioning of Midwest streams and rivers.

Accurate assessment of stream habitat characteristics is essential to the protection, restoration and enhancement of aquatic life uses. The ability to manage rivers in a tiered framework provides benefits in protecting truly high quality rivers, insight into aspects of restoring river habitats, and an ability to resolve management issues for rivers where full restoration is not feasible. Availability of habitat assessment tools that balance accuracy and precision with cost-effectiveness and that match the resolution of biological assessment tools is a key aspect of managing rivers using TALUs. The goal of this work is to establish baseline relationships between habitat as measured by the Minnesota Stream Habitat Assessment (MSHA) index and fish and macroinvertebrate assemblages in Minnesota. The purpose is to identify habitat features that can limit the performance of key aquatic response metrics and that can be used to characterize tiers of aquatic life uses in Minnesota. Ideally these habitat attributes can be used to accurately identify habitat stressors limiting to aquatic life and enable analyses to determine whether such attributes are feasibly restorable or likely to provide a ceiling to aquatic life use attainment under acceptable best management practices. It is important to minimize the misclassification of habitat limited sites that might be a candidate for a “modified” use, and less stringent aquatic life use goals. Thus we need to understand the links between habitat and biological performance and to be able to identify exceptions where high biological performance can be attained despite poor habitat.

Background

Ohio was one of the first states to develop biocriteria and to develop “modified” aquatic life uses based on identified limitations to aquatic biota related to habitat alteration deemed to be not feasibly restorable with accepted management practices and feasible restoration options (Yoder and Rankin 1999). Analyses of streams in Ohio found strong associations between biodiversity and biological condition and measures of habitat diversity and condition as measured by the Qualitative Habitat Evaluation Index (QHEI; Rankin 1986; 1995). The QHEI measures multiple aspects of stream habitat and the condition of these features (*e.g.*, degree of siltation, embeddedness, and channelization) associated with human alteration of the stream itself and its surrounding landscape. Ohio EPA has used the QHEI since the mid 1980s and has derived habitat “attributes” that are predictive of high quality or poor quality fish assemblages (Rankin 1989, 1995). The accumulation of identified positive (“good”) or negative (“poor”) habitat attributes at sites or reaches has been a useful tool in assigning causes of impairment and discerning whether physical characteristics were limiting to aquatic life. These attributes provide information that is used to determine whether limitations are extensive enough and permanent enough to justify an alternative tier of aquatic life use. In Ohio there are occasional exceptions to the typical habitat-biology relationship where habitat is rather poor, yet biology attains the CWA biological goals. These streams are protected because Ohio relies on the biota as the ultimate arbiter of aquatic life use attainment and these exceptions are uncommon, but explainable (*e.g.*, high groundwater derived baseflows and cooler water counter some of the impacts of channelization; very localized scale of habitat degradation compensated by nearby excellent habitat). The purpose of this analysis is to develop a similar list of “positive” and “negative” habitat attributes for Minnesota streams and rivers that will be predictive of biological performance, provide a template for TALU designations, identify scenarios where biological performance is high despite localized habitat degradation and provide a framework for habitat-based stressor analysis for Minnesota warm water streams.

Methods

Habitat Data

We used the Minnesota Pollution Control Agency's (MPCA) Minnesota Stream Habitat Assessment (MSHA) data collected under standardized protocols (MPCA 2009a, Appendix 1). The MSHA is similar to the QHEI, but has been modified for conditions found in Minnesota streams. The MSHA is a visual tool that rates key habitat features of streams and rivers including surrounding or floodplain land use, riparian zone features including width, bank erosion, and shade, instream conditions including substrate size, types, embeddedness and siltation and, instream structure (cover) types and amount, characteristics of stream channel condition including sinuosity, development, channel modification and stability, velocity types, depth variability, and pool to riffle width ratio (MPCA 2009a). The index is composed of a series of attributes (individual scoring choices or "boxes" that can aggregated into sub-metric scores or metric scores which are then aggregated into the final MSHA score which ranges from approximately 0 to 100. All scorers were qualified biologists and received training and annual internal reviews and conduct periodic self-checks by comparing results with other trained scores (MPCA 2009a).

Minnesota's Human Disturbance Score

Minnesota has created a Human Disturbance Score (HDS) as an integrated scoring of disturbance along which to ordinate biological assemblage data and account for potential changes from natural conditions in streams (MPCA 2016). It consists of a series of metrics and adjustment scores and ranges from 0 (most disturbed) to 81 (least disturbed). We used these data to censor sites with potential point source impacts, impervious surface impacts or acute livestock impacts that could confound the habitat gradient in the MSHA. For most analyses sites were excluded that: 1) had continuous point sources discharges <5 stream miles from a site where the stream was less than 50 mi^2 drainage; 2) had visual evidence of a feedlot at a site or immediately upstream of a site; or 3) had a city or town at the site or immediately adjacent to the site (proximity scores of -1 in the HDS, Table 1).

Table 1. Variables of the Minnesota human disturbance score (HDS)

Metric	Range	Type/Scale	Description
audenscore	0-10	watershed	# of animal units per km2 (feedlots)
pctagsco	0-10	watershed	% agriculture in watershed
ptscore	0-10	watershed	# of point sources per km2
pctimpscore	0-10	watershed	% impervious surface in watershed
pctdistripscore	0-10	watershed	% disturbed riparian habitat in the watershed
DITCHPCTSCORE	0-10	watershed	% channelized stream per stream km
siteriparian	0-10	reach	"intactness" of site riparian zone
stiechannel	0-10	reach	channel condition
pointsourceprox	-1	proximity adjustment	Continuous discharge <5 stream miles into stream <50SqMi.
feedlotprox	-1	proximity adjustment	Visual evidence (from DOQ) of feedlot at site or immediately upstream of site
urbanluprox	-1	proximity adjustment	City or town at the site or immediately adjacent to site

feedscore	-1	adjustment	
roadscore	-1 or +1	adjustment	
ag3pctscore	-1	adjustment	Amount of agricultural landuse on 3% slope as a percentage of total watershed area
pctagripscor	-1	adjustment	% agriculture in 100 meter buffer

Biological Data

Fish data were collected by the MPCA from 1996-2009 during multiple projects. Fish were collected with pulsed DC electrofishing as described by MPCA (MPCA 2009b). Fish were processed in the field and identified to species and counted, weighed, and examined for any external abnormalities (deformities, eroded fins, lesions or tumors). We used the Minnesota Fish Index of Biological Integrity (FIBI; MPCA 2014a) for each classification strata and key individual metrics (*e.g.,* sensitive species richness) as response variables. Where multiple fish samples were collected at a site during a year, but only a single MSHA score was recorded, each IBI score was considered an independent sample. In addition to the fish assemblage we used Minnesota's macroinvertebrate data and their Macroinvertebrate IBI (MIBI) as an additional response variable (MPCA 2000, MPCA 2014b). Sites where IBI scores were not calculated or where samples were considered invalid because of flow or other problems were excluded from analyses.

Table 2. Symbol codes for plots of Minnesota Fish data by classification strata used in this report

Classification Strata	Symbol/Color
Southern Rivers	o
Southern Streams	i
Southern Headwaters	Δ
Northern Rivers	n
Northern Streams	l
Northern Headwaters	p
Low Gradient	t
Sites Combined	i

Stream Classification

Minnesota has examined the strength of different classification strata on fish assemblages (MPCA 2014a) and macroinvertebrate assemblages. For fish they have defined seven warmwater stream classes that reflect a stream size gradient, a north-south gradient, and a local reach classification (low gradient streams) that explain much of the natural variation in fish assemblage differences (Table 2). For macroinvertebrates there are also seven stream classes that reflect a similar North-South gradient and a Prairie stream classification and gradients related to riffle/run versus glide/pool type streams (MPCA 2014b). For certain analyses we aggregated data, but at a minimum analyzed data separately for each classification stratum. To ease interpretation of graphs we standardized symbol types and colors by classification on plots (Tables 2 and 3).

Table 3. Symbol codes for plots of Minnesota Macroinvertebrate data by classification strata used in this report

Classification Strata	Symbol/Color
Prairie Forest Rivers	2
Prairie Streams (Glide/Pool)	$
Northern Forest Rivers	n
Northern Forest Streams (Riffle/Run)	l
Northern Forest Streams (Glide/Pool)	a
Southern Streams (Riffle/Run)	i
Southern Streams (Glide/Pool)	t
Sites Combined	i

Statistical Analyses

We used classification tree analyses as an initial exploratory approach to understanding the strength of association between the FIBI and MIBI and individual habitat submetrics and HUC-8 average habitat scores for each classification stratum. We also examined data summarized at the HUC-10 and HUC-12 scales, but did not include these in the classification tree analyses because there were too many watersheds with insufficient data. Instead we analyzed this data separately and recommend how it can be included in the decisions about the attainability of uses in addition to HUC-8 data. We used the provisional impairment thresholds for each classification unit as the response variable (Attaining versus Impaired) and submetric scores as the independent variables to gain insight into which categories of habitat appear to be limiting within each region. We also used the HUC-8 average total MSHA score as a measure of effect of the scale of habitat degradation on assemblages at sites.

We used correlation analyses to explore the relationships between individual and composite habitat metrics, submetrics or attributes (Table 4) of the MSHA and biological response measures including the FIBI and MIBI, their metrics, as well as other candidate metrics not kept as components of these IBIs. We identified meaningful MSHA habitat attributes, defined as whether FIBI scores or MIBI scores varied significantly ($P < 0.05$) between attributes, in an exploratory mode, using an Analysis of Variance (ANOVA) (KaleidaGraph 4.1, Synergy Inc.). Where differences were significant we ran Tukey multiple comparisons to help us identify attributes most associated with higher FIBI and MIBI scores ("good" habitat attributes) or lower FIBI and MIBI scores ("poor" habitat attributes). Professional judgment was used to select final attributes, particularly where statistical results were marginal because of reduced sample sizes in rare categories. The Tukey test is a pairwise test, so that we looked for differences between any pair to identify that the attribute was contributing to either a high or low FIBI or MIBI score. We used the strength of the difference (P-value) to arrive at a weighting of attributes. Attributes significant at greater than at $P<0.001$ were given a weighting of 2 points (to each attribute in the pair), those with a significance >0.001, but less than $P<0.05$ were given a weighting of 1 point, and those less significant, but strongly trending or where a lack of significance was due to small sample size were give a weighting of 0.5 points. The ANOVA and Tukey test were not used in a strict hypothesis testing mode, but rather as a method to construct indices (*i.e.,* attributes) to help predict direction and strength of IBI scores with aggregations of habitat attributes. Identification of key habitat attributes could be selected based on literature citations or best professional judgement. Our method here is less arbitrary than professional judgement alone, although it uses judgement in weighting weaker attributes that may be important, but uncommon in classification strata.

Sites identified as having modified channels were given an additional score of 5 points to the poor attributes. Results are illustrated in tables of FIBI or MIBI scores by metrics for individual MSHA attributes. In some cases we contrasted results from Minnesota with similar data from Ohio which has a very strong habitat gradient. Ohio's relationship may be particularly strong because the extensive wetland and base flow losses in Ohio tend to intensify the habitat impacts and its more southern latitude and warmer maximum stream temperatures compared to Minnesota may also contribute to this association.

Table 4. Hierarchy of habitat variables used in this study

Metrics/ Variables	Sub-metrics	Attributes
Substrate Score	Predominate Substrate Types	Boulder, Cobble, Gravel, Bedrock, Sand, Silt, Muck, Detritus, Sludge (by habitat type (pool, glide, riffle, run)
	Embeddedness	None, Light, Moderate. Severe, No Coarse Substrate
	Number of Types	Greater than 4, Less than or equal to 4
Land Use Score	-	Forest, Wetland, Prairie, Shrub; Residential/Park; Old Field/Hay Field; Urban/Industrial; Fenced Pasture; Open Pasture ; Conservation Tillage, No Till; Row Crop
Riparian	Riparian Width, Bank Erosion, Shade	Width: Extensive, Wide, Moderate, Narrow, Very Narrow, None Erosion: None, Little, Moderate, Heavy, Severe Shade: Heavy, Substantial, Moderate, Light, None
Cover	Number of Types, Cover Amount	Types: Undercut Banks, Macrophytes, Overhanging Vegetation, Deep Pools, Logs or Woody Debris, Boulders, Rootwads Amount: Extensive, Moderate, Sparse, Nearly Absent, Choking Vegetation
Channel	Depth Variability, Channel Stability, Velocity Types, Sinuosity, Morphology, Channel Development	Depth Variability: Deep, Moderate, Shallow Stability: High, Moderate/High, Moderate, Low Velocity Types: Torrential, Fast, Moderate, Slow, Eddies, Intermittent, Interstitial Sinuosity: Excellent, Good, Fair, Poor Development: Excellent, Good, Fair, Poor Morphology: Poor Width > Riffle Width, Poor Width = Riffle Width, Poor Width < Riffle Width, No Riffle
HUC-8, HUC-10 and HUC-12 Average MSHA Scores		

The use of biological indicators is typically anchored to some form of reference condition (Stoddard et al. 2006) with the most advanced approach anchored to a "as naturally occurs" condition which allows a consistent context for determining the biological condition of streams along a gradient especially where tiers of aquatic life uses are to be constructed (Davies and Jackson 2006). Anchoring stressor conditions (*e.g.,* physical habitat) in a "as naturally occurs" condition can create a strong foundation for interpreting tiers of condition that deviate from these conditions with human changes in landscape condition. We begin the analyses by extrapolating the MSHA to periods of time during early or pre-European settlement (an "as naturally occurred" condition) based on historical descriptions of the land use and cover during these periods.

Results

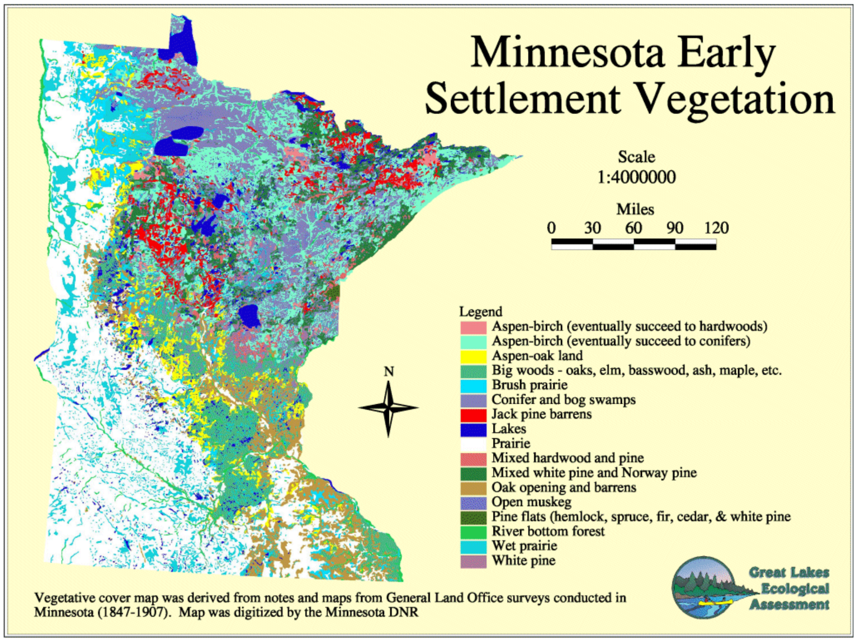
Fish and Macroinvertebrate Assemblages

In the next sections of the report we examine the correlation of the FIBI and MIBI scores by individual MSHA metrics, sub-metrics and attributes to identify potential indicators of habitat impact. The goal of these analyses is to identify attributes that more consistently represent the potential candidate "good" or "poor" habitat attributes that can form the basis for interpreting potential mechanisms of impact related to habitat conditions. The accrual of poor habitat attributes that cannot be readily restored will form the basis for decision trees that support designation of "Modified" or "Limited" aquatic life uses. In this process we will "err" in favor of a higher aquatic life use to minimize an error where we designate a "lower" use when a higher, more protective use is attainable. The procedure need not be onerous, but must be based in sound science. Prior to these detailed analyses; however, we consider the natural state of stream habitats in Minnesota and the relationship between Minnesota fish assemblages, the biological condition gradient (BCG) levels, and the MSHA.

Exploration of Natural Habitat Conditions in Minnesota's Fish Regions

Minnesota developed an aquatic classification system for fish that divided warmwater streams in the State into 7 classification strata: Northern Rivers, Southern Rivers, Northern Streams, Southern Streams, Northern Headwaters, Southern Headwaters, and Low Gradient Streams (Table 2; MPCA 2014a). Similarly Minnesota was divided into seven warmwater classification strata for macroinvertebrates (Table 3; MPCA 2014b). The classification strata were selected to minimize variation in assemblage structure that could be attributable to natural variation in a North-South gradient, a stream size gradient, and in low versus higher gradient streams. The North-South gradient reflects both a temperature classification and a biogeographic classification. Minnesota completed a BCG exercise which uses a combination of data and expert opinion to identify attributes of assemblages that approximate "natural" conditions as well those that exhibit substantial stress from pollutants and physical stressors (*e.g.,* flow and habitat) that commonly occur within each region (Gerritsen *et al.* 2013).

We suggest an important component is to describe the "natural" habitat conditions that likely existed prior to substantial human disturbance, sometimes termed "hindcasting." One goal of this study is to consider the implementation of a "modified" stream use related to the effects of channelization that cannot be feasibly restored. FIBI scores in boatable sites (Northern Rivers and Southern Rivers types) indicated warmwater habitat (WWH) conditions are typically attainable, thus we did not consider boatable rivers in this analysis. In this effort we use the sites identified as having BCG Level 2 biological assemblages, along with historical descriptions of Midwest streams from settler and early naturalists to help set bounds on the likely habitat that exists in "Level 1" streams in terms of a physical disturbance gradient. During the BCG exercise no wadeable or headwater sites were classified as "Level 1" (Gerritsen et al. 2013) which is a "pristine" anchor. Level 2 is defined as having: "minimal changes in structure of the biotic community and minimal changes in ecosystem function" (Davies and Jackson 2009). Minnesota was characterized by diverse natural vegetation types during the early European settlement period that included aspen, hardwood and pine forests, bottomland forests, prairie and wet prairie, muskeg and pine barrens (Figure 1). Approaches including historical survey data and pollen surveys have been useful in examining changes in landuse from pre-settlement to current conditions (Sisk 1998, Cole et al. 1998). Land use in the Great Lakes region has changed more in the past 150 years than it did in the 1,000 years prior (Cole 1998). The dominance of natural vegetation in pre-settlement conditions (Figure 1), although varied, would maximize the MSHA land use, riparian, bank erosion, substrate, cover and channel metrics. The amount of shading might vary with stream type with streams in prairie areas, areas dominated by wetlands, or where beavers impounded or removed riparian trees resulting in more open channels. With the high proportion of mature vegetation (*e.g.*, forest, wetland) one would expect little erosion of fines. The extensive vegetation and wetlands, often mediated by beavers in many areas, would contribute to stable and strong base flows compared to today's heavily drained landscapes, particularly in the southern part of the State. Sedimentation rates are significant higher now than they were in pre-settlement periods: a study in Lake Pepin using sediment cores demonstrated a large increase in sediment accumulation beginning with European settlement in 1830 (Engstrom et l. 2009). Although historical levels of excess sediments were likely low historically, bottom substrates would vary with natural conditions (*e.g.,* low versus high gradient, types of natural outwash materials versus bedrock, *etc*.). In Figure 2 we illustrate actual MSHA scores at Level 2 and Level 6 sites with the hypothetical "hind-casted" Level 1 scores superimposed. It is likely Level 1 sites would have more of a tail of score distributions than depicted here that would overlap with existing scores caused by natural disturbances (*e.g.,* fire, landslides, *etc*.), natural climatic fluctuations in precipitation that could alter background erosion rates, or from localized disturbance by Native Americans (*e.g.*, setting of fires, agriculture). There is overlap with some Level 2 sites in the Northern streams and headwaters, but in general the distribution of scores is lower than Level 1 site habitat scores. Level 6 sites represent a substantial difference from Level 1 and Level 2 scores (Figure 2).



Vegetative cover map was derived from notes and maps from General Land Office surveys conducted in Minnesota (1847-1907). Map was digitized by the Minnesota DNR

Figure 1. Map of Minnesota's early settlement vegetation (source: Minnesota DNR).

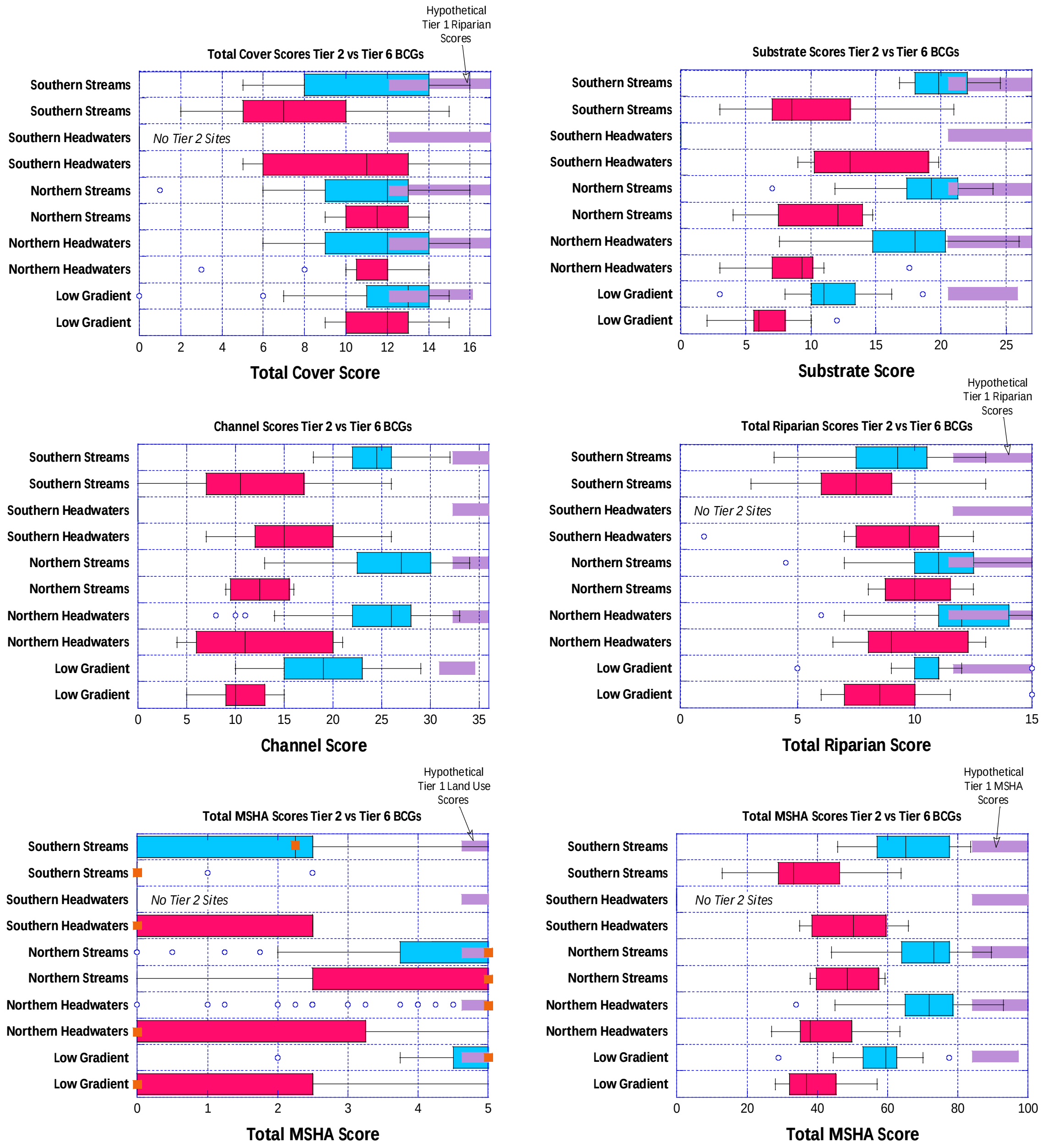


Figure 2. Box and whisker plots of MSHA metric scores by classification strata for Minnesota stream and by BCG Level 2 (blue) and Level 6 (red) sites. Theoretical maximum historical ("pre-settlement") scores are indicated by smaller purple boxes. Data represents summary metric scores (cover, upper left; substrate, upper right; channel, middle left; riparian, middle right; land use, lower left) and the total MSHA score (lower right).

As depicted in Figure 2, for most metrics and for the total MSHA score there is a clear difference between Level 2 and Level 6 sites. When we examined the total MSHA score for each classification strata by BCG Level (Figure 3), there is generally a pattern of decreasing scores with decreasing Tiers between Levels 2 through 4; however, Level 4 and Level 5 are not particularly different from one another. The demarcation between Level 4 and Level 5 is generally the region where CWA aquatic life use attainment thresholds are set. One goal for this paper to consider is whether certain habitat attributes are more predictive of the Level 4 – Level 5 threshold and the actual FIBI/MIBI thresholds derived by Minnesota as their attainment thresholds for their baseline or minimum CWA aquatic life use.

There are several explanations that we will consider to this end. Separation of the total MSHA score between Level 4 and Level 5 conditions could be confounded by metrics that have lesser influence on aquatic life. In Figure 2 the substrate and channel conditions had the greatest difference between Level 2 and Level 6 sites while cover and riparian differences were lesser and more variable. We will also explore the influence of cumulative watershed habitat impacts on biological condition. It may be that very local disturbances in watersheds where habitat is generally very intact (*e.g.,* Northern streams and headwaters) may have muted effects on assemblage condition. In contrast, in watersheds where habitat impacts related to channelization are widespread, local high quality reaches may perform poorly biologically because watershed scale effects limit populations of habitat sensitive species. Finally, strong base stream flow and lower stream temperature may moderate some of the potential effects of habitat degradation particularly where the extent of habitat loss is not overwhelming. In such cases, channelization caused habitat degradation may not be limiting the attainment of the baseline CWA aquatic life use goal, although it may limit the ability to attain a higher tier use.

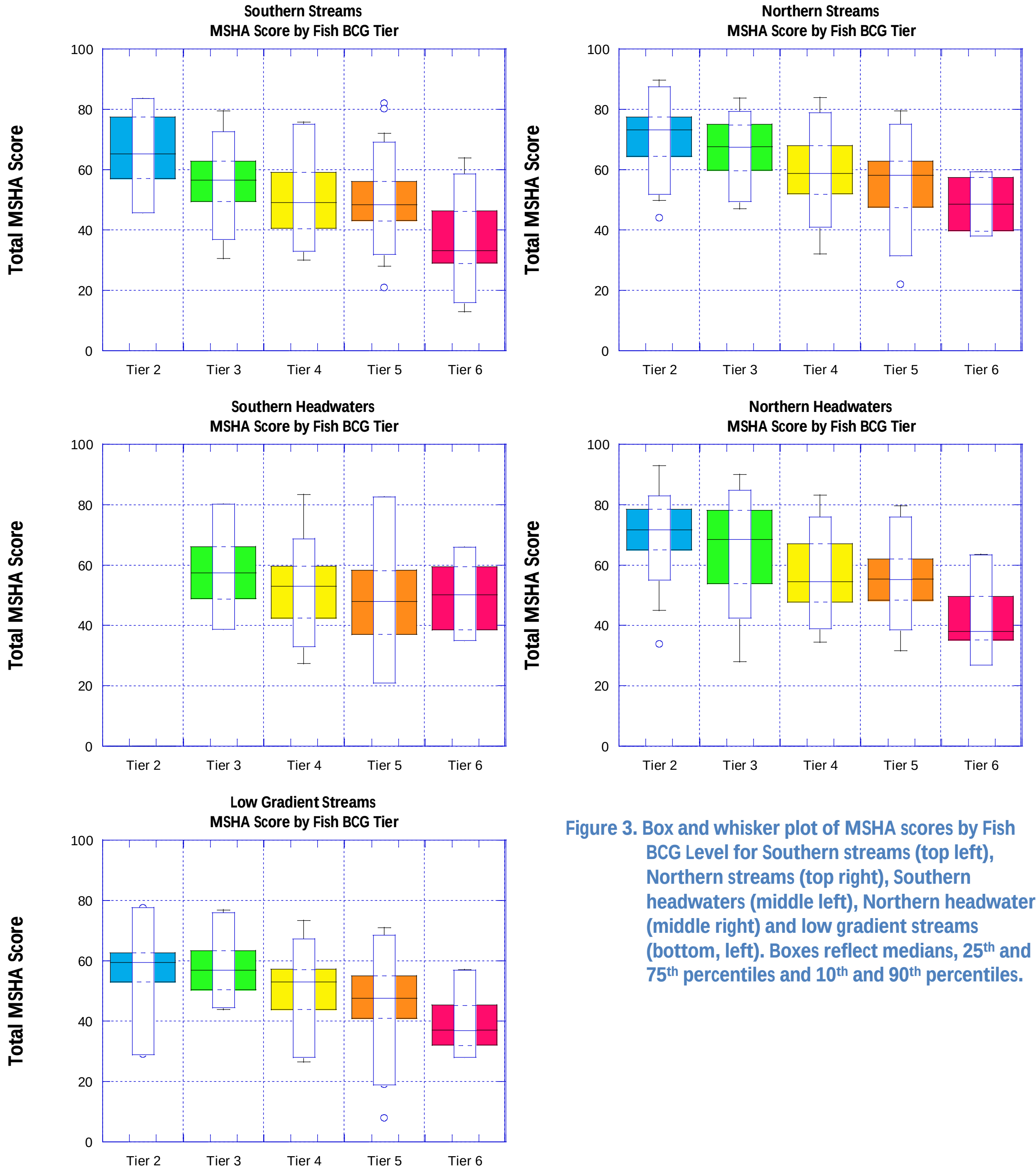


Figure 3. Box and whisker plot of MSHA scores by Fish BCG Level for Southern streams (top left), Northern streams (top right), Southern headwaters (middle left), Northern headwaters (middle right) and low gradient streams (bottom, left). Boxes reflect medians, 25th and 75th percentiles and 10th and 90th percentiles.

Identification of Key Habitat Attributes

The results of our analyses are presented hierarchically with a focus on metrics (correlation), then sub-metrics (classification tree analyses) and finally individual attributes to arrive at lists of attributes for each classification strata that are the best predictors that the habitat that is either limiting attainment of a higher use or confirms that a higher use is attainable. There is an aspect of the scale of habitat impacts (*i.e.,* cumulative impacts) that is important to this process as well. Habitat limitations tend to act at multiple spatial scales. The end product of these analyses results in a continuum of habitat effects on aquatic life that includes scale of impact. At the extremes of the habitat continuum decisions are rather simple (high quality habitat within watersheds with largely intact habitats versus poor quality habitats in watersheds with widely disturbed and modified habitats); however, other situations are more complex and these results are designed to give scientists and managers the tools to conduct a weight-of-evidence risk assessment for assigning tiered use designations. Central to this approach is consideration of whether the habitat limitations to the biota are feasibly restorable over a short time frame (*e.g.,* typically 10-20 years) or can recover naturally versus the need and feasibility of more active restoration actions. The results of these analyses can also be valuable in identifying habitat features that should be included in the design of stream restoration efforts. In this analysis we explicitly added points to the poor habitat scores when watersheds exceeded a specified level of cumulative habitat loss as well as when the stream had been channelized. Alternatively, these factors can be considered separately[1] and not “baked-into” the attribute scores.

The form of the FIBI and MIBI in Minnesota varies with each of the seven classification strata for each index and as a result identical scores, although generally similar, do not necessary represent the same level of biological condition among regions. Because of this we did not conduct analyses at a statewide scale, but rather separately for each of the seven classification strata. The first analyses we performed were simple correlations between the FIBI and the total MSHA score. The Minnesota FIBI was most strongly associated with the total MSHA score in the Low Gradient, Southern Stream, Northern Stream and Northern Headwater strata and more weakly associated with the MSHA in the Northern and Southern Rivers and Southern Headwaters (Figure 4). For the MIBI the relationship was strongest in the Glide/Pool strata and weakest in Rivers and Riffle/Run streams (Figure 5). Thus the MSHA is correlated with FIBI and MIBI, but not strongly enough to where the overall MSHA score alone is predictive of limitations to the FIBI or MIBI. Low total MSHA scores at individual sites are not sufficient by themselves to classify a site as being a likely “Modified” aquatic life use because high IBI scores, consistent with CWA goal tiers, can occur commonly at such sites.

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[1] The approach taken in the more recent Minnesota Habitat Tool (MPCA 2015) analyses excluded the watershed score from the attribute calculation

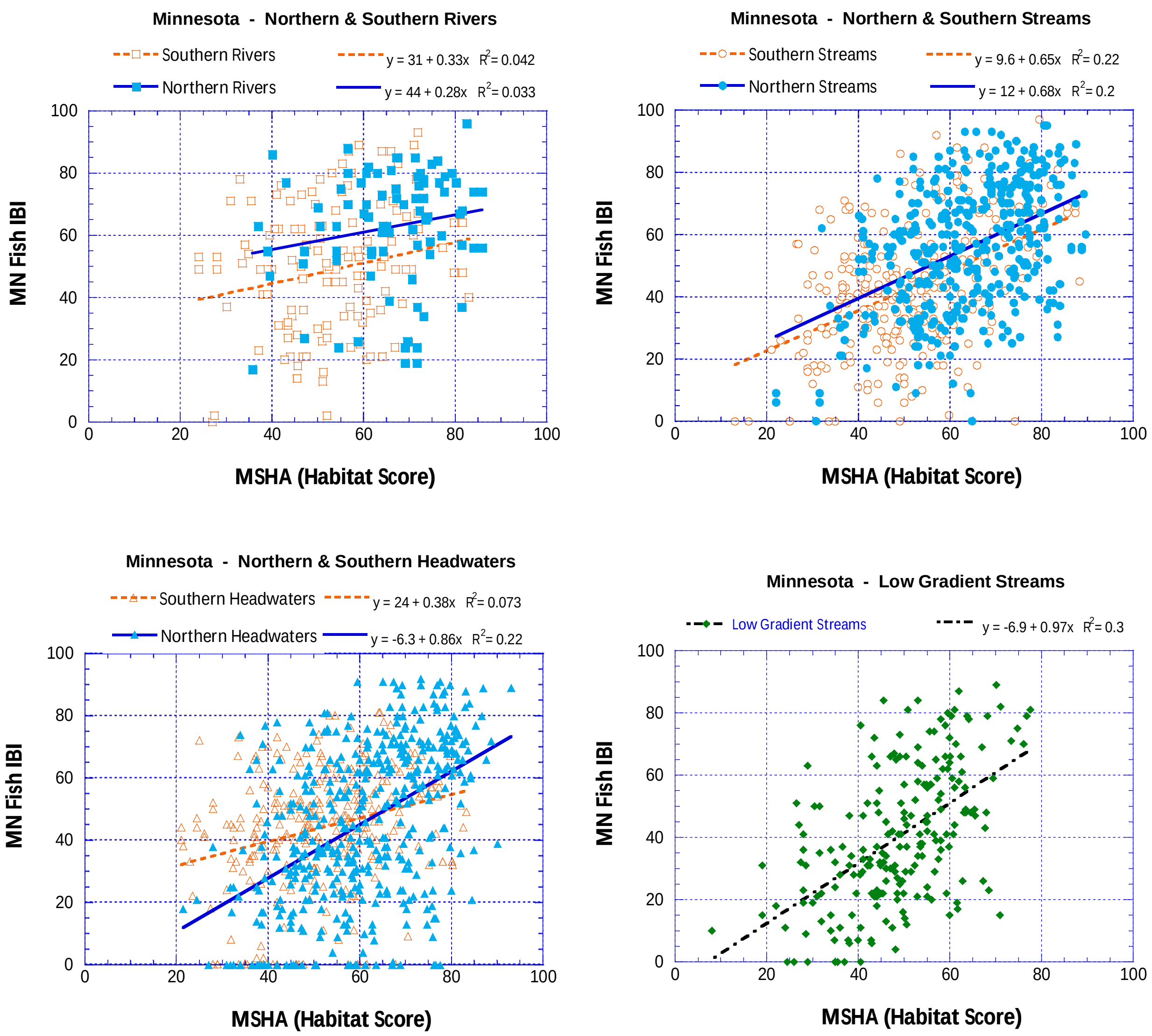
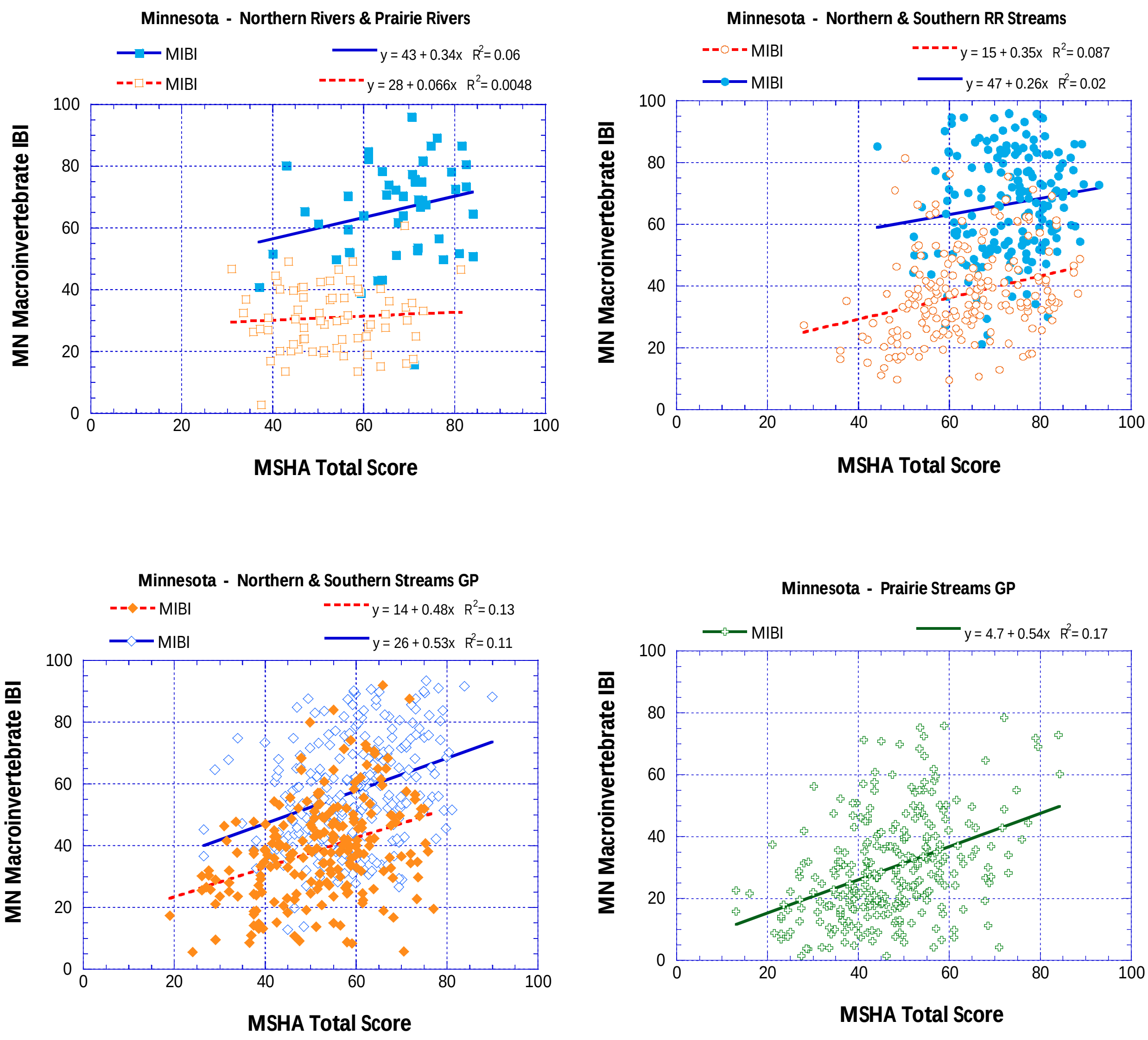


Figure 4. Plots of Fish IBI versus MSHA separately for Minnesota Northern and Southern rivers (top left), streams (top right), headwaters (bottom left) and statewide for low gradient streams (bottom right).


Minnesota - Northern Rivers & Prairie Rivers

Minnesota - Northern & Southern RR Streams

Minnesota - Northern & Southern Streams GP

Minnesota - Prairie Streams GP

Figure 5. Plots of MIBI versus Total MSHA score separately for Minnesota Northern Forest and Prairie rivers (top left), Northern and Southern Riffle/Run streams (top right), Northern and Southern Glide/Pool streams (bottom left) and Prairie Glide/Pool streams(bottom right).

Watershed and Basin Scale Habitat Effects

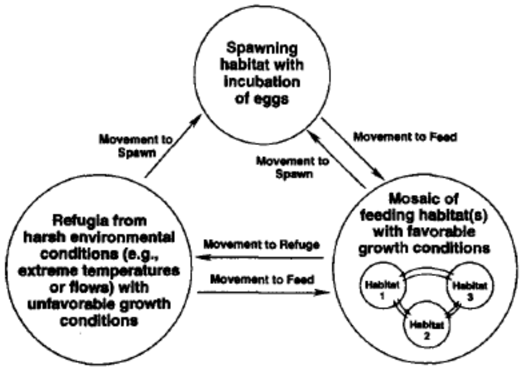


Fig. 1. The basic life cycle of stream fish with emphasis on patterns of habitat use and movement.
[Based on Jones (1968), Northcote (1978), and Schlosser (1991).]

Figure 6. Figure from Schlosser (1995) illustrating the movement between different habitats for headwater fish species.

Before we examined the local scale effects of metrics, submetrics, and attributes on the FIBI and MIBI, we explored the influence of the scale of habitat impact on aquatic assemblages. Stream ecosystems are largely “open” ecosystems with organisms often spending different parts of their life histories in different reaches of the stream “continuum.” Many species spawn in headwaters or smaller streams and then migrate to downstream reaches as they grow and feed and may move to refuges during periods of environmental stress (*e.g.,* deep pools during droughts, banks and cover during winter, etc.). A number of recent authors have summarized the influence of cumulative, watershed scale influence of habitat on aquatic assemblage condition (Richards et al. 1996; Wang et al. 2003; Brazner et al. 2005; Pease et al. 2011, Alford 2014; Radinger et al. 2015) and the relative influence of large scale habitat (*i.e.,* cumulative) effects appear stronger as human influence increases (Wang et al. 2003). Schlosser (1995) summarizes some of these needs and complexities for populations of headwater species (Figure 6). Even for species that generally have small home ranges, abiotic events (*e.g.,* storms, floods) tend to redistribute organisms within a watershed. As a result populations not only reflect local habitat conditions, but also upstream and downstream habitats. As crucial habitat types become scarce, the likelihood of local extirpations increases and may affect the species pool available to colonize suitable habitats for other life history stages.

Figure 7 (top left) is a plot of HUC-8 watershed average MSHA scores versus average FIBI scores for HUC-8 watersheds. Although the specific FIBIs do vary in meaning between classifications, the overall pattern is clearly one where average habitat quality in HUC-8 watersheds influences and limits the FIBI in these watersheds. We also examined the pattern in three key FIBI metrics common to most of the IBI variations: the number of sensitive fish species, the percent of species that are sensitive and the percent of fish individuals that are sensitive. These plots also showed a strong correlation and the limiting effects of habitat on the number of sensitive species collected (Figure 7, top right), the percent of species that are sensitive (middle left) and the percent sensitive species at stations (Figure 7, middle right). This supports the contention that as habitat degradation accumulates in a watershed it decreases or eliminates populations of sensitive fish species. The mechanism is likely a loss of critical habitat types for key life history aspects (*e.g.,* spawning, feeding, and refuge) of these species. We observed a similar relationship when we plotted the average HUC-8 habitat conditions versus the MIBI (Figure 7, lower left). A significant correlation between average HUC-8 FIBIs versus average HUC-8 MIBIs provides evidence that both organism groups are responding to cumulative habitat impacts in a similar fashion (Figure 7, lower right). We also looked at smaller watershed scales (HUC-10 and HUC-12) and observed very similar responses (Figures 8 and 9). At these smaller scales some watersheds have insufficient sites to include in the analyses. We used watersheds where we had greater than five sites for HUC-8 and HUC-10 plots and greater than three sites for the smallest HUC-12 scale. We are developing our analyses based on the HUC-8 watershed scale because the data is available for most of the sites and patterns between scales are similar. As Minnesota accumulates more data at smaller watershed scales (*e.g.,* HUC-10) it may want to rely on these smaller scales as being more accurate and appropriate when extrapolating physical limitations in a given stream.

The pattern of cumulative impacts observed in Minnesota is consistent with that described in the ecological literature. The concept of “sources and sinks” in terms of population biology and landscape ecology has been explicitly discussed in the ecological literature for several decades (*e.g.,* Pulliam 1988, Wiens et al. 1993, Lowe et al. 2006, Waits et al. 2008). Essentially some habitats are “sources” of individuals of a certain species (*e.g.,* sensitive) because of positive ecological attributes (*e.g.,* habitat features, prey) that support successful reproduction of that species. Other habitats are marginal and are considered sinks, where species may persist only because adjacent areas of good habitat produce individuals that migrate into these more marginal habitats. These marginal habitats alone would not be sufficient to maintain persistent populations of that specific species (*e.g.,* sensitive taxa or species). This concept has recently been expanded by Vandermeer et al. (2010). As habitats are degraded in a watershed, habitat sensitive fish populations may respond by declining in abundance or become extirpated in a reach of stream. As degradation accumulates in a watershed death rates may increase, birth rates may decrease, and migration rates may decline until a species is extirpated or rare in a watershed of a given scale. This occurs at multiple spatial scales and this scale can impact whether a reach of “good” habitat is large enough to act as refuge for a species or whether the population dynamics are such that during natural bottlenecks (*e.g.,* drought, flood, etc.) the species is extirpated.

From a practical “designated use” perspective this scale of impact can be important in determining whether a given aquatic life use can be attained in a given stream. If a stream is habitat degraded, but adjacent to patches of excellent habitat, the aquatic community may perform better than expected based on local habitat alone and be able to attain a higher tier of aquatic life use. Alternatively an “oasis” stream within a watershed of degraded habitat sinks may not be able to attain a regional biological endpoint because the species need to support the FIBI or MIBI may be extirpated or in low abundance. Our goal is to identify the key habitat gradients along which the biological indices change. The ends of the gradients often form obvious management endpoints where biology is attainable or likely not attainable. The selection of the breakpoint for identifying the threshold for tiered uses should consider the feasibility of restoration including economic and social factors in addition to scientific constraints.

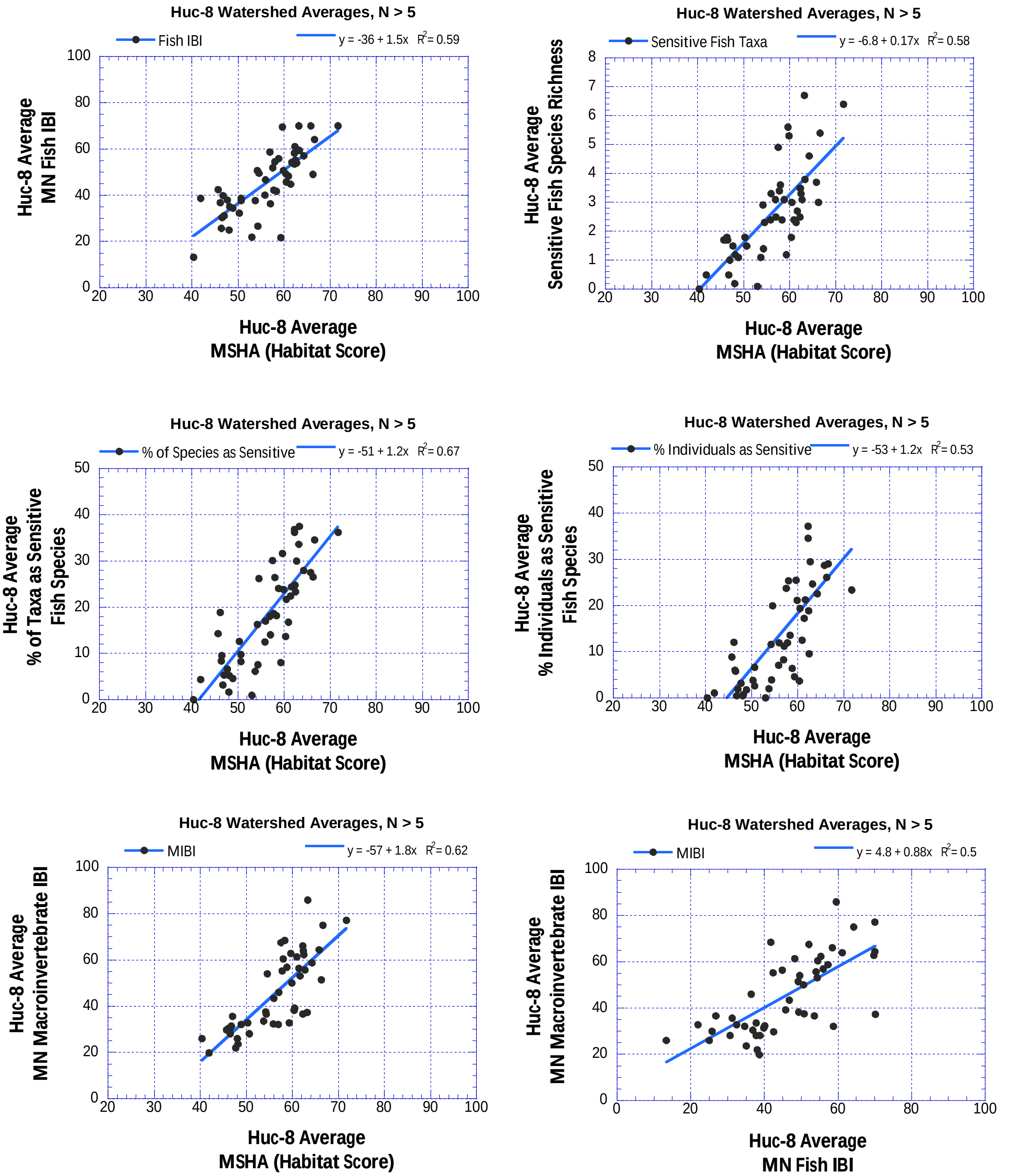


Figure 7. Plot of HUC-8 average MSHA scores versus HUC-8 average fish IBI scores (top left), average number of sensitive fish species (top right), average percent of taxa as sensitive (bottom left), average percent sensitive individuals (bottom right), MIBI (bottom left) and a plot of HUC-8 average fish IBI versus HUC-8 average MIBI (bottom right).

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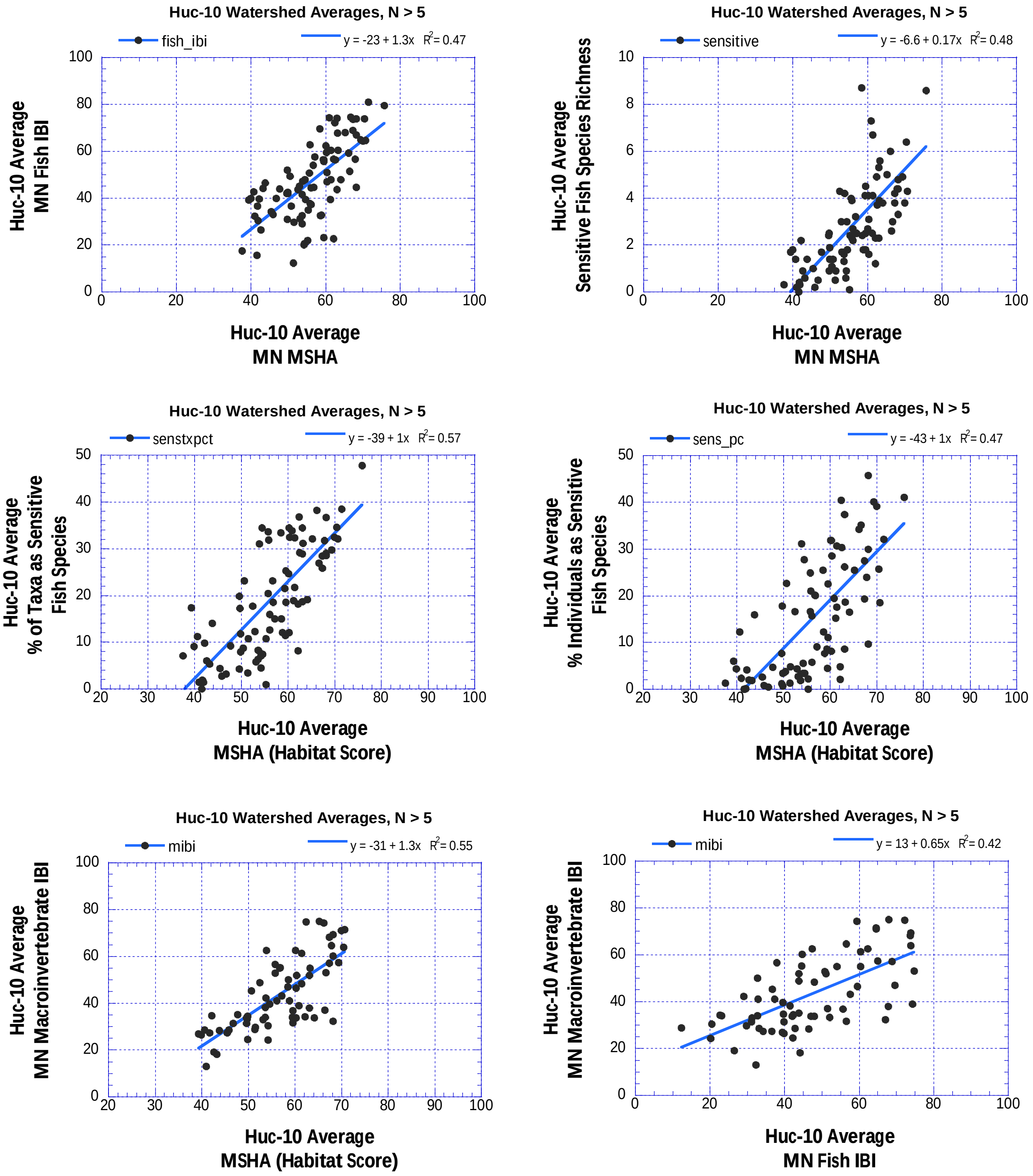

Figure 8. Plot of HUC-10 average MSHA scores versus HUC-10 average fish IBI scores (top left), average number of sensitive fish species (top right), average percent of taxa as sensitive (middle left), average percent sensitive individuals (middle right), MIBI scores (bottom left) and a plot of HUC-10 average fish IBI scores versus HUC-10 average MIBI scores (bottom right).

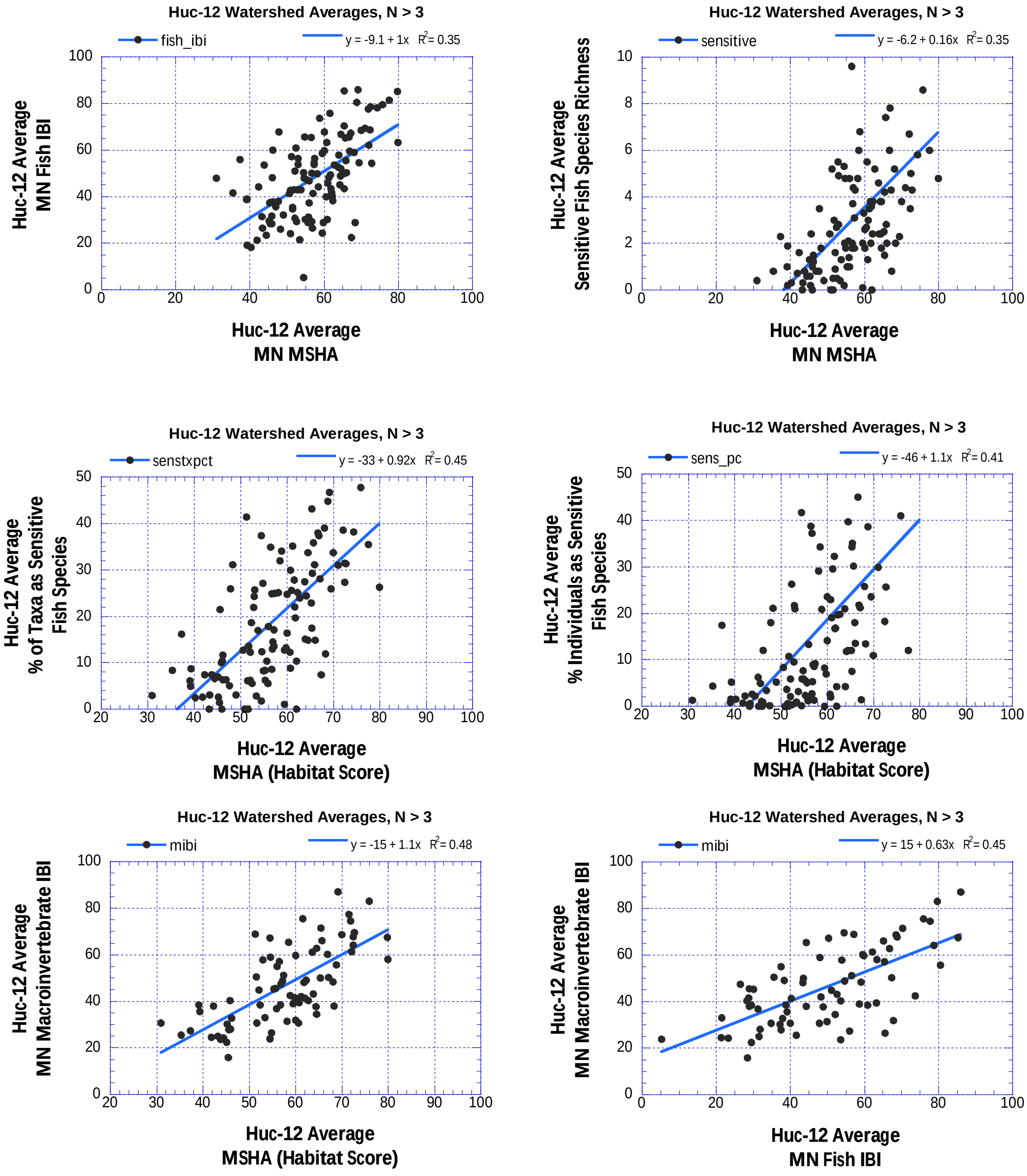

Figure 9. Plot of HUC-12 average MSHA scores versus HUC-12 average fish IBI scores (top left), average number of sensitive fish species (top right), average percent of taxa as sensitive (middle left), average percent sensitive individuals (middle right), MIBI scores (bottom left) and a plot of HUC-12 average fish IBI scores versus HUC-12 average MIBI scores (bottom right).

Classification Tree Results

Classification tree plots for each region with and without HUC-8 average MSHA habitat data as a variable are found in Appendix 2 for fish assemblages and Appendix 3 for macroinvertebrates. Important variables in explaining deviation in attainment status of fish assemblages within each region are summarized in Table 5. The dependent variable was attainment or non-attainment based on the interim FIBI biocriteria for each classification strata. The most important variable in explaining variance is at the "root" of the tree (primary variable) and nodes or branches decrease in importance with the distance from the root (*e.g.,* secondary and then other variables). The distance on the plots is proportional to the deviance explained. De'ath and Fabricus (2000) illustrated the usefulness of regression trees for "interactive exploration and for description and prediction of patterns and processes" and listed a number of key advantages over more traditional statistical tools including the ease and robustness of construction and ease of interpretation. In every classification strata where we included HUC-8 average MSHA score as a variable, it came out as the most important "primary" split in the analyses. Because of the dominance of average habitat conditions we also ran analyses with the average MSHA excluded to explore the relative importance of local submetrics. For both Northern and Southern rivers, cover amount (Southern) or cover type (Northern) was an important (Table 5, Appendix 2) classification variable as was channel stability (Northern) or channel development (Southern). In addition, other features related to channel and banks (sinuosity, riparian and bank erosion) were also identified as important, but at lower levels in the classification trees.

In Southern headwaters, good substrate type scores were a key factor explaining FIBI scores as was lack of shade. Occasionally terminal leaf variables can be counter-intuitive (*e.g.,* high sinuosity associated with impaired IBIs) although this may be related to lesser gradient in streams with high sinuosity, compared to straighter, faster flowing waters. In Northern headwaters, land use score was the primary explanatory variable and other variables were more "distantly" important and somewhat counter-intuitive. It is likely that the overwhelming importance of the small scale of habitat degradation or intactness is overwhelming other variables in this region. Northern strata results are also confounded somewhat by an "incomplete" habitat gradient with fewer habitat-degraded sites.

In Southern streams, sites with few cover types were usually impaired while sites with a diversity of current types (score > 3.5) were attaining IBI thresholds. Less strongly, sites with poor land use scores (< 0.25 of 5) were impaired and sites with better land uses attained when channel stability was > 1.5. For Northern streams, sites with land use scores > 4.8 (near the maximum of 5) attained and other streams were impaired when embeddedness was high. For low gradient streams the primary split was on land uses with scores < 1.9 (impaired) and sites with better channel development attained while heavily embedded streams were more likely impaired.

Overall, these analyses indicate that widespread habitat degradation has a scale effect that is, of greater influence on attaining an IBI threshold than any single local habitat variable. This suggests that whether a stream is capable of attaining an IBI threshold is related to the scale of habitat impact.

Table 5. Key variables explaining deviance in the attainment of the FIBI region for each of the seven classification regions in Minnesota. Classification tree analyses done with sub-metrics alone and sub-metrics plus the average MSHA score for each HUC-8 watershed as a variable.

Classification and Independent Variables	**Response Variable**	**Primary Variable**	**Secondary Variables**	**Other Variables**
Southern Rivers versus Sub-metrics	Attainment	Channel Development > 7.5	Two Predom. Substrates > 7.5 (Attain)	Cover Amount > 4.5 (Attain) Embeddedness < 0.5 (Attain) Substrate Type Score ≥ 12.4 (Attain)
Southern Rivers versus Sub-metrics and HUC-8 MSHA Average	Attainment	MSHA HUC-8 > 54.2 (Attain)	Channel Development > 7.5 (Attain)	Substrate Metric < 9.2 (Attain) Cover Metric < 7.5 (Impaired)
	Poor (Lower CI)	MSHA HUC-8 > 53.8 (Not Poor)	Cover Metric > 9.5 (> Poor)	Low Depth Variation (Poor) Low Shade (Poor)
	Good (Upper CI)	MSHA HUC-8 > 54.2 (Good)		
	Regression Tree (Node Mean)	MSHA HUC-8 > 54.2 (72.5)	Substrate Metric < 7.6 (62.1)	Cover Metric ≥ 9.5 (47.4) Cover Metric < 9.5 (35.8)
Southern Headwaters versus Sub-metrics	Attainment	Pool Substrate Score > 1.5 (Attain) < 1.5 (Impaired)	Current Types > 3.5 (Attain)	Cover Amount <1.5 (Impaired) Channel Stability (Attain) Rip. Width (Impaired)
Southern Headwaters versus Sub-metrics and HUC-8 MSHA Average	Attainment	MSHA HUC-8 > 53.8	Pool Substrate Score ≥ 0.3 (Attain) Pool Substrate Score > 0.3 (Impaired)	Current Types > 3.5 (Attain) MSHA HUC-8 < 46.3 and Land Use Metric > 0.25 (Attain) Otherwise (Impaired)
	Poor (Lower CI)	MSHA HUC-8 > 49.5 (Not Poor)	Substrate Type Score < 8 (Poor)	Current Types > 3.5 (Not Poor) Riparian Metric > 9.3 (Not Poor) Otherwise (Poor)
	Good (Upper CI)	MSHA HUC-8 > 53.8 (< Good)	Single Good Node: Pool Substrate > 1.5 and MSHA HUC-8 < 45.7 and Land Use Metric > 0.63	
	Regression Tree (Node Mean)	MSHA HUC-8 > 53.8 (54.1)	Substrate Type Score > 7.6 (41.0)	MSHA HUC-8 > 49.5 (36.2) Otherwise (7.8)
Southern Streams versus Sub-metrics	Attain	Shade > 1.3	Substrate Metric Score > 20.3 (Attain)	Riparian Metric Score < 6.3 (Impaired) Two Predominant Substrate < 6.5 (Attain) Otherwise (Impaired)
Southern Streams versus Sub-metrics and HUC-8 MSHA Average	Attain	MSHA HUC-8 < 53	Pool Substrate Score > 0.95 (Attain) else (Impaired) Riparian Metric Score < 6.3 (Impaired	Channel Metric Score > 25.5 (Attained) Else (Mostly Impaired)
	Poor (Lower CI)	Shade > 1.3	Substrate Metric Score > 17.9 (Not Poor unless Run Substrate < 6.8) or Riparian Metric Score > 6.3 (Not Poor) otherwise (Poor)	
	Good (Upper CI)	MSHA HUC-8 > 55 (Good unless Run Substrate > 12.4)	Channel Metric > 26.5 (Good) Otherwise (< Good)	
	Regression Tree (Node Mean)	MSHA HUC-8 > 56.2 (71.8)	Channel Metric Score > 26.5 (56.6)	Cover Types Score > 2.5 (36.8) Substrate Metric Score > 7.4 (33.7) Otherwise (8.2)

Northern Rivers versus Sub-metrics	Attain	Cover Amount > 5 (Attain)	Run Substrate < 9.4 (Attain)	Sinuosity Score > 3 (Impaired) Otherwise (Attain)
Northern Rivers versus Sub-metrics and HUC-8 MSHA Average	Attain	MSHA HUC-8 < 54.9 (Impaired) Otherwise (Attain)		
	Poor (Lower CI)	Insufficient Poor Sites		
	Good (Upper CI)	MSHA HUC-8 > 54.9 (Good)	Cover Metric Score < 12.5 (Good)	MSHA HUC-8 > 59.7 (Good) Otherwise (Not Good)
	Regression Tree (Node Mean)	MSHA HUC-8 < 54.9 (22.5)	MSHA HUC-8 > 60.7 (71.7) Otherwise (59.3)	
Northern Headwaters versus Sub-metrics	Attain	Land Use Score > 3.6 (Attain)	Substrate Metric Score 17.95 (Attain) Otherwise (Impaired)	
Northern Headwaters versus Sub-metrics and HUC-8 MSHA Average	Attain	Land Use Score > 3.6	MSHA HUC-8 > 61.6 (Attain) Substrate Metric Score ≥ 18 (Attain)	MSHA HUC-8 < 61.6 Riffle Substrate Score > 1.5 (Attain) Otherwise (Impaired) Substrate Metric Score < 18 (Impaired)
	Poor (Lower CI)	Land Use Score > 4.13 (Not Poor)	Pool Substrate Score > 3.5 (Not Poor)	Cover Types Score < 2.5 (Poor) Shade Score < 4.5 (Poor) Riffle Substrate > 5 (Not Poor) else (Poor)
	Good (Upper CI)	Land Use Score < 4.8 (Not Good)	Substrate Type Score > 11.5 (Good) Otherwise (Not Good)	
	Regression Tree (Node Mean)	Land Use Score < 4.8 and Substrate Score > 18 (47.6) Otherwise (29.9) Land Use Score ≥ 4.8 and Substrate Score > 20 (73.6) Otherwise (55.5)		
Northern Streams versus Sub-metrics	Attain	Land Use Score ≥ 2.6 and Riffle Substrate > 0.95 (mostly attain, except where current type score < 1.5 Land Use Score < 2.6 and Pool Substrate Score > 0.9 (Attains), Otherwise Impaired)		
Northern Streams versus Sub-metrics and HUC-8 MSHA Average	Attain	MSHA HUC-8 > 60.7 (Attain)	MSHA HUC-8 < 54.6 (Impaired) Otherwise (Attain)	
	Poor (Lower CI)	MSHA HUC-8 > 60.7 (Not Poor)	MSHA HUC-8 < 41.8 (Poor)	MSHA HUC-8 ≥ 41.8 and Riffle Substrate Score < 0.9 (Poor) Otherwise (Not Poor)
	Good (Upper CI)	MSHA HUC-8 > 59.4 (Good)	MSHA HUC-8 > 54.6 and Erosion Score <2.8 (Good)	Otherwise (Not Good)
	Regression Tree (Node Mean)	MSHA HUC-8 ≥ 60.7 and Substrate Metric Score > 18.2 (73.9); Substrate Metric Score < 18.2 (59.5) MSHA HUC-8 < 60.7 and MSHA HUC-8 ≥ 41.8 (45.7); MSHA HUC-8 < 41.8 (17.2)		
Low Gradient Streams versus Sub-metrics	Attain	Land Use Score < 1.9 (Impaired)	Channel Metric Score > 17.5 (Attain)	Riparian Metric Score < 6.3 (Attain) Riparian Metric Score ≥ 6.3 and Pool Substrate Score > 3.1 and Cover Amount Score < 8.5 (Attain), Otherwise (Impaired)
Low Gradient Streams versus Sub-metrics and	Attain	MSHA HUC-8 < 54.2 (Impaired)	Channel Metric Score ≥ 16.5 and Land Use Metric Score > 3.6 (Attain) Channel Metric Score < 16.5 and Riparian Metric Score > 6.8 and MSHA HUC-8 < 62 (Impaired) Otherwise (Attain)	

HUC-8 MSHA Average	Poor (Lower CI)	MSHA HUC-8 < 54.1 (Poor)	Channel Metric Score ≥ 17.5 (Not Poor) Channel Metric Score <17.5 and Riparian Metric ≥ 9.8 and MSHA HUC-8 <60 (Poor) Otherwise (Not Poor)	
	Good (Upper CI)	Land Use Metric Score < 1.9 (Not Good)	Channel Metric Score ≥ 17.5 (Good) Channel Metric Score < 17.5 and Erosion Score < 3.8 (Good),Otherwise (Not Good)	
	Regression Tree (Node Mean)	MSHA HUC-8 < 54.1 (16.5)	Channel Metric Score < 17.5 (35.7)	Channel Metric Score ≥ 17.5 MSHA HUC-8 < 64.9 (49.7) MSHA HUC-8 ≥ 64.9 (71.9)

Metric-by-Metric Analyses

The next sections focus on a MSHA metric-by-metric exploration of effects on the FIBI and MIBI and other key biological metrics by classification strata to identify, where possible, key attributes that might be limiting these assemblages. Our goal was to derive a list of “good” and “poor” habitat attributes for each organism group and classification strata that can serve as indicators when selecting appropriate and protective aquatic life uses

Substrate Metrics

Substrate types and condition (*i.e.*, siltation and sedimentation) can have substantial impacts on aquatic life (Waters 1995). Coarse substrates have important functions including feeding and spawning sites, habitat niches for macroinvertebrates, providing areas of reduced velocity as well as increased turbulence in fast flowing areas, and providing stable surface area for biofilms for lower taxonomic groups (*e.g.*, periphyton, protists, and bacteria). Measures of bed stability including visual methods have been correlated to macroinvertebrate composition and diversity (Schwendel et al. 2011). Other workers have identified association of sensitive fish assemblages with coarse or rocky substrates and more tolerant species with finer and mud/silt substrates (Berkman and Rabeni 1987; Pease et al. 2011, Bey and Sullivan 2015) or with the aggradation of fines that embed coarser substrates (Sullivan and Watzin 2010).

Scatter plots of the summary substrate metric versus FIBI are illustrated in Figure 10 for each classification strata. Substrate is a key metric of the MSHA. The MSHA substrate *type* metric differs from the QHEI substrate type metric in that it separately identifies predominate materials in pool, runs, riffles and glides; whereas the QHEI identifies predominate substrate types over the entire reach. Overall correlation of the FIBI to the MSHA substrate metric score was weak for all of the classification strata although there seems to be somewhat of a limiting threshold for the Northern and Southern stream classes and at the upper and lower end of the substrate score gradient. Plot of a key habitat-sensitive metric, the number of sensitive fish species demonstrated a stronger threshold response than did the FIBI (Figure 11). An alternate measure of sensitivity, the number of sensitive fish taxa showed a more variable threshold. This may be related to loss of species at sites with the most degraded substrates which led to greater variability in the metric at the most degraded sites.

The MIBI also showed a rather weak association with the substrate metric score, especially for rivers and riffle/run type streams (Figure 12). Relationships were stronger in “Glide/Pool” morphology streams versus “Riffle/Run” type streams. Riffle/Run type streams generally had higher average substrate scores and were likely less susceptible to accumulating fines because of their gradients and morphology. Glide/Pool streams tend to have lower gradients and, with depositional type habitats, are more likely affected by fines. The Glide/Pool streams had a wider range of substrate scores and better correlations than Riffle/Run streams.

Substrate Submetrics

To identify key habitat attributes we examined which substrate types were strongly associated with high and low FIBI scores using box and whisker plots, ANOVA and the Tukey multiple comparison tests in an exploratory mode to identify potential good and/or poor habitat attributes and to compose a weighted index of total good or poor habitat attributes. Certain substrate types occurred infrequently within certain stream size categories and were usually ignored if sample size was less than 5. We identified two sets of attributes for Minnesota streams, one based on “theoretical” expectations based on literature and experience and second set that was more data driven based on the results of the ANOVAs and Tukey comparisons within each classifications strata.

Substrates are scored separately for pool, riffle, run, and glide habitats in the MSHA and will be discussed individually. Aside from river classifications, coarser materials in pools were typically more often associated with higher IBIs scores and fine materials (silts) were associated with lower IBI scores on average (Tables 6 and 7). There was some variation between fish (Table 6) and macroinvertebrate strata (Table 7) with macroinvertebrate assemblages showing more variation between strata than fish. Low sample sizes can have some effect on the identification of significant patterns by substrate type. Coarser materials (*e.g.,* boulder, cobble) were less often present in macroinvertebrate strata defined by glide and pool habitats (Table 11 and 13).

In riffles, boulders were identified as important substrate types in three fish strata, but the influence of finer substrate types as negative attributes (*e.g.,* silts) were less commonly identified in riffles (Table 8). This is largely because such fines are typically not found where water velocity is high enough to flush most of these out with exception of Southern Streams where sand was also a negative attribute. Riffle substrates were a weak predictor of MIBIs. Again, where riffles are an important feature, velocities define the types likely to be chosen as a predominant type (Table 8 and 9).

For fish assemblages in run habitats, with the exception of river and low gradient strata, coarse substrates were generally associated with higher IBI scores and silts were associated with lower IBI scores (Table 10). For macroinvertebrates that pattern was evident in Southern or Glide/Pool type strata, but results were not significant in Northern and Prairie Rivers where fines were uncommon (Table 11). No significant relationships were observed between substrate types in glides and FIBI or MIBI in any strata, largely because these habitat types were rarely identified in sufficient numbers to test for many strata (Tables 12 and 13).

Embeddedness

In addition to the identification of predominant major substrate types that comprise the stream bed, the MSHA measures substrate condition by estimating the embeddedness of substrates in the reach. Besides the silt fraction of the bedload of rivers, aggradation of sands and fine gravels on coarser sediments (*e.g.*, cobbles, boulders) has also been identified as a problem in Midwest streams and rivers. In some severe cases, particularly in lower gradient reaches; "sand slugs" have been identified and shown to impact fisheries (Bond and Lake 2005). Concerns related to populations of large Midwest species such as paddlefish have been related to smothering of eggs and embryos by bedload (Jennings and Zigler 2000). Work in southern Appalachian streams identified a 5 to 9-fold increase in bedload in disturbed streams compared to reference streams (Sutherland *et al*. 2002). Similarly, key fish metrics in Georgia streams responded to a key number of key substrates measures such as embeddedness (Rashleigh and Kennen 2003). In Minnesota (Nerbonne and Vondracek 2001) found that percent fines and embeddedness were negatively correlated with buffer width and Wang et al. (2006) reported that in Wisconsin the installation of best management practices (*e.g.,* fencing) increased substrate size, reduced sediment depth, embeddedness, and bank erosion.

For fish assemblages we saw a significant association between severe embeddedness and lower IBI scores and low to no embeddedness and higher IBI scores in all strata except Northern Rivers where severe embeddedness was rare (Table 14). For macroinvertebrates there was a less uniform pattern with higher IBIs in streams with low to no embeddedness in Northern streams (severe embeddedness being less common) and less of a relationship in River and Southern strata, although there was a significant pattern in Prairie Glide/Pool streams (Table 15). Stronger relationships may have been observed if there were more "severely embedded" sites in Northern streams and more sites with "no embeddedness" in Southern streams to increase the range of scores

Substrate Types

The MSHA tracks the number of substrate types as a measure of how many stream bottom types may be available to organisms ($\leq$ 4 types or > 4 types). We only observed a strong relationship in the fish assemblages in Northern Headwaters and Low Gradient strata (Table 16) and in macroinvertebrates in Northern Glide/Pool and Prairie Glide/Pool strata (Table 17). Ohio uses a similar metric in their QHEI, but altered it several years ago to only count "high quality" substrates after they recognized that a higher score a site might occur because of silt or muck being the 5th substrate type. This could be responsible for the lack of association in Southern Strata (Tables 16 and 17) or the positive association in the Northern Headwaters for fish where silts were uncommon and > 4 types represented a richness of good substrate types.

Tables 18 and 19 summarize the variables selected as key "good" or "poor" substrate habitat attributes by organism group and classification strata. The presence of any of these key attributes will contribute to the count of good versus poor habitat attributes and can become a factor in determining whether some habitat alteration is feasibly restorable or likely to lead to biological limitation of achieving an aquatic life goal.

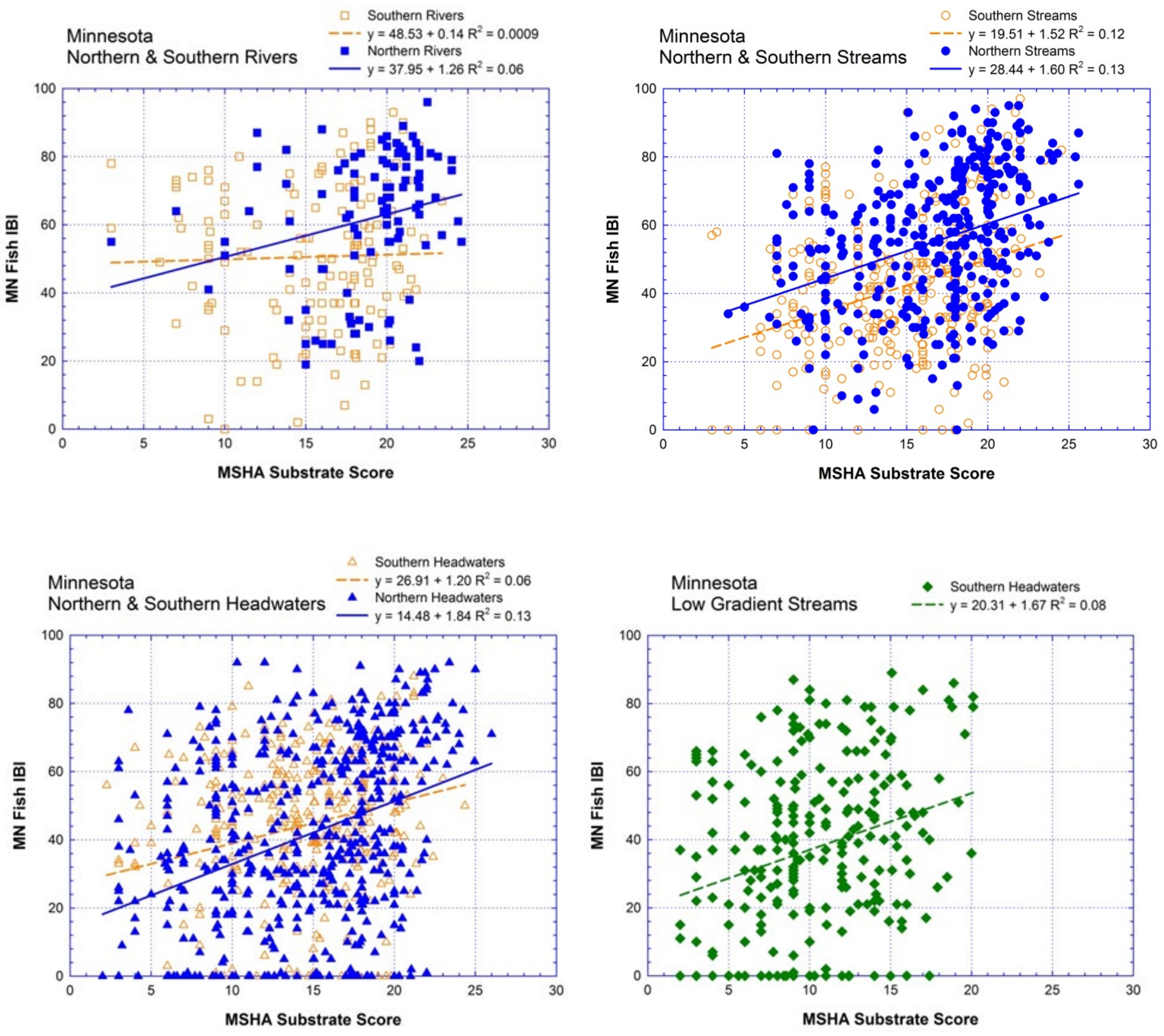

Figure 10. Plots of Fish IBI scores versus MSHA substrate score separately for Minnesota Northern and Southern rivers (top left), streams (top right), headwaters (bottom left) and statewide for low gradient streams (bottom right).

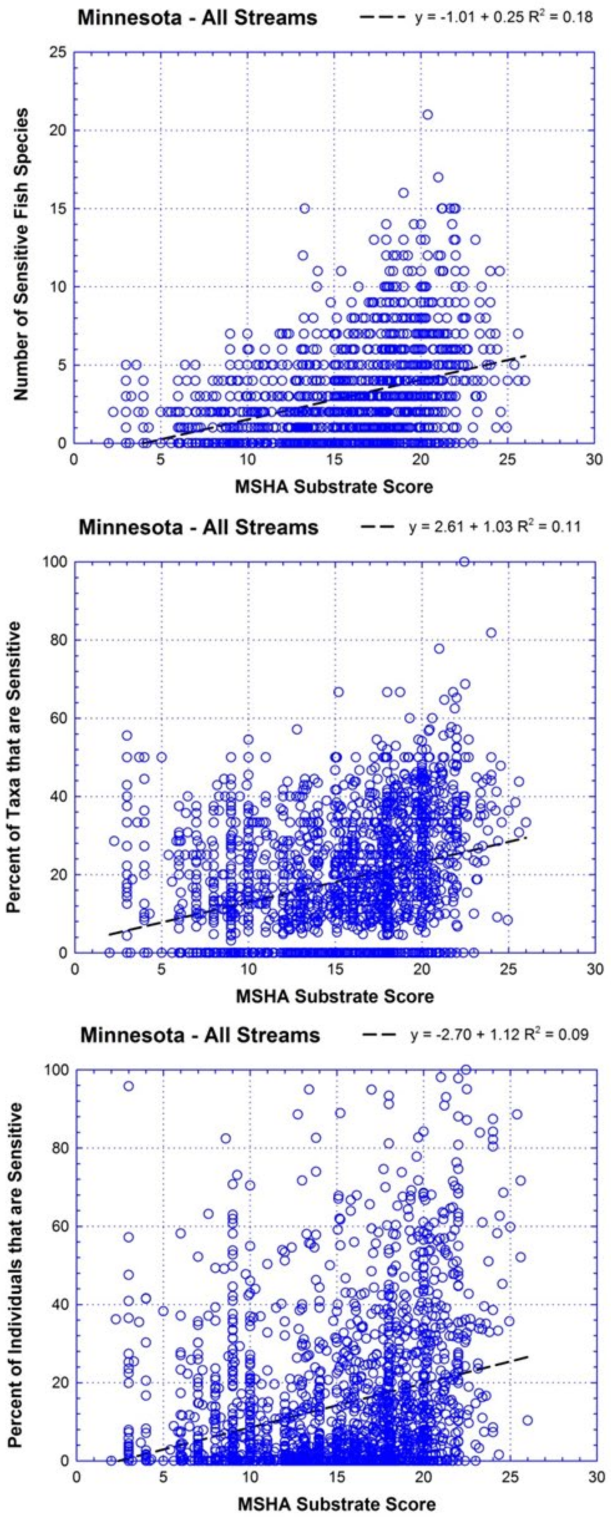

Figure 11. Plots of MSHA substrate metric score versus number of sensitive fish taxa (top) and percent of taxa that are sensitive (bottom). All classifications combined.

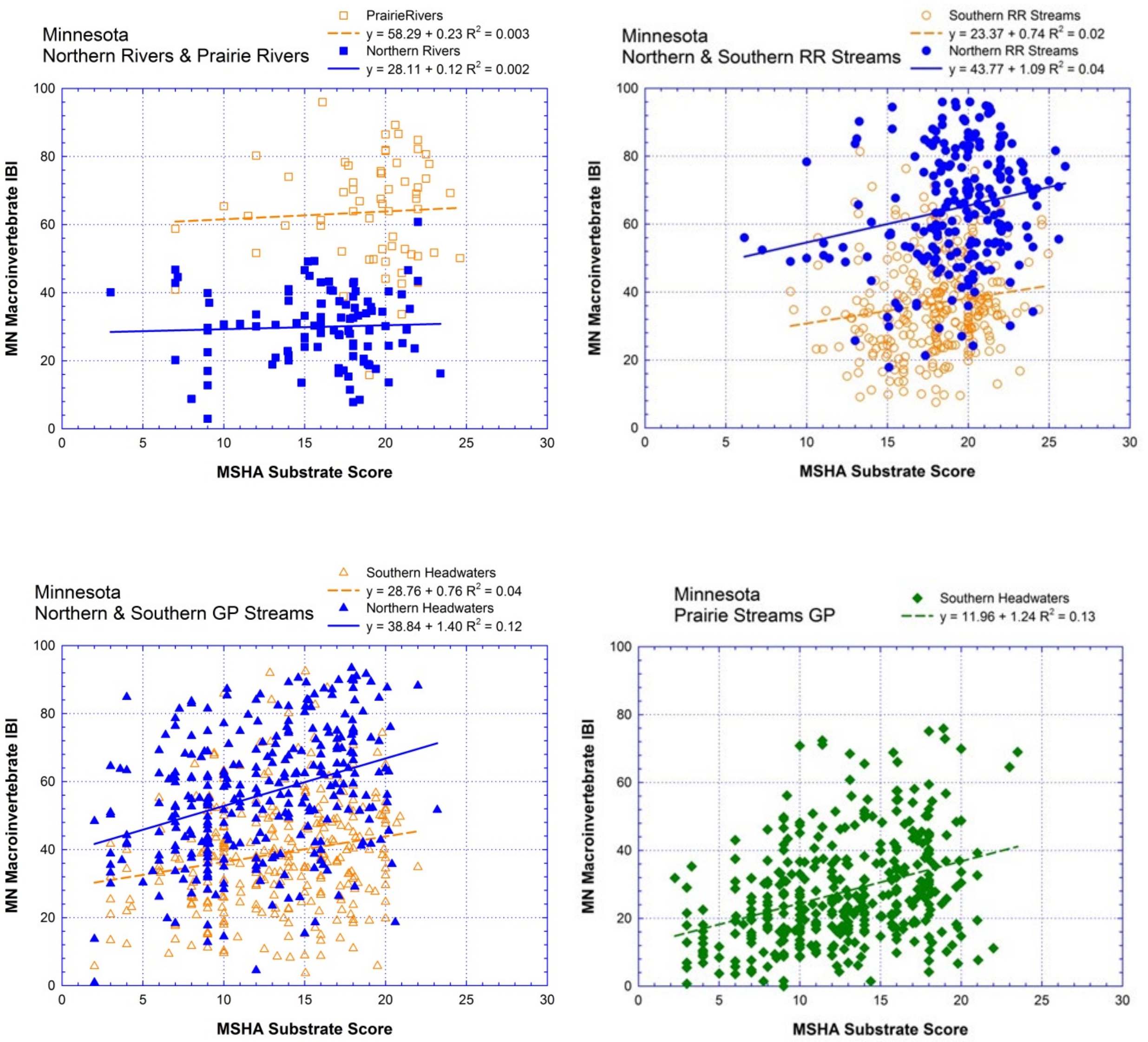

Figure 12. Plots of MIBI scores versus MSHA substrate score separately for Minnesota Northern and Prairie rivers (top left), Northern and Southern Riffle/Run streams (top right), Northern and Southern Glide/Pool streams (bottom left) and Prairie Glide/Pool streams (bottom right).

Table 6. Mean Fish IBI values (SE) for individual MSHA substrate types in pool habitats. Attributes with <5 samples are not included. Highest values are highlighted in blue (+) or red (-). Darker shades are significant (Tukey) and light shades are near significant and biologically meaningful. ANOVA results are at bottom. Tests with asterisks are significant at P<0.05 were followed with a Tukey multiple comparison test.

Attribute	*Reach Type*	*Southern Rivers*	*Southern Streams*	*Southern Headwaters*	*Northern Rivers*	*Northern Streams*	*Northern Headwaters*	*Low Gradient Streams*
Boulder	Pool	46.9 (6.4)	44.4 (8.5)	56.8 (6.2)	65.5 (3.8)	68.7 (3.0)	53.5 (5.2)	42.0 (12.8)
Cobble	Pool	58.9 (7.2)	53.3 (4.5)	57.5 (5.0)	66.1 (4.1)	68.9 (2.2)	50.6 (2.6)	-
Gravel	Pool	47.9 (4.3)	47.1 (2.2)	50.2 (2.3)	60.0 (3.5)	57.7 (1.7)	47.7 (2.0)	39.1 (5.7)
Sand	Pool	49.2 (2.5)	44.1 (1.5)	48.3 (1.3)	59.9 (2.6)	53.3 (1.3)	44.6 (1.4)	41.3 (2.2)
Clay	Pool	59.4 (2.9)	42.9 (2.8)	40.8 (3.5)	73.6 (3.0)	55.5 (2.5)	43.9 (3.5)	43.9 (5.3)
Bedrock	Pool	-	-	-	-	-	-	-
Silt	Pool	46.4 (3.4)	40.1 (2.0)	46.0 (1.9)	58.4 (7.2)	48.0 (1.8)	39.4 (1.8)	44.1 (2.0)
Muck	Pool	-	-	-	-	-	-	31.3 (6.5)
Detritus	Pool	-	-	39.0 (9.6)	-	35.5 (5.8)	32.7 (4.2)	45.4 (4.6)
ANOVA		**F=1.524 P=0.185 NS**	**F=2.208 P=0.0526 NS**	**F= 2.197 P=0.0421 ***	**F=1.276 P=0.278 NS**	**F=13.590 P<0.0001 ***	**F=4.160 P=0.0004 ***	**F=0.580 P=0.7460 NS**
Attribute Scores		**Good: P<0.001**	🟦	**Good: P<0.05-0.001**	🟦	**Good: > 0.05 but trending or low sample size**		🟩
		Poor: P<0.001	🟥	**Poor: P<0.05-0.001**	🟥	**Poor: > 0.05 but trending or low sample size**		🟧

Table 7. Mean Macroinvertebrate IBI values (SE) for individual MSHA substrate types in pool habitats. Attributes with <5 samples are not included. Highest values are highlighted in blue (+) or red (-). Darker shades are significant (Tukey) and light shades are near significant and biologically meaningful. ANOVA results are at bottom. Tests with asterisks are significant at P<0.05 were followed with a Tukey multiple comparison test.

Attribute	*Reach Type*	*Northern Forests Rivers (1)*	*Prairie Forest Rivers (2)*	*Northern Streams Riffle-Run (3)*	*Northern Streams Glide-Pool (4)*	*Southern Streams Riffle-Run (5)*	*Southern Streams Glide-Pool (6)*	*Prairie Streams Glide-Pool (7)*
Boulder	Pool	70.5 (4.2)	35.6 (2.7)	67.5 (2.7)	59.7 (5.9)	35.8 (3.1)	38.4 (8.4)	-
Cobble	Pool	63.9 (4.5)	33.5 (4.0)	70.1 (1.5)	64.6 (8.7)	43.6 (2.4)	34.3 (11.2)	32.6 (7.5)
Gravel	Pool	66.9 (4.0)	29.1 (2.3)	67.5 (1.6)	61.9 (2.2)	38.3 (1.3)	40.1 (2.5)	34.1 (2.8)
Sand	Pool	63.1 (2.5)	29.7 (1.4)	62.6 (1.6)	58.1 (1.5)	36.8 (0.9)	41.9 (1.2)	31.3 (1.2)
Clay	Pool	68.1 (4.8)	32.0 (3.8)	56.8 (3.0)	60.3 (2.1)	29.8 (2.7)	33.9 (3.1)	25.9 (2.0)
Bedrock	Pool	-	-	-	-	-	-	-
Silt	Pool	54.2 (4.0)	31.1 (2.1)	50.2 (2.5)	53.6 (1.4)	32.6 (1.6)	40.0 (1.4)	28.3 (1.2)
Muck	Pool	-	-	-	-	-	23.4 (5.2)	-
Detritus	Pool	-	-	-	52.1 (3.8)	-	34.5 (4.5)	25.7 (5.7)
ANOVA		**F=1.096 P=0.369 NS**	**F=0.695 P=0.628 NS**	**F=9.096 P<0.0001 ***	**F=2.602 P=0.0172 ***	**F=4.718 P=0.0003 ***	**F=1.997 P=0.0543 NS**	**F=1.730 P=0.128 NS**

Table 8. Mean Fish IBI values (SE) for individual MSHA substrate types in riffle habitats. Attributes with <5 samples are not included. Highest values are highlighted in blue (+) or red (-). Darker shades are significant (Tukey) and light shades are near significant and biologically meaningful. ANOVA results are at bottom. Tests with asterisks are significant at P<0.05 were followed with a Tukey multiple comparison test.

Attribute	*Reach Type*	*Southern Rivers*	*Southern Streams*	*Southern Headwaters*	*Northern Rivers*	*Northern Streams*	*Northern Headwaters*	*Low Gradient Streams*
Boulder	Riffle	55.2 (4.2)	42.4 (4.9)	45.7 (7.6)	65.7 (4.2)	70.6 (2.1)	55.7 (3.5)	49.4 (8.7)
Cobble	Riffle	48.6 (2.9)	51.6 (2.2)	51.1 (2.3)	60.2 (3.0)	63.9 (1.5)	49.0 (1.9)	56.5 (7.3)
Gravel	Riffle	42.7 (2.6)	47.9 (1.7)	48.6 (1.4)	56.6 (3.6)	56.4 (1.7)	43.8 (1.8)	46.4 (4.9)
Sand	Riffle	54.7 (3.9)	40.9 (2.0)	46.9 (1.8)	48.6 (9.8)	49.6 (2.3)	41.2 (2.4)	46.5 (4.0)
Clay	Riffle	-	43.1 (6.8)	-	-		43.5 (14.9)	-
Bedrock	Riffle	-	-	-	-		-	-
Silt	Riffle	-	33.0 (7.1)	19.2 (11.0)	-		32.6 (6.8)	46.4 (5.7)
Muck	Riffle	-	-	-	-		-	-
Detritus	Riffle	-	-	-	-		-	-
		F=3.448 P=0.0189 *	**F=3.02 P=0.0111 ***	**F=3.954 P=0.0037 ***	**F=1.403 P=0.246 NS**	**F=17.24 P<0.0001 ***	**F=4.002 P=0.0014 ***	**F=0.456 P=0.7680 NS**

Table 9. Mean Macroinvertebrate IBI values (SE) for individual MSHA substrate types in riffle habitats. Attributes with <5 samples are not included. Highest values are highlighted in blue (+) or red (-). Darker shades are significant (Tukey) and light shades are near significant and biologically meaningful. ANOVA results are at bottom. Tests with asterisks are significant at P<0.05 were followed with a Tukey multiple comparison test.

Attribute	*Reach Type*	*Northern Forests Rivers (1)*	*Prairie Forest Rivers (2)*	*Northern Streams Riffle-Run (3)*	*Northern Streams Glide-Pool (4)*	*Southern Streams Riffle-Run (5)*	*Southern Streams Glide-Pool (6)*	*Prairie Streams Glide-Pool (7)*
Boulder	Riffle	65.9 (3.1)	26.9 (3.4)	68.2 (1.7)	55.4 (7.4)	41.2 (2.3)	-	46.9 (11.1)
Cobble	Riffle	66.4 (2.5)	29.5 (1.7)	66.0 (1.3)	57.7 (4.0)	38.0 (1.1)	46.2 (4.8)	32.3 (3.3)
Gravel	Riffle	67.7 (3.9)	31.3 (1.6)	63.3 (1.7)	61.4 (2.7)	35.4 (0.9)	41.5 (1.7)	33.4 (1.5)
Sand	Riffle	80.6 (1.1)	28.1 (2.8)	50.9 (4.3)	54.6 (2.6)	35.0 (1.7)	40.5 (1.7)	33.3 (1.8)
Clay	Riffle	-	-	-	-	-	-	32.9 (6.6)
Bedrock	Riffle	-	-	-	-	-	-	-
Silt	Riffle	-	-	-	46.4 (4.2)	-	31.5 (3.6)	21.4 (5.9)
Muck	Riffle	-	-	-	-	-	-	-
Detritus	Riffle	-	-	-	-	-	-	-
		F=1.105 P=0.355 NS	**F=0.773 P=0.512 NS**	**F=6.042 P=0.0005 ***	**F=1.419 P=0.2310 NS**	**F=2.778 P=0.0407 ***	**F=1.388 P=0.247 NS**	**F=1.268 P=0.2790 NS**

Table 10. Mean Fish IBI values (SE) for individual MSHA substrate types in run habitats. Attributes with <5 samples are not included. Highest values are highlighted in blue (+) or red (-). Darker shades are significant (Tukey) and light shades are near significant and biologically meaningful. ANOVA results are at bottom. Tests with asterisks are significant at P<0.05 were followed with a Tukey multiple comparison test.

Attribute	*Reach Type*	*Southern Rivers*	*Southern Streams*	*Southern Headwaters*	*Northern Rivers*	*Northern Streams*	*Northern Headwaters*	*Low Gradient Streams*
Boulder	Run	56.1 (6.1)	49.4 (12.2)	-	66.2 (2.2)	74.9 (2.9)	60.6 (5.1)	-
Cobble	Run	55.8 (3.6)	55.7 (3.2)	55.0 (4.1)	68.7 (3.3)	68.8 (1.6)	57.3 (2.1)	-
Gravel	Run	44.6 (2.4)	45.1 (1.5)	46.0 (1.6)	58.8 (2.7)	55.7 (1.3)	44.1 (1.6)	38.4 (3.9)
Sand	Run	49.6 (2.1)	40.9 (1.2)	46.2 (1.2)	57.9 (2.5)	49.5 (1.2)	39.7 (1.4)	41.8 (1.8)
Clay	Run	59.8 (3.2)	40.2 (2.6)	38.1 (3.9)	72.4 (7.0)	53.6 (3.0)	33.5 (4.4)	33.4 (4.5)
Bedrock	Run	-	-	-	-	-	-	-
Silt	Run	49.4 (3.7)	33.9 (2.2)	41.3 (1.9)	56.2 (4.5)	44.7 (2.4)	32.9 (1.9)	37.0 (2.1)
Muck	Run	-	-	-	-	-	-	-
Detritus	Run	-	-	22.9 (5.8)	-	-	26.2 (3.4)	34.8 (3.9)
		F=2.455 P=0.0339 *	**F=8.456 P<0.0001 ***	**F=5.725 P<0.0001 ***	**F=2.323 P=0.0447 ***	**F=25.74 P<0.0001 ***	**F=16.77 P<0.0001 ***	**F=1.448 P=0.217 NS**

Table 11. Mean Macroinvertebrate IBI values (SE) for individual MSHA substrate types in run habitats. Attributes with <5 samples are not included. Highest values are highlighted in blue (+) or red (-). Darker shades are significant (Tukey) and light shades are near significant and biologically meaningful. ANOVA results are at bottom. Tests with asterisks are significant at P<0.05 were followed with a Tukey multiple comparison test.

Attribute	*Reach Type*	*Northern Forests Rivers (1)*	*Prairie Forest Rivers (2)*	*Northern Streams Riffle-Run (3)*	*Northern Streams Glide-Pool (4)*	*Southern Streams Riffle-Run (5)*	*Southern Streams Glide-Pool (6)*	*Prairie Streams Glide-Pool (7)*
Boulder	Run	57.4 (3.0)	33.5 (5.6)	68.9 (2.6)	-	50.7 (4.5)	-	38.9 (12.6)
Cobble	Run	66.1 (3.1)	33.8 (2.6)	68.8 (1.4)	62.1 (4.8)	42.3 (1.6)	40.3 (6.3)	36.7 (5.0)
Gravel	Run	65.8 (2.6)	30.2 (1.5)	64.8 (1.5)	64.3 (1.9)	36.5 (0.9)	41.4 (1.6)	31.1 (1.2)
Sand	Run	62.0 (2.7)	29.4 (1.1)	59.4 (1.8)	57.5 (1.2)	35.3 (0.9)	41.0 (1.0)	30.2 (1.0)
Clay	Run	-	30.6 (5.1)	-	57.4 (2.9)	30.0 (3.3)	40.5 (4.6)	24.9 (1.5)
Bedrock	Run	-	-	-	-	-	-	-
Silt	Run	-	28.1 (2.8)	49.4 (2.0)	51.5 (1.4)	31.7 (2.9)	35.2 (1.4)	24.1 (1.2)
Muck	Run	-	-	-	-	-	-	-
Detritus	Run	-	-	-	48.0 (3.2)	-	27.3 (3.0)	21.0 (3.6)
		F=1.148 P=0.334 NS	**F=0.733 P=0.599 NS**	**F=6.487 P<0.0001 ***	**F=7.367 P<0.0001 ***	**F=5.089 P=0.0001 ***	**F=3.978 P=0.0015 ***	**F=5.571 P<0.0001 ***

Table 12. Mean Fish IBI values (SE) for individual MSHA substrate types in glide habitats. Attributes with <5 samples are not included. Highest values are highlighted in blue (+) or red (-). Darker shades are significant (Tukey) and light shades are near significant and biologically meaningful. ANOVA results are at bottom. Tests with asterisks are significant at P<0.05 were followed with a Tukey multiple comparison test.

Attribute	*Reach Type*	*Southern Rivers*	*Southern Streams*	*Southern Headwaters*	*Northern Rivers*	*Northern Streams*	*Northern Headwaters*	*Low Gradient Streams*
Boulder	Glide	-		-	-	-	-	-
Cobble	Glide	-	-	-	-	73.8 (3.3)	-	-
Gravel	Glide	-	-	-	-	70.7 (8.7)	-	-
Sand	Glide	-	25.0 (4.4)	-	-	78.2 (3.2)	36.8 (10.2)	25.8 (8.9)
Clay	Glide	-	-	-	-	-	-	24.3 (9.2)
Bedrock	Glide	-	-	-	-	-	-	-
Silt	Glide	-	24.4 (7.4)	-	-	-	35.0 (10.9)	21.0 (5.8)
Muck	Glide	-	-	-	-	-	-	-
Detritus	Glide	-	-	-	-	-	-	-
		-	**F=0.004** **P=0.951** **NS**	**-**	**-**	**F=0.422** **P=0.6640** **NS**	**F=0.014** **P=0.907** **NS**	**F=0.116** **P=0.8910** **NS**

Table 13. Mean Macroinvertebrate IBI values (SE) for individual MSHA substrate types in glide habitats. Attributes with <5 samples are not included. Highest values are highlighted in blue (+) or red (-). Darker shades are significant (Tukey) and light shades are near significant and biologically meaningful. ANOVA results are at bottom. Tests with asterisks are significant at P<0.05 were followed with a Tukey multiple comparison test.

Attribute	*Reach Type*	*Northern Forests Rivers (1)*	*Prairie Forest Rivers (2)*	*Northern Streams Riffle-Run (3)*	*Northern Streams Glide-Pool (4)*	*Southern Streams Riffle-Run (5)*	*Southern Streams Glide-Pool (6)*	*Prairie Streams Glide-Pool (7)*
Boulder	Glide	-		-	-	-	-	-
Cobble	Glide	-	-	-	-	-	-	-
Gravel	Glide	-	-	-	-	-	-	-
Sand	Glide	-	-	-	65.3 (6.8)	-	16.8 (3.8)	22.2 (3.0)
Clay	Glide	-	-	-	-	-	-	15.8 (3.2)
Bedrock	Glide	-	-	-	-	-	-	-
Silt	Glide	-	-	-	51.6 (9.3)	-	19.0 (2.7)	15.9 (3.0)
Muck	Glide	-	-	-	-	-	-	-
Detritus	Glide	-	-	-	-	-	-	-
		-	**-**	**-**	**F=1.488** **P=0.2380** **NS**	**-**	**F=0.2280** **P=0.6440** **NS**	**F=1.240** **P=0.3120** **NS**

Table 14. Mean Fish IBI values (SE) for the MSHA embeddedness score. Attributes with <5 samples are not included. Highest values are highlighted in blue (+) or red (-). Darker shades are significant (Tukey) and light shades are near significant and biologically meaningful. ANOVA results are at bottom. Tests with asterisks are significant at P<0.05 were followed with a Tukey multiple comparison test.

Embedded-ness Score	*Reach Type*	*Southern Rivers*	*Southern Streams*	*Southern Headwaters*	*Northern Rivers*	*Northern Streams*	*Northern Headwaters*	*Low Gradient Streams*
No Coarse	All	52.2 (1.7)	34.2 (1.3)	38.8 (2.1)	-	47.7 (1.9)	35.0 (2.1)	32.4 (2.2)
Severe	All	40.3 (8.0)	37.0 (2.0)	39.9 (3.6)	-	40.5 (3.5)	37.7 (3.0)	27.2 (3.9)
Moderate	All	42.8 (2.7)	41.9 (2.0)	45.8 (1.7)	52.9 (5.2)	51.1 (1.8)	36.6 (2.1)	41.0 (3.5)
Light	All	53.5 (2.6)	48.6 (2.1)	47.4 (1.8)	62.5 (2.3)	56.8 (1.7)	50.2 (1.8)	44.3 (3.8)
None	All	-	41.6 (5.7)	35.9 (4.7)	-	67.6 (2.9)	57.9 (3.8)	44.0 (4.7)
		F=5.57 **P=0.001** *****	**F=5.41** **P<0.001** *****	**F=3.62** **P<0.007** *****	**F=3.19** **P=0.08** **NS**	**F=10.39** **P<0.001** *****	**F=16.83** **P<0.001** *****	**F=3.67** **P=0.006** *****

Table 15. Mean Macroinvertebrate IBI values (SE) for individual MSHA embeddedness score. Attributes with <5 samples are not included. Highest values are highlighted in blue (+) or red (-). Darker shades are significant (Tukey) and light shades are near significant and biologically meaningful. ANOVA results are at bottom. Tests with asterisks are significant at P<0.05 were followed with a Tukey multiple comparison test.

Embedded-ness Score	*Reach Type*	*Northern Forests Rivers (1)*	*Prairie Forest Rivers (2)*	*Northern Streams Riffle-Run (3)*	*Northern Streams Glide-Pool (4)*	*Southern Streams Riffle-Run (5)*	*Southern Streams Glide-Pool (6)*	*Prairie Streams Glide-Pool (7)*
No Coarse [0]	All	-	36.3 (2.7)	-	49.9 (1.8)	34.4 (1.4)	38.3 (1.6)	26.3 (1.3)
Severe [-1]	All	-	-	-	52.4 (3.1)	34.3 (4.0)	35.5 (2.0)	27.1 (1.7)
Moderate [1]	All	69.2 (5.2)	28.5 (1.6)	57.3 (2.5)	59.7 (2.2)	32.3 (1.3)	39.3 (1.9)	30.1 (1.3)
Light [3]	All	62.2 (2.4)	31.2 (1.7)	64.2 (1.7)	61.6 (2.1)	38.0 (1.1)	41.2 (1.6)	33.5 (1.9)
None [5]	All	-	-	76.1 (2.0)	60.8 (3.2)	44.7 (4.4)	36.4 (4.3)	28.0 (6.2)
		F=1.04 **P=0.315** **NS**	**F=0.002** **P=0.99** **NS**	**F=10.45** **P<0.001** *****	**F=9.049** **P<0.001** *****	**F=3.11** **P<0.027** *****	**F=1.127** **P=0.344** **NS**	**F=5.22** **P<0.001** *****

Table 16. Mean Fish IBI values (SE) for individual MSHA number of substrate types (>4 or < 4). Attributes with < 5 samples are not included. Highest values are highlighted in blue (+) or red (-). Darker shades are significant (Tukey) and light shades are near significant and biologically meaningful. ANOVA results are at bottom. Tests with asterisks are significant at P<0.05 were followed with a Tukey multiple comparison test.

No. of Substrate Types	*Reach Type*	*Southern Rivers*	*Southern Streams*	*Southern Headwaters*	*Northern Rivers*	*Northern Streams*	*Northern Headwaters*	*Low Gradient Streams*
> 4	All	46.0 (3.1)	44.9 (2.0)	44.9 (2.0)	65.4 (2.4)	56.3 (1.4)	50.3 (1.8)	45.0 (3.7)
< 4	All	52.0 (1.4)	39.2 (1.1)	36.0 (1.3)	60.7 (1.4)	52.6 (1.3)	38.3 (1.4)	30.8 (1.6)
		F=4.61 P=0.034 *	**F=2.04 P=0.15 NS**	**F=1.94 P=0.165 NS**	**F=0.917 P=0.34 NS**	**F=0.714 P=0.398 NS**	**F=19.64 P<0.001 ***	**F=8.457 P=0.004 ***

Table 17. Mean Macroinvertebrate IBI values (SE) for individual MSHA number of substrate types (>4 or < 4). Attributes with <5 samples are not included. Highest values are highlighted in blue (+) or red (-). Darker shades are significant (Tukey) and light shades are near significant and biologically meaningful. ANOVA results are at bottom. Tests with asterisks are significant at P<0.05 were followed with a Tukey multiple comparison test.

No. of Substrate Types	*Reach Type*	*Northern Forests Rivers (1)*	*Prairie Forest Rivers (2)*	*Northern Streams Riffle-Run (3)*	*Northern Streams Glide-Pool (4)*	*Southern Streams Riffle-Run (5)*	*Southern Streams Glide-Pool (6)*	*Prairie Streams Glide-Pool (7)*
> 4	All	66.1 (2.8)	30.9 (2.0)	65.0 (1.5)	61.2 (1.7)	36.6 (1.1)	39.4 (2.1)	34.4 (1.7)
< 4	All	69.2 (2.6)	34.9 (1.7)	70.3 (1.9)	55.1 (1.3)	37.6 (1.4)	39.4 (1.1)	28.5 (1.1)
		F=0.011 P=0.917 NS	**F=0.004 P=0.944 NS**	**F=3.422 P=0.066 NS**	**F=8.17 P=0.005 ***	**F=2.32 P=0.128 NS**	**F=0.00 P=0.999 NS**	**F=11.83 P<0.001 ***

Table 18. Theoretical and data-driven "good" and "poor" habitat attributes for the substrate metric for fish assemblages in Minnesota rivers and streams. "Good" attributes are those expected to be associated with higher fish IBI scores and "poor" attributes are those expected to be associated with lower fish IBI scores. Numbers in bracket are weighted scores using to calculate the good or bad attribute score.

Sub-Metric	***Theoretical Attributes***	***Data Driven Attributes***						
		Southern Rivers (1)	***Southern Streams (2)***	***Southern Headwaters (3)***	***Northern Rivers (4)***	***Northern Streams (5)***	***Northern Headwaters (6)***	***Low Gradient Streams (7)***
Substrate Metric								
Good Pool Substrate Types	Boulder, Cobble, Gravel	-	Cobble [1]	Boulder[.5] Cobble[.5]	-	Boulder[2] Cobble[2] Gravel[1]	Boulder[.5] Cobble[1] Gravel[1]	-
Poor Pool Substrate Types	Silt	-	Silt [1]	Clay[.5] Detritus[.5]	-	Silt[2] Sand[2] Clay[1] Detritus[2]	Silt[1] Detritus[1]	-
Good Riffle Substrate Types	Boulder, Cobble, Gravel	Boulder[.5] Sand[1]	Cobble[1]	Boulder[.5] Cobble[1] Gravel[1] Sand[1]	-	Boulder[2] Cobble[2]	Boulder[1]	-
Poor Riffle Substrate Types	Silt,	Gravel[1]	Sand[1] Silt[.5]	Silt[1]	-	Gravel[2] Sand[2]	Gravel[1] Sand[1] Silt[.5]	-
Good Run Substrate Types	Boulder, Cobble, Gravel	Clay[1]	Boulder[.5] Cobble[2] Gravel[2]	Cobble[2] Gravel[1] Sand[1]	Cobble[1]	Boulder[2] Cobble[2]	Boulder[2] Cobble[2] Gravel[2]	-
Poor Run Substrate Types	Silt	Gravel[1]	Sand[2] Clay[1] Silt[2]	Clay[1] Silt[1] Detritus[2]	Sand[1]	Gravel[2] Sand[2] Clay[2] Silt[2]	Sand[2] Clay[2] Silt[2] Detritus[2]	-
Good Embedded-ness	None	No Coarse[1] Light[2]	Light[1]	Light[1]	-	None[2] Light[1]	None[2] Light[2]	Light[1] None[.5]
Poor Embedded-ness	Severe	Severe[2]	Severe[1] No Coarse[1]	Severe[.5] No Coarse[1]	-	Severe[2] No Coarse[2]	Moderate[2] Severe[1] No Coarse[2]	Severe[1] No Coarse[.5]
Good – No. Substrate Types	> 4	≤4 [.5]	> 4 [.5]	> 4 [.5]	> 4 [.5]	-	> 4 [2]	> 4 [1]
Poor – No. Substrate Types	≤ 4	> 4 [.5]	≤4 [.5]	≤4 [.5]	≤4 [.5]	-	≤ 4 [2]	≤ 4 [1]

Table 19. Theoretical and data-driven “good” and “poor” habitat attributes for the substrate metric for macroinvertebrate assemblages in Minnesota rivers and streams. “Good” attributes are those expected to be associated with higher fish IBI scores and “poor” attributes are those expected to be associated with lower fish IBI scores. Numbers in bracket are weighted scores using to calculate the good or bad attribute score.

		Data Driven Attributes						
Sub-Metric	***Theoretical Attributes***	***Northern Forest Rivers (1)***	***Prairie Forest Rivers (2)***	***Northern Streams Riffle-Run (3)***	***Northern Streams Glide-Pool (4)***	***Southern Streams Riffle-Run (5)***	***Southern Streams Glide-Pool (6)***	***Prairie Streams Glide-pool (7)***
Substrate Metric								
Good Pool Substrate Types	Boulder, Cobble, Gravel	-	-	Boulder[2] Cobble[2] Gravel[2]	Boulder[.5] Gravel[.5] Clay[.5]	Cobble[1]	-	-
Poor Pool Substrate Types	Silt, Clay	-	-	Sand[1] Clay[.5] Silt[2]	Silt[.5] Detritus[.5]	Clay[1] Silt[2]	-	-
Good Riffle Substrate Types	Boulder, Cobble, Gravel	-	-	Boulder[2] Cobble[1] Gravel[1]	-	Boulder[.5]	-	-
Poor Riffle Substrate Types	Silt, Clay	-	-	Sand[2]	-	Gravel[.5] Sand[.5]	-	-
Good Run Substrate Types	Boulder, Cobble, Gravel	-	-	Boulder[1] Cobble[2] Gravel[.5]	Gravel[2]	Boulder[1] Cobble[1]	Cobble[.5] Gravel[1] Sand[1]	Boulder[.5] Cobble[.5] Gravel[1] Sand[1]
Poor Run Substrate Types	Silt, Clay	-	-	Sand[2] Silt[1]	Sand[1] Silt[2] Detritus[2]	Gravel[1] Sand[1] Clay[1] Silt[1]	Silt[1] Detritus[1]	Clay[.5] Silt[1] Detritus[.5]
Good Embedded-ness	None	-	-	None[2]	None[1] Light[1]	None[1]	-	Light[1] Moderate[1]
Poor Embedded-ness	Severe	-	-	Moderate[2]	Severe[.5] No Coarse[2]	-	-	No Coarse[2]
Good – No. Substrate Types	> 4	-	-	-	> 4[1]	-	-	> 4[2]
Poor – No. Substrate Types	≤ 4	-	-	-	≤ 4[1]	-	-	≤ 4[2]

Instream Structure or "Cover"

There is extensive literature linking various types of instream cover to abundance and biomass of various fish species (Angermeier and Karr 1984, Hrodey et al. 2009, Simon and Morris 2014). Macroinvertebrate taxa have also been associated with various cover types, especially types such as large woody debris (Angermeier and Karr 1984, Smock et el. 1989, Wallace et al. 1995, Benke and Wallace. 2003). Sport fish populations have been manipulated by the addition of instream cover as a way to increased sport fish biomass in streams although many restoration projects have insufficient monitoring data to assess the efficacy of such projects (Brooks et al. 2002, Bernhardt et al. 2005, Roni et al. 2008) and results at the reach level have been mixed, especially for macroinvertebrates (Palmer et al. 2010). The presence of high quality cover (*e.g.*, rootwads, logs, undercut banks) has also been associated with presence of highly sensitive fish species and large woody debris can be fundamental to development of heterogeneous channels and pool/riffle habitats (Davidson and Eaton 2013).

There were only weak relationships in associations between the overall cover metric score and fish assemblages (Figure 13) or macroinvertebrate assemblages (Figure 14) in any of the classification strata. There does seem to be a threshold response with fish assemblages at the lowest scores for most regions and along the range of scores for low gradient streams (Figure 13). This is weaker to non-existent in the macroinvertebrate plots (Figure 14).

Cover Types

ANOVA results for individual cover types were similarly weak with differences related to slightly higher FIBI scores associated with rootwads and logs and woody debris in Southern Streams, rootwads and deep pools in Southern Headwaters, and boulders, in Northern Streams and Northern Headwaters (Table 20). Single cover types may not be expected to be strongly correlated by themselves, but rather with a diversity of cover types instead. For macroinvertebrates slightly higher MIBI scores were associated with logs and woody debris in Southern GP Streams and deep pools, rootwads, logs and boulders in Prairie GP Streams (Table 21). For this reason we did not select the presence of any single cover type as indicators of good or poor habitat attributes, but concentrated on the amount of overall cover among sites.

Cover Score

There were stronger associations between FIBI and number of cover types with low FIBIs associated with sites with only 1-2 cover types in all but Northern and Southern Rivers and high numbers of cover types (5-7) associated with higher FIBI scores in all but Northern and Southern Rivers and Northern Streams (Table 22). Few cover types (≤ 3) were associated with lower MIBI scores in Southern RR and GP streams and Prairie GP Streams and more cover types (6-7) were associated with higher MIBI scores in these same strata (Table 23).

Cover Amount

In addition to identifying each type of cover present, the MSHA tracks the overall amount of cover available to organisms. Overall estimates of cover amount (sparse to extensive) did show a significant or trending relationships with higher FIBI scores with more extensive cover and lower scores with more sparse cover in all but Southern and Northern Rivers (Table 24). However, macroinvertebrates showed no trend with cover amount (Table 25).

The pattern of little to no difference may be partially an artifact of the original scoring of the QHEI cover presence/absence attributes that were used in the MSHA. This method identifies either absence (none of a cover type) or presence which can range from a relative small amount to a large, well developed amount of cover. We observed the same pattern in Ohio wadeable streams where no single cover type was more strongly associated with IBIs than any other (P>0.05). QHEI cover scoring and was modified several years ago to rate each cover type individually with regard to cover amount and quality.

Tables 26 and 27 summarize the “good” and “poor” habitat attributes selected for fish and macroinvertebrate assemblage by classification strata. This metric is more influential for fish assemblages than macroinvertebrates (note numbers of attributes on Table 26 versus Table 27). Part of this may be related to the scale at which we measure habitat features such as cover. Macroinvertebrate taxa may be able to persist and thrive where certain cover types may be in low abundance. In addition many of the invertebrate taxa that make up certain substrate metric s are more substrate dependent than “cover”-dependent. Loss of cover is often associated with stream channelization, but the MIBI may be responding to losses of substrate quality that often co-occur with channel modification (Figure 15).

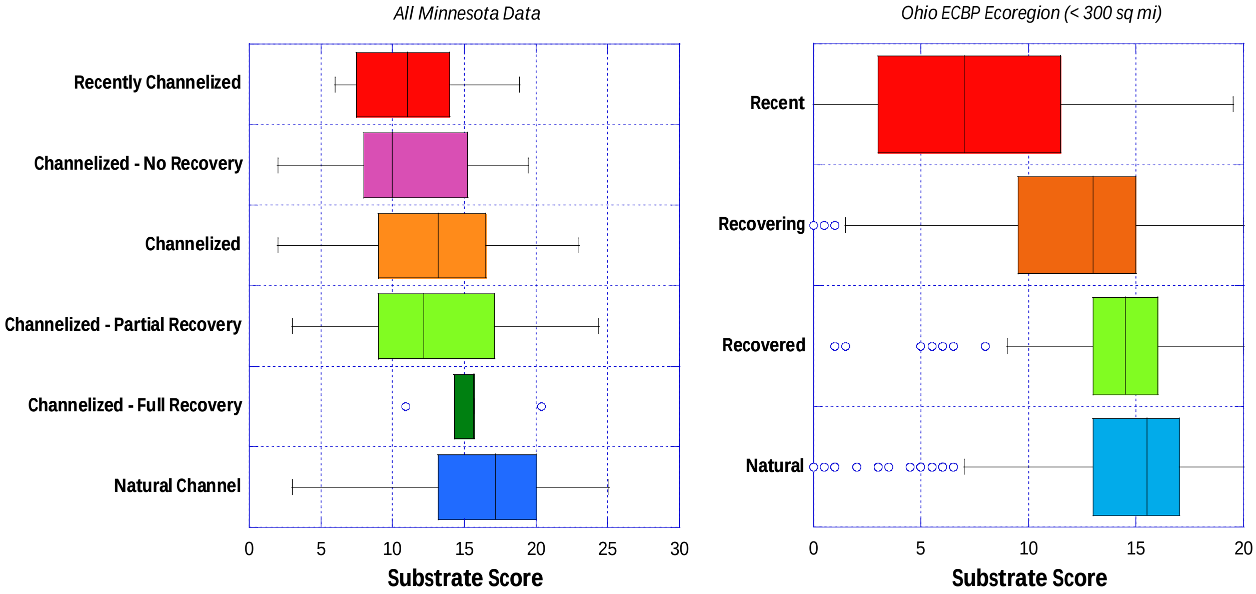

Figure 13. Box and whisker plot of MN MSHA channel modification state and MSHA substrate score (left) and box and whisker plot of QHEI channel modification state and QHEI substrate score (right) in wadeable streams of the ECBP ecoregion

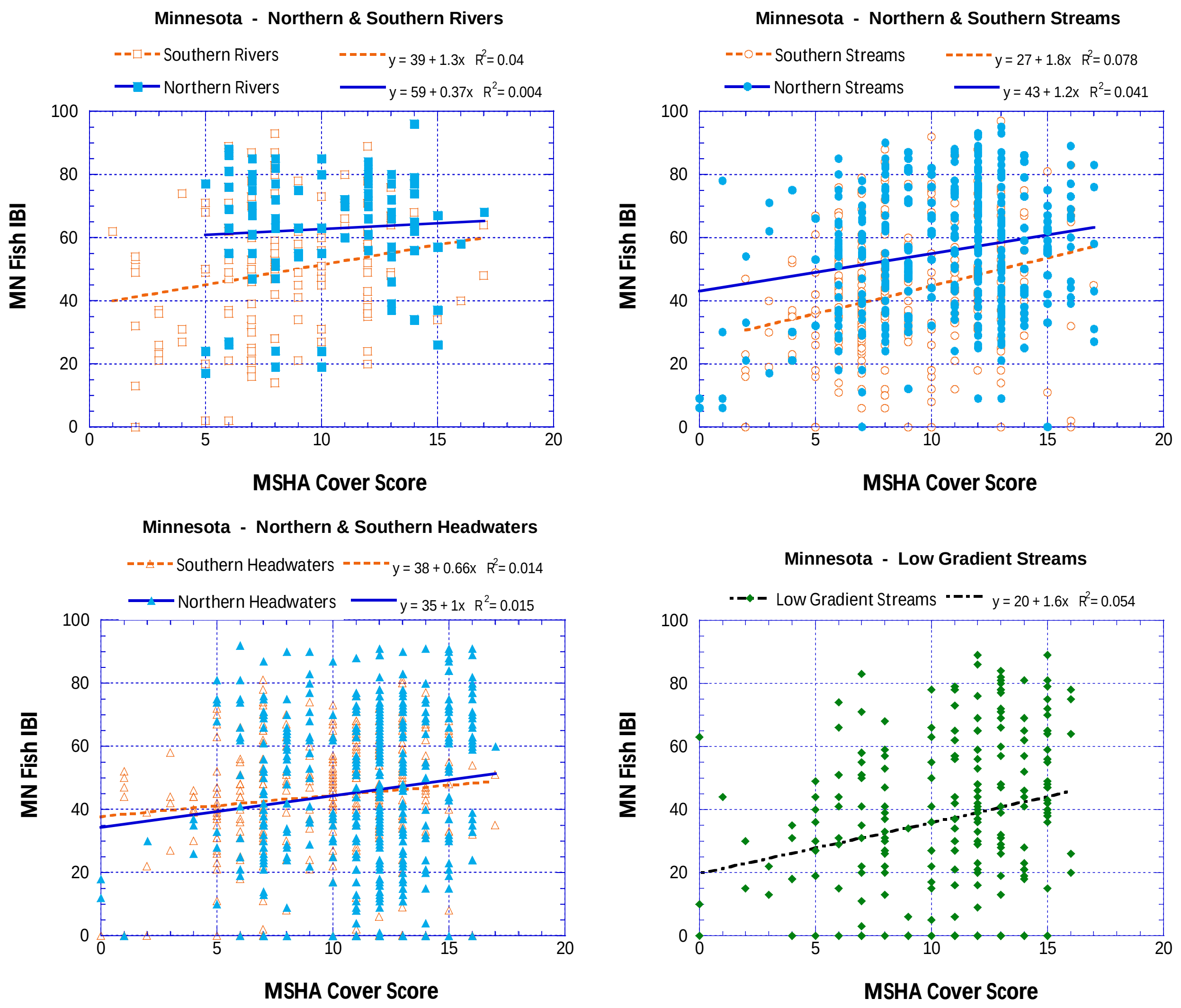

Figure 14. Plots of Fish IBI scores versus MSHA cover score separately for Minnesota Northern and Southern rivers (top left), streams (top right), headwaters (bottom left) and statewide for low gradient streams (bottom right).

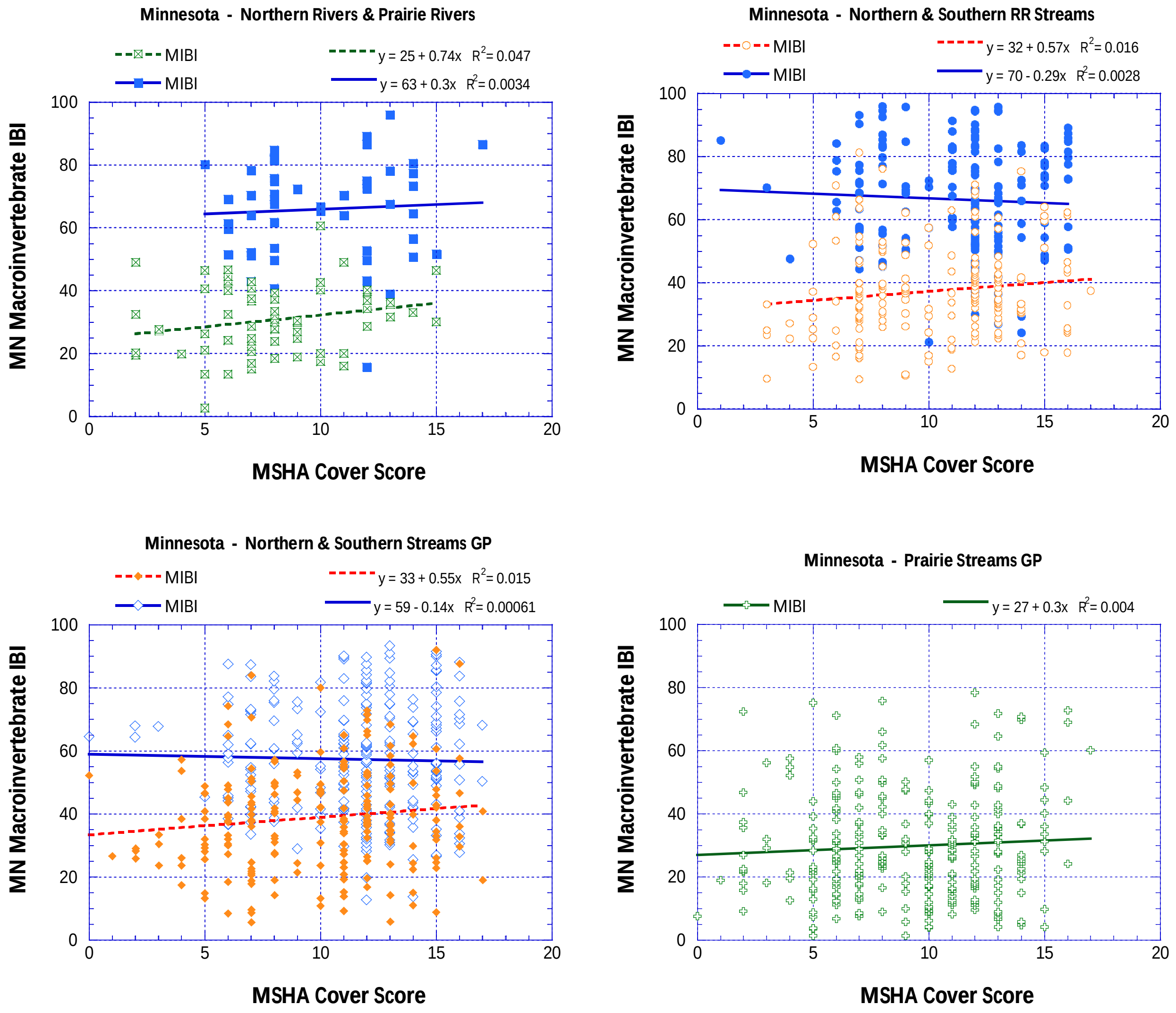

Figure 15. Plots of MIBI scores versus MSHA cover score separately for Minnesota Northern and Prairie rivers (top left), Northern and Southern Riffle/Run streams (top right), Northern and Southern Glide/Pool streams (bottom left) and Prairie Glide/Pool streams (bottom right).

Table 20. Mean FIBI values (SE) for individual MSHA cover types. Attributes with <5 samples are not included. Highest values are highlighted in blue (+) or red (-). Darker shades are significant (Tukey) and light shades are near significant and biologically meaningful. ANOVA results are at bottom. Tests with asterisks are significant at P<0.05 were followed with a Tukey multiple comparison test.

Cover Type	*Reach Type*	*Southern Rivers*	*Southern Streams*	*Southern Headwaters*	*Northern Rivers*	*Northern Streams*	*Northern Headwaters*	*Low Gradient Streams*
Undercut Banks	All	44.6 (2.5)	43.1 (1.3)	45.4 (1.4)	59.7 (3.1)	53.8 (1.3)	42.8 (1.4)	42.6 (2.0)
Overhang Vegetation	All	50.3 (2.1)	41.8 (1.2)	44.6 (1.1)	60.1 (2.4)	53.7 (1.2)	42.1 (1.2)	36.9 (1.7)
Deep Pools	All	52.4 (2.0)	46.7 (1.5)	49.4 (1.3)	61.2 (2.1)	56.6 (1.2)	45.3 (1.4)	42.4 (2.4)
Logs and Woody Debris	All	51.7 (1.8)	47.6 (1.3)	47.4 (1.4)	60.8 (2.0)	55.4 (1.1)	44.3 (1.3)	42.8 (1.9)
Boulders	All	49.6 (2.1)	45.1 (1.6)	46.5 (1.7)	62.2 (2.1)	57.5 (1.3)	48.7 (1.6)	46.7 (3.8)
Rootwads	All	53.9 (2.7)	48.8 (2.3)	51.4 (2.2)	53.8 (4.2)	52.7 (2.3)	45.1 (3.3)	41.2 (3.9)
Macrophytes	All	51.2 (2.6)	40.5 (1.4)	42.9 (1.3)	63.6 (1.9)	54.7 (1.2)	42.4 (1.2)	36.5 (1.6)
		F=0.118 P=0.312 NS	**F=4.14 P<0.001 ***	**F=3.17 P=0.004 ***	**F=0.83 P=0.547 NS**	**F=1.38 P=0.218 NS**	**F=2.48 P=0.022 ***	**F=2.76 P=0.011 NS**

Table 21. Mean MIBI values (SE) for individual MSHA cover types. Attributes with <5 samples are not included. Highest values are highlighted in blue (+) or red (-). Darker shades are significant (Tukey) and light shades are near significant and biologically meaningful. ANOVA results are at bottom. Tests with asterisks are significant at P<0.05 were followed with a Tukey multiple comparison test.

Cover Type	*Reach Type*	*Northern Forests Rivers (1)*	*Prairie Forest Rivers (2)*	*Northern Streams Riffle-Run (3)*	*Northern Streams Glide-Pool (4)*	*Southern Streams Riffle-Run (5)*	*Southern Streams Glide-Pool (6)*	*Prairie Streams Glide-Pool (7)*
Undercut Banks	All	71.8 (3.8)	30.3 (2.2)	66.3 (1.8)	58.9 (1.4)	36.6 (1.2)	42.1 (1.4)	31.3 (1.3)
Overhang Vegetation	All	67.3 (2.9)	32.3 (1.5)	65.5 (1.4)	56.9 (1.2)	36.6 (1.1)	39.2 (1.1)	29.8 (1.0)
Deep Pools	All	64.5 (2.6)	30.5 (1.4)	66.6 (1.4)	59.2 (1.4)	39.3 (1.2)	40.8 (1.2)	35.3 (1.6)
Logs and Woody Debris	All	65.7 (2.3)	31.0 (1.3)	66.3 (1.3)	57.9 (1.1)	39.4 (1.1)	43.0 (1.2)	35.8 (1.5)
Boulders	All	66.8 (2.3)	30.6 (1.5)	66.0 (1.3)	60.0 (1.9)	38.4 (1.1)	39.7 (1.8)	34.0 (1.7)
Rootwads	All	63.1 (7.3)	33.4 (1.9)	60.2 (3.2)	58.3 (2.5)	37.9 (1.6)	40.7 (2.2)	38.1 (3.1)
Macrophytes	All	67.2 (2.2)	31.0 (2.3)	65.9 (1.3)	56.8 (1.1)	37.4 (1.3)	37.6 (1.1)	28.1 (1.1)
		F=0.53 P=0.797 NS	**F=.379 P=0.892 NS**	**F=0.479 P=0.824 NS**	**F=0.699 P=0.650 NS**	**F=0.969 P=0.444 NS**	**F=2.221 P=0.039 ***	**F=5.78 P<0.001 ***

Table 22. Mean FIBI values (SE) for number of MSHA cover score. Attributes with <5 samples are not included. Highest values are highlighted in blue (+) or red (-). Darker shades are significant (Tukey) and light shades are near significant and biologically meaningful. ANOVA results are at bottom. Tests with asterisks are significant at P<0.05 were followed with a Tukey multiple comparison test.

Cover Score	*Reach Type*	*Southern Rivers*	*Southern Streams*	*Southern Headwaters*	*Northern Rivers*	*Northern Streams*	*Northern Headwaters*	*Low Gradient Streams*
1	All	-	22.7 (5.4)	26.4 (5.7)	-	37.9 (9.1)	18.0 (4.6)	19.1 (7.5)
2	All	47.1 (6.0)	31.7 (3.5)	35.5 (3.0)	43.5 (8.9)	40.4 (5.1)	26.0 (4.8)	22.5 (3.5)
3	All	51.4 (3.6)	37.1 (2.4)	41.8 (2.5)	63.9 (6.6)	46.9 (2.9)	35.5 (2.8)	30.0 (3.8)
4	All	50.5 (4.2)	42.5 (2.1)	47.6 (1.9)	65.3 (3.6)	54.1 (2.2)	38.9 (2.2)	36.3 (2.9)
5	All	51.8 (3.2)	47.1 (2.3)	48.6 (2.2)	63.7 (3.2)	56.3 (1.9)	44.0 (1.8)	44.5 (2.7)
6	All	48.3 (4.1)	49.4 (2.9)	46.6 (3.1)	60.3 (3.3)	57.5 (2.1)	52.9 (2.6)	55.9 (5.4)
7	All	-	50.9 (6.0)	55.3 (5.1)	50.8 (7.3)	54.3 (5.3)	53.6 (7.2)	-
		F=0.211 P=0.932 NS	**F=5.35 P<0.001 ***	**F=5.59 P<0.001 ***	**F=1.89 P=0.102 NS**	**F=3.078 P=0.006 ***	**F=8.069 P<0.001 ***	**F=8.50 P<0.001 ***

Table 23. Mean MIBI values (SE) for individual MSHA cover score. Attributes with <5 samples are not included. Highest values are highlighted in blue (+) or red (-). Darker shades are significant (Tukey) and light shades are near significant and biologically meaningful. ANOVA results are at bottom. Tests with asterisks are significant at P<0.05 were followed with a Tukey multiple comparison test.

Cover Score	*Reach Type*	*Northern Forests Rivers (1)*	*Prairie Forest Rivers (2)*	*Northern Streams Riffle-Run (3)*	*Northern Streams Glide-Pool (4)*	*Southern Streams Riffle-Run (5)*	*Southern Streams Glide-Pool (6)*	*Prairie Streams Glide-Pool (7)*
1	All	-	-	-	-	-	-	32.8 (2.4)
2	All	-	-	-	-	-	-	25.6 (4.3)
3	All	-	29.2 (3.8)	-	48.9 (4.1)	27.4 (5.0)	31.5 (2.2)	24.0 (2.3)
4	All	61.8 (2.8)	33.7 (2.7)	67.7 (5.6)	51.8 (2.7)	33.1 (4.1)	38.8 (2.3)	26.6 (1.6)
5	All	63.0 (3.1)	27.9 (2.7)	67.9 (2.3)	56.5 (2.0)	34.9 (2.2)	37.0 (2.1)	28.2 (1.7)
6	All	66.1 (3.6)	32.2 (1.8)	66.3 (2.0)	59.3 (1.9)	42.5 (1.8)	42.7 (1.9)	38.7 (2.4)
7	All	-	29.4 (2.2)	65.1 (2.5)	59.9 (2.6)	38.2 (1.7)	44.0 (2.7)	42.4 (4.1)
		F=0.268 P=0.766 NS	**F=0.782 P=0.541 NS**	**F=0.221 P=0.881 NS**	**F=1.93 P=0.124 NS**	**F=3.47 P=0.009 ***	**F=3.12 P=0.016 ***	**F=8.03 P<0.001 ***

Table 24. Mean FIBI values (SE) for overall MSHA cover amount. Attributes with <5 samples are not included. Highest values are highlighted in blue (+) or red (-). Darker shades are significant (Tukey) and light shades are near significant and biologically meaningful. ANOVA results are at bottom. Tests with asterisks are significant at P<0.05 were followed with a Tukey multiple comparison test.

Cover Amount	*Reach Type*	*Southern Rivers*	*Southern Streams*	*Southern Headwaters*	*Northern Rivers*	*Northern Streams*	*Northern Headwaters*	*Low Gradient Streams*
Choking Veg. [-1]	All	-	-	13.5 (6.8)	-	-	14.3 (6.1)	30.0 (7.2)
Absent [0]	All	48.5 (1.8)	33.0 (1.3)	39.3 (2.4)	-	48.2 (2.6)	41.2 (3.6)	-
Sparse [3]	All	49.4 (2.3)	41.5 (1.3)	43.7 (1.7)	57.4 (3.3)	50.8 (1.8)	40.8 (2.0)	33.2 (2.7)
Moderate [7]	All	56.9 (2.5)	48.6 (2.2)	49.4 (1.5)	65.1 (2.4)	58.0 (1.5)	42.5 (1.7)	41.5 (2.9)
Extensive [10]	All	-	36.4 (4.3)	35.0 (3.2)	58.4 (5.0)	52.6 (2.6)	43.4 (2.3)	35.1 (2.7)
		F=5.979 P=0.003 *	**F=8.29 P<0.001 ***	**F=8.702 P<0.001 ***	**F=1.82 P=0.168 NS**	**F=4.891 P=0.002 ***	**F=2.67 P=0.047 ***	**F=1.77 P=0.15 NS**

Table 25. Mean MIBI values (SE) for overall MSHA cover amount. Attributes with <5 samples are not included. Highest values are highlighted in blue (+) or red (-). Darker shades are significant (Tukey) and light shades are near significant and biologically meaningful. ANOVA results are at bottom. Tests with asterisks are significant at P<0.05 were followed with a Tukey multiple comparison test.

Cover Amount	*Reach Type*	*Northern Forests Rivers (1)*	*Prairie Forest Rivers (2)*	*Northern Streams Riffle-Run (3)*	*Northern Streams Glide-Pool (4)*	*Southern Streams Riffle-Run (5)*	*Southern Streams Glide-Pool (6)*	*Prairie Streams Glide-Pool (7)*
Choking Vegetation	All	-	-	-	-	-	-	-
Absent	All	-	37.7 (2.8)	-	-	33.9 (1.5)	39.7 (2.4)	32.5 (2.1)
Sparse	All	65.1 (2.6)	30.3 (1.7)	67.9 (2.0)	58.6 (2.1)	37.4 (1.7)	37.9 (1.6)	31.1 (1.5)
Moderate	All	66.2 (4.5)	33.9 (2.0)	64.1 (1.9)	57.9 (1.6)	38.3 (1.5)	41.8 (1.6)	29.7 (1.7)
Extensive	All	66.3 (5.0)	-	69.9 (2.5)	55.4 (2.1)	38.6 (3.5)	37.7 (2.8)	27.4 (2.1)
		F=0.032 P=0.968 NS	**F=1.56 P=0.218 NS**	**F=1.856 P=0.159 NS**	**F=0.75 P=0.472 NS**	**F=1.99 P=0.116 NS**	**F=1.019 P=0.385 NS**	**F=0.763 P=0.515 NS**

Table 26. Theoretical and data-driven "good" and "poor" habitat attributes for the cover metric for fish assemblages in Minnesota rivers and streams. "Good" attributes are those expected to be associated with higher FIBI scores and "poor" attributes are those expected to be associated with lower FIBI scores. Numbers in bracket are weighted scores using to calculate the good or bad attribute score.

Sub-Metric	*Theoretical Attributes*	*Data Driven Attributes*						
		Southern Rivers (1)	*Southern Streams (2)*	*Southern Headwaters (3)*	*Northern Rivers (4)*	*Northern Streams (5)*	*Northern Headwaters (6)*	*Low Gradient Streams (7)*
Cover Metric								
Good Cover Types	-	-	Logs[1] Rootwad[1] Deep pools[.5]	Deep Pools[1] Rootwads[1]	-	-	Boulders[1]	Boulders[.5]
Poor Cover Types	-	-	-	-	-	-	-	Overhang. Veg[.5] Macro-phytes[.5]
Number of Cover Types – Good	5-7	-	6[1] 7[1] 5[.5]	7[2] 6[.5] 5[1] 4[1]	-	-	6[2] 7[1]	6[2] 5[1]
Number of Cover Types – Poor	0-2	-	1[1] 2[1] 3[.5]	1[2] 2[1]	2[.5]	1[.5] 2[.5]	1[2] 2[2] 3[1] 4[1]	1[2] 2[2] 3[1]
Good Overall Cover Amount	Extensive	Mod.[1]	Mod.[2]	Mod.[1]	-	Mod.[1]	Mod.[1] Extensive[1]	Mod.[.5]
Poor Overall Cover Amount	Sparse, Choking	Absent[1] Sparse[.5]	Absent[2] Sparse[.5]	Absent[1] Choking Veg.[.5]	-	Absent[1] Sparse[.5]	Absent[1]	-

Table 27. Theoretical and data-driven “good” and “poor” habitat attributes for the cover metric for macroinvertebrate assemblages in Minnesota rivers and streams. “Good” attributes are those expected to be associated with higher MIBI scores and “poor” attributes are those expected to be associated with lower MIBI scores. Numbers in bracket are weighted scores using to calculate the good or bad attribute score.

Sub-Metric	***Theoretical Attributes***	***Data Driven Attributes***						
		Northern Forest Rivers (1)	***Prairie Forest Rivers (2)***	***Northern Streams Riffle-Run (3)***	***Northern Streams Glide-Pool (4)***	***Southern Streams Riffle-Run (5)***	***Southern Streams Glide-Pool (6)***	***Prairie Streams Glide-Pool (7)***
Cover Metric								
Good Cover Types	-	-	--	-	-	-	Logs[.5]	Logs[1] Deep Pools[1] Rootwads[1] Boulders[1]
Poor Cover Types	-	-	-	-	-	-	-	Macrophytes[1]
Number of Cover Types – Good	5-7	-	-	-	6[.5] 7[.5]	6[1] 7[.5]	6[1] 7[1]	6[2] 7[2]
Number of Cover Types – Poor	0-2	-	-	-	-	3[1]	3[1]	1[1] 2[1] 3[2] 4[1]
Good Overall Cover Amount	Extensive	-	-	-	-	-	-	-
Poor Overall Cover Amount	Sparse, Choking	-	-	-	-	-	-	-

Stream Channel Characteristics

Stream channel characteristics are typically among the strongest predictors of aquatic life potential at a site and have been frequently modified in Midwest Rivers (Weigel *et al*. 2006). Many of the channel attributes integrate the co-occurrence of multiple positive habitat attributes under natural conditions (*e.g.*, natural channel, high sinuosity) or the loss of attributes when a stream is modified (*e.g.*, channelized or impounded). Numerous authors have identified the detrimental effects of channelization or impoundment (see Baxter 1977) on fish assemblages and the attributes of the stream channel metric is an attempt to capture both the positive and negative aspects related to both of these activities. Similar effects of channelization on invertebrates have also been observed (Heatherly et al. 2007, Kennedy and Turner 2011).

The channel metric score was among the strongest correlates with the FIBI (Figure 16), but the relationship between the MIBI was weaker (Figure 17) and there was still a great deal of scatter in the relationships. As was discussed earlier, we attribute some of this variation to watershed scale impacts on assemblages. Watersheds with predominantly natural channels can compensate for short reaches of modified channels while watersheds with widespread channel modifications reduces populations of species that might otherwise exist in short reaches with natural channel characteristics. It appears the open nature of these ecosystems (*i.e.,* ecosystem impacts in upstream and downstream directions) exerts a strong impact on local assemblage condition. In addition, cool water temperatures and strong base flows may moderate some of the most negative effects in certain watersheds. Some evidence for this may come from comparing Minnesota streams to Ohio streams. In Figure 18 we compare the Ohio FIBI scores by the QHEI channel metric divided in approximate quartiles of value with the MN FIBI scores for the Southern Streams strata were the channel metric had the strongest correlation with a MN FIBI (see Figure 16). The Ohio data showed less variability in biological response to altered channel conditions, particularly where channels were more severely altered (lower quantiles of channel scores for QHEI and MSHA, red boxes). Ohio streams can have higher average temperatures during summer because of latitudinal differences in climate. In addition, measures of baseflow (*i.e.*, percent of low flows as base flow) are generally higher in Minnesota compared to Ohio except for perhaps the Red River basin and some of the western-most streams (Santhi et al. 2008). Higher baseflow tends to moderate extreme temperatures and dissolved oxygen swings. Some authors suggest that

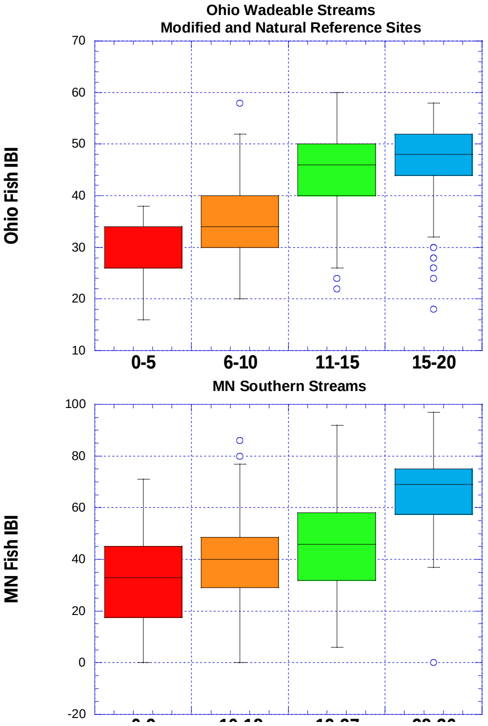

Figure 16. Box and whisker plots of the Ohio fish IBI versus ranges of the QHEI channel score (top) and the MN fish IBI and ranges of the MSHA channel score (bottom)

areas of high base flow can provide refuge for macroinvertebrates sensitive to low or high flow events and explain persistence of sensitive macroinvertebrate taxa (Lancaster and Hildrew 1993).

To bolster this contention we used the QHEI and MSHA identifications of intermittent and interstitial flows plotted by drainage size category ranges (3 mi^2 intervals) (Figure 19). Although the percent of sites sampled that were characterized as interstitial were similar between states, Ohio characterized more sites as intermittent (more flow starved than interstitial) particularly at large drainage areas; this may reflect greater cumulative loss of flows at watershed scales or the cumulative effects of having less base flow in general in Ohio streams. In any case altered channels in Ohio may result in more severe impacts to biota which may interact with high nutrients to create more severe habitat influenced biological impairments. Lower water temperatures, higher flows and less nutrient enrichment may explain the somewhat weaker correlations between the MSHA metrics such as channel condition and fish assemblage condition as measured by the FIBI and MIBI. Even so there is a correlation with multiple aspects of channel condition which may be used to identify watersheds where habitat factors may be limiting to one or more biological criteria goals.

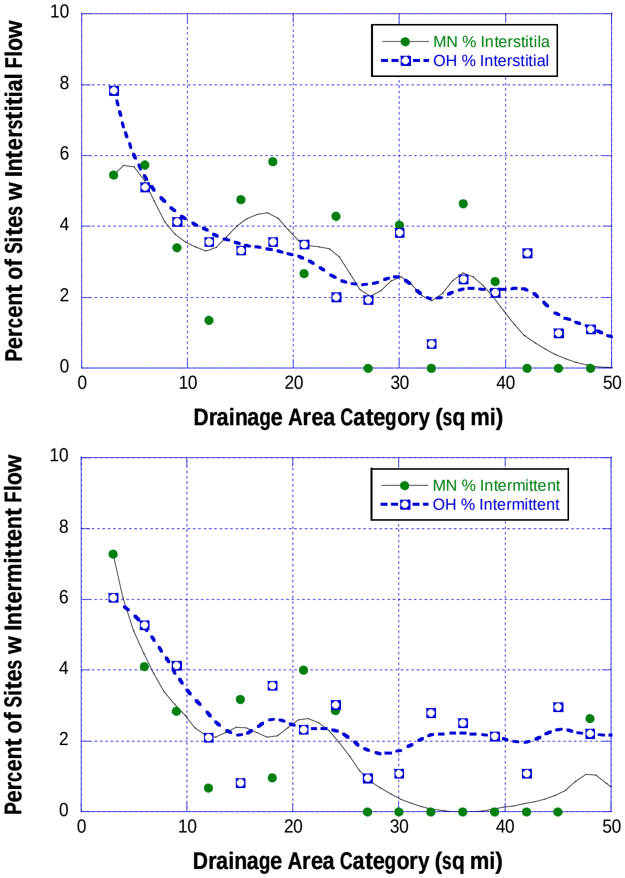

Figure 17. Plots of percent of sites with interstitial (top) or intermittent (bottom) flows by drainage size category for MN streams (green dots) or OH streams (open squares).

Sinuosity

The sinuosity of the channel of rivers provides substantial insight, in many cases, as to whether natural channel characteristics are present. Neither fish nor macroinvertebrate assemblages showed significant variation in IBIs in large river strata (Tables 28 and 29). For fish, poor sinuosity was significantly associated with lower FIBIs in all wadeable stream strata, although excellent sinuosity was only associated with high FIBIs in Northern Headwaters and Low Gradient Streams (Table 28). MIBIs were generally lower in streams with poor sinuosity in all wadeable strata, except the Northern Stream Riffle/Run strata. High gradient streams reaches can often run rather straight compared to more meandering lower gradient streams with Glide/Pool morphologies. In such streams, sinuosity typically results in pool formation on outside bends and deposition on inside bends and this increases depth and habitat heterogeneity.

Table 28. Mean FIBI values (SE) for MSHA channel sinuosity categories. Attributes with <5 samples are not included. Highest values are highlighted in blue (+) or red (-). Darker shades are significant (Tukey) and light shades are near significant and biologically meaningful. ANOVA results are at bottom. Tests with asterisks are significant at P<0.05 were followed with a Tukey multiple comparison test.

Sinuosity Score	*Reach Type*	*Southern Rivers*	*Southern Streams*	*Southern Headwaters*	*Northern Rivers*	*Northern Streams*	*Northern Headwaters*	*Low Gradient Streams*
Excellent [6]	All	50.7 (3.6)	43.7 (2.7)	48.7 (2.5)	60.9 (7.9)	51.5 (1.8)	51.9 (2.7)	47.8 (3.3)
Good [4]	All	49.3 (2.5)	48.1 (2.0)	47.9 (2.1)	58.7 (2.9)	60.3 (1.7)	48.0 (2.0)	44.4 (3.1)
Fair [2]	All	53.8 (3.2)	44.2 (2.1)	47.9 (2.3)	65.1 (2.9)	54.3 (2.1)	40.7 (2.0)	34.5 (3.3)
Poor [0]	All	49.4 (1.9)	33.6 (1.2)	37.7 (1.5)	61.0 (1.4)	44.4 (2.0)	33.4 (1.9)	28.0 (2.2)
		F=1.22 P=0.303 NS	**F=9.65 P<0.001 ***	**F=8.97 P<0.001 ***	**F=1.005 P=0.394 NS**	**F=15.74 P<0.001 ***	**F=19.44 P<0.001 ***	**F=9.86 P<0.001 ***

Table 29. Mean MIBI values (SE) for MSHA channel sinuosity categories. Attributes with <5 samples are not included. Highest values are highlighted in blue (+) or red (-). Darker shades are significant (Tukey) and light shades are near significant and biologically meaningful. ANOVA results are at bottom. Tests with asterisks are significant at P<0.05 were followed with a Tukey multiple comparison test.

Sinuosity Score	*Reach Type*	*Northern Forests Rivers (1)*	*Prairie Forest Rivers (2)*	*Northern Streams Riffle-Run (3)*	*Northern Streams Glide-Pool (4)*	*Southern Streams Riffle-Run (5)*	*Southern Streams Glide-Pool (6)*	*Prairie Streams Glide-Pool (7)*
Excellent [6]	All	74.0 (4.6)	28.7 (2.2)	64.8 (2.9)	59.4 (1.9)	41.0 (1.9)	45.8 (2.5)	39.7 (3.7)
Good [4]	All	68.3 (3.5)	34.5 (1.9)	71.1 (1.7)	60.5 (1.8)	39.7 (1.6)	41.9 (1.7)	37.3 (2.0)
Fair [2]	All	65.0 (3.0)	27.9 (2.6)	63.3 (2.1)	54.9 (2.2)	36.4 (2.2)	41.6 (1.9)	27.1 (1.8)
Poor [0]	All	-	37.9 (2.7)	67.0 (3.3)	51.7 (2.8)	31.7 (1.4)	31.8 (1.5)	28.2 (1.2)
		F=0.814 P=0.449 NS	**F=2.27 P=0.089 NS**	**F=4.557 P=0.004 ***	**F=4.64 P=0.003 ***	**F=9.05 P<0.001 ***	**F=13.96 P<0.001 ***	**F=9.20 P<0.001 ***

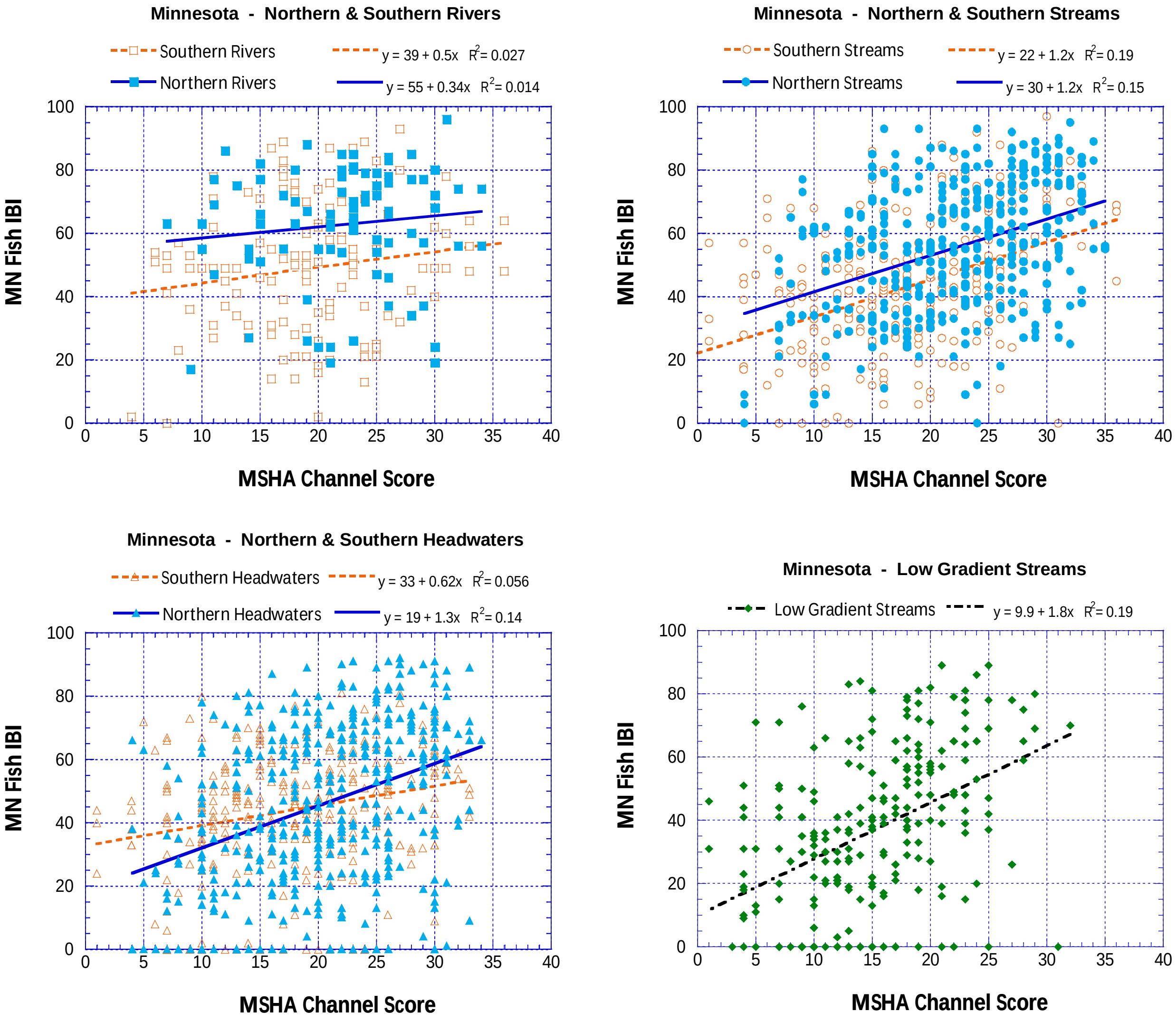

Figure 18. Plots of Fish IBI versus MSHA channel score separately for Minnesota Northern and Southern rivers (top left), streams (top right), headwaters (bottom left) and statewide for low gradient streams (bottom right).

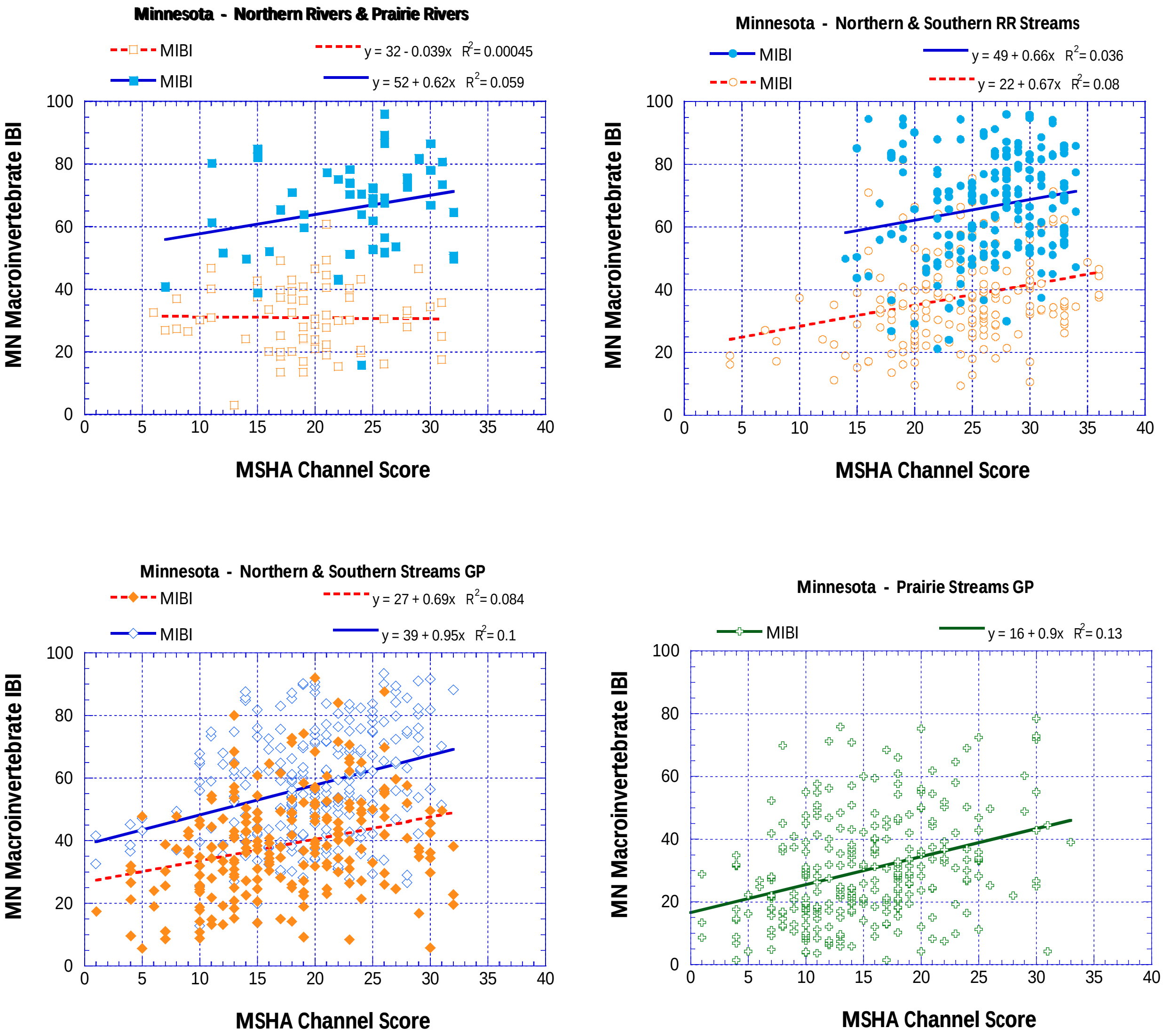

Figure 19. Plots of MIBI versus MSHA channel score separately for Minnesota Northern and Prairie Rivers (top left), Northern and Southern Riffle/Run streams (top right), Northern and Southern Glide/Pool Streams (bottom left) and Prairie GP Streams (bottom right).

Pool Width versus Riffle Width Score

The morphology and formulation of riffle and pool sequences has been an active subject for geomorphologists (*e.g.,* Yang 1971, Pasternack et al. 2008), but the characteristics of pool/glide and riffle/run habitats are also fundamental to the distribution and population of aquatic organisms. The lack of a riffle in the sample reach was a negative attribute for four fish and two macroinvertebrate stream strata (Table 30, Table 31). Pool widths greater than or equal to the width of the riffle was largely a positive attribute for several fish and macroinvertebrate stream strata.

Table 30. Mean FIBI values (SE) for the MSHA Pool Width/Riffle Width score. Attributes with <5 samples are not included. Highest values are highlighted in blue (+) or red (-). Darker shades are significant (Tukey) and light shades are near significant and biologically meaningful. ANOVA results are at bottom. Tests with asterisks are significant at P<0.05 were followed with a Tukey multiple comparison test.

Pool Width/Riffle Width	*Reach Type*	*Southern Rivers*	*Southern Streams*	*Southern Headwaters*	*Northern Rivers*	*Northern Streams*	*Northern Headwaters*	*Low Gradient Streams*
PW>RW	All	48.0 (2.6)	46.3 (1.8)	49.1 (1.6)	48.4 (6.6)	57.8 (2.1)	43.4 (2.1)	46.8 (4.7)
PW=RW	All	47.0 (3.0)	48.3 (2.7)	44.4 (2.6)	61.6 (8.0)	52.4 (3.8)	44.6 (4.4)	28.0 (6.4)
PW<RW	All	-	-	-	-	-	-	-
No Riffle	All	50.6 (2.2)	35.1 (1.4)	38.3 (1.8)	63.7 (3.2)	53.9 (1.9)	36.2 (1.9)	31.2 (2.1)
ANOVA		**F=0.479 P=0.62 NS**	**F=16.39 P<0.0001 ***	**F=30.12 P<0.0001 ***	**F=2.304 P=0.109 NS**	**=1.32 P=0.269 NS**	**F=3.747 P=0.0245 ***	**F=5.427 P=0.0052 ***

Table 31. Mean MIBI values (SE) for individual MSHA Pool Width/Riffle Width score. Attributes with <5 samples are not included. Highest values are highlighted in blue (+) or red (-). Darker shades are significant (Tukey) and light shades are near significant and biologically meaningful. ANOVA results are at bottom. Tests with asterisks are significant at P<0.05 were followed with a Tukey multiple comparison test.

Pool Width/Riffle Width	*Reach Type*	*Northern Forests Rivers (1)*	*Prairie Forest Rivers (2)*	*Northern Streams Riffle-Run (3)*	*Northern Streams Glide-Pool (4)*	*Southern Streams Riffle-Run (5)*	*Southern Streams Glide-Pool (6)*	*Prairie Streams Glide-Pool (7)*
PW>RW	All	69.3 (5.4)	31.8 (2.7)	65.1 (1.5)	57.4 (2.4)	36.2 (1.3)	37.9 (1.9)	32.3 (2.1)
PW=RW	All	61.4 (7.0)	-	66.1 (4.6)	57.9 (3.9)	35.4 (2.6)	49.4 (2.7)	33.0 (3.2)
PW<RW	All	-	-	-	-	-	-	-
No Riffle	All	63.2 (2.2)	28.4 (1.5)	67.3 (3.0)	56.5 (1.4)	40.9 (3.3)	37.9 (1.6)	24.5 (1.2)
ANOVA		**F=0.553 P=0.578 NS**	**F=1.106 P=0.297 NS**	**F=0.278 P=0.758 NS**	**F=0.078 P=0.925 NS**	**F=1.272 P=0.283 NS**	**F=5.25 P=0.00598 ***	**F=7.503 P=0.0007 ***

Channel Development

The channel development submetric of the MSHA is similar to the pool/riffle development metric of the QHEI and tracks "the complexity of the stream channel or the degree to which the stream has developed different channel types, creating sequences of riffles, runs, and pools." These are rated excellent, good, fair or poor. There was no significant association between channel development and FIBI scores in Northern or Southern Rivers or with MIBI scores in Northern or Prairie River strata (Tables 32 and 33). For both fish and macroinvertebrates in wadeable streams poor development was associated with lower FIBI and MIBI scores. Either good or excellent attributes were associated with higher FIBI or MIBI scores for wadeable streams with small sample size often associated with increased variation and non-significance of attributes.

Table 32. Mean FIBI values (SE) for MSHA channel development attributes. Attributes with <5 samples are not included. Highest values are highlighted in blue (+) or red (-). Darker shades are significant (Tukey) and light shades are near significant and biologically meaningful. ANOVA results are at bottom. Tests with asterisks are significant at P<0.05 were followed with a Tukey multiple comparison test.

Channel Develop Attribute	*Reach Type*	*Southern Rivers*	*Southern Streams*	*Southern Headwaters*	*Northern Rivers*	*Northern Streams*	*Northern Headwaters*	*Low Gradient Streams*
Excellent [9]	All	54.5 (3.4)	54.0 (3.9)	44.9 (3.4)	66.7 (4.9)	64.2 (2.4)	53.9 (2.7)	46.3 (9.0)
Good [6]	All	47.0 (3.5)	48.8 (2.0)	48.3 (2.0)	59.6 (2.8)	57.7 (1.6)	47.7 (2.0)	51.4 (4.4)
Fair [3]	All	52.8 (2.5)	40.9 (1.8)	46.0 (1.8)	61.3 (3.9)	49.1 (1.9)	40.0 (1.8)	40.3 (2.2)
Poor [0]	All	49.6 (1.7)	33.5 (1.1)	37.8 (1.7)	61.1 (1.4)	46.2 (1.9)	33.1 (2.1)	27.1 (2.2)
		F=1.12 P=0.342 NS	**F=14.41 P<0.001 ***	**F=6.50 P<0.001 ***	**F=0.671 P=0.572 NS**	**F=15.03 P<0.001 ***	**F=19.88 P<0.001 ***	**F=10.77 P<0.001 ***

Table 33. Mean MIBI values (SE) for individual MSHA channel development attributes. Attributes with <5 samples are not included. Highest values are highlighted in blue (+) or red (-). Darker shades are significant (Tukey) and light shades are near significant and biologically meaningful. ANOVA results are at bottom. Tests with asterisks are significant at P<0.05 were followed with a Tukey multiple comparison test.

Channel Develop Attribute	*Reach Type*	*Northern Forests Rivers (1)*	*Prairie Forest Rivers (2)*	*Northern Streams Riffle-Run (3)*	*Northern Streams Glide-Pool (4)*	*Southern Streams Riffle-Run (5)*	*Southern Streams Glide-Pool (6)*	*Prairie Streams Glide-Pool (7)*
Excellent	All	70.5 (2.8)	-	71.1 (1.7)	68.9 (4.3)	42.7 (1.8)	37.4 (6.2)	46.0 (5.6)
Good	All	67.0 (4.1)	28.6 (2.1)	63.9 (1.7)	60.5 (2.3)	38.1 (1.4)	42.1 (1.9)	38.2 (2.3)
Fair	All	59.6 (3.4)	31.0 (2.0)	65.4 (3.8)	56.7 (1.4)	34.0 (2.4)	42.2 (1.6)	31.3 (1.6)
Poor	All	-	39.0 (2.5)	-	54.1 (2.3)	33.5 (1.6)	33.9 (1.5)	26.4 (1.2)
		F=1.749 P=0.186 NS	**F=0.69 P=0.503 NS**	**F=3.35 P=0.037 ***	**F=3.57 P=0.015 ***	**F=5.61 P=0.001 ***	**F=6.42 P<0.001 ***	**F=15.76 P<0.001 ***

Channel Stability

Channel stability refers to the permanence of key channel structures such as riffle and run features with indicators of instability including aggradation of fines and eroding banks. Increasing instability is associated with degraded biological assemblages because of unstable habitat features not compatible with various life history aspects of sensitive organism (*e.g.,* spawning, feeding, and refuge). High stability was associated with higher FIBI scores in Southern River, Northern Streams and Headwaters and in Low Gradient streams, but low stability was only clearly associated with low stability in Southern Streams (Table 34). The macroinvertebrates were only weakly associated with channel stability in Northern Riffle Run streams and Southern Glide/Pool streams (Table 35).

Table 34. Mean FIBI values (SE) for MSHA channel stability attributes. Attributes with <5 samples are not included. Highest values are highlighted in blue (+) or red (-). Darker shades are significant (Tukey) and light shades are near significant and biologically meaningful. ANOVA results are at bottom. Tests with asterisks are significant at P<0.05 were followed with a Tukey multiple comparison test.

Channel Stability Attribute	*Reach Type*	*Southern Rivers*	*Southern Streams*	*Southern Headwaters*	*Northern Rivers*	*Northern Streams*	*Northern Headwaters*	*Low Gradient Streams*
High [9]	All	61.1 (5.2)	41.3 (3.6)	41.9 (2.8)	64.4 (2.6)	62.7 (1.8)	47.5 (2.2)	42.7 (3.5)
Mod.-High [6]	All	52.4 (3.1)	40.9 (2.5)	41.1 (1.9)	58.5 (3.7)	51.0 (1.8)	41.9 (1.8)	35.5 (2.4)
Moderate [3]	All	48.6 (2.6)	44.2 (1.5)	47.5 (1.8)	60.2 (3.5)	50.0 (1.9)	37.4 (2.0)	32.2 (2.7)
Low [0]	All	49.3 (1.7)	35.6 (1.2)	41.1 (2.1)	-	48.2 (2.4)	40.6 (3.3)	31.2 (4.0)
		F=2.21 P=0.0895 NS	**F=0.081 P=0.493 NS**	**F=2.384 P=0.069 NS**	**F=0.953 P=0.389 NS**	**F=11.49 P<0.001 ***	**F=6.26 P<0.001 ***	**F=2.019 P=0.111 NS**

Table 35. Mean MIBI values (SE) for individual MSHA channel stability attributes. Attributes with <5 samples are not included. Highest values are highlighted in blue (+) or red (-). Darker shades are significant (Tukey) and light shades are near significant and biologically meaningful. ANOVA results are at bottom. Tests with asterisks are significant at P<0.05 were followed with a Tukey multiple comparison test.

Channel Stability Attribute	*Reach Type*	*Northern Forests Rivers (1)*	*Prairie Forest Rivers (2)*	*Northern Streams Riffle-Run (3)*	*Northern Streams Glide-Pool (4)*	*Southern Streams Riffle-Run (5)*	*Southern Streams Glide-Pool (6)*	*Prairie Streams Glide-Pool (7)*
High [9]	All	67.0 (3.1)	29.7 (4.1)	69.8 (1.6)	58.2 (2.1)	39.0 (2.4)	32.9 (2.2)	28.4 (2.0)
Mod.-High	All	68.1 (3.9)	29.4 (3.2)	59.6 (2.3)	58.5 (1.7)	35.6 (2.0)	41.4 (1.7)	28.7 (1.6)
Moderate	All	59.8 (4.3)	32.4 (1.5)	62.5 (3.0)	56.0 (2.1)	38.1 (1.6)	39.7 (1.6)	30.5 (1.7)
Low	All	-	37.7 (2.4)	-	-	35.5 (1.4)	40.5 (2.2)	33.4 (2.0)
		F=1.014 P=0.370 NS	**F=0.343 P=0.794 NS**	**F=6.881 P=0.001 ***	**F=0.435 P=0.648 NS**	**F=0.52 P=0.669 NS**	**F=2.743 P=0.044 ***	**F=1.086 P=0.355 NS**

Depth Variability

Depth variability is "the difference in thalweg depth between the shallowest stream cross section and the deepest stream cross section and indicates the degree to which the thalweg depths vary within the stream reach." This attribute, except for rivers, was one of the strongest submetrics across all strata with streams with good variation in depth associated with higher FIBI scores (Table 36) and in most cases MIBI scores (Table 37). Northern RR streams had few sites with low depth variation which explains the lack of a significant difference in this stratum. Channelized streams often have less depth variation than natural streams and this metric may track the degree of channel modification.

Table 36. Mean FIBI values (SE) for MSHA depth variability attributes. Attributes with <5 samples are not included. Highest values are highlighted in blue (+) or red (-). Darker shades are significant (Tukey) and light shades are near significant and biologically meaningful. ANOVA results are at bottom. Tests with asterisks are significant at P<0.05 were followed with a Tukey multiple comparison test.

Depth Variability Attribute	*Reach Type*	*Southern Rivers*	*Southern Streams*	*Southern Headwaters*	*Northern Rivers*	*Northern Streams*	*Northern Headwaters*	*Low Gradient Streams*
4X Var [6]	All	53.0 (2.2)	48.1 (1.5)	46.0 (1.5)	60.5 (2.4)	57.1 (1.3)	45.4 (1.5)	43.1 (2.8)
2-4X Var [3]	All	46.3 (3.3)	37.1 (1.9)	45.6 (1.7)	62.7 (4.2)	50.7 (2.0)	39.3 (1.9)	40.3 (2.4)
<2X Var [0]	All	43.7 (4.6)	33.2 (1.2)	36.4 (2.1)	61.4 (1.4)	46.3 (2.1)	35.9 (2.7)	24.6 (2.3)
		F=2.32 P=0.102 NS	**F=19.73 P<0.001 ***	**F=10.33 P<0.001 ***	**F=0.097 P=0.907 NS**	**F=11.16 P<0.001 ***	**F=12.03 P<0.001 ***	**F=15.64 P<0.001 ***

Table 37. Mean MIBI values (SE) for MSHA depth variability attributes. Attributes with <5 samples are not included. Highest values are highlighted in blue (+) or red (-). Darker shades are significant (Tukey) and light shades are near significant and biologically meaningful. ANOVA results are at bottom. Tests with asterisks are significant at P<0.05 were followed with a Tukey multiple comparison test.

Depth Variability Attribute	*Reach Type*	*Northern Forests Rivers (1)*	*Prairie Forest Rivers (2)*	*Northern Streams Riffle-Run (3)*	*Northern Streams Glide-Pool (4)*	*Southern Streams Riffle-Run (5)*	*Southern Streams Glide-Pool (6)*	*Prairie Streams Glide-Pool (7)*
4X Var [6]	All	65.5 (2.6)	31.1 (1.5)	66.3 (1.3)	60.6 (1.6)	38.5 (1.1)	43.4 (1.4)	34.9 (1.6)
2-4X Var [3]	All	65.4 (4.0)	31.9 (2.4)	67.2 (3.3)	56.1 (1.7)	36.9 (2.8)	38.2 (1.7)	27.9 (1.6)
<2X Var [0]	All	-	38.7 (2.9)	-	51.9 (2.6)	33.1 (1.6)	32.5 (1.9)	27.4 (1.5)
		F=0.001 P=0.873 NS	**F=0.282 P=0.755 NS**	**F=0.07 P=0.790** NS	**F=6.80 P=0.001 ***	**F=6.869 P=0.001 ***	**F=13.80 P<0.001 ***	**F=11.716 P<0.001 ***

Current Velocity Types

Stream flow and current velocity has been shown to be critical factors for many species of fishes and macroinvertebrates in flowing waters with some species/taxa being identified as fluvial specialists or dependents related to their reliance on flow for one or more parts of their life histories (Allan 2007, Arthington et al 2006). We examined both the occurrence of IBIs in response to the occurrence individual current velocity types (*e.g.,* fast, moderate, slow) and in response to the cumulative association measure based on a sum of the scores of all types found in a reach. The association of any single flow attribute was rather weak with the presence of fast flow and eddies in Southern Streams showing a significant association with higher FIBI scores (Table 38). For macroinvertebrates fast flow was associated with higher MIBI scores in Northern and Prairie Glide/Pool streams and higher MIBI scores were associated with eddies in the Northern and Southern Glide/Pool streams (Table 39).

Table 38. Mean FIBI values (SE) for MSHA current velocity attributes. Attributes with <5 samples are not included. Highest values are highlighted in blue (+) or red (-). Darker shades are significant (Tukey) and light shades are near significant and biologically meaningful. ANOVA results are at bottom. Tests with asterisks are significant at P<0.05 were followed with a Tukey multiple comparison test.

Depth Variability Attribute	*Reach Type*	*Southern Rivers*	*Southern Streams*	*Southern Headwaters*	*Northern Rivers*	*Northern Streams*	*Northern Headwaters*	*Low Gradient Streams*
Torrential	All	-	-	-	-		-	-
Fast	All	51.3 (2.3)	49.1 (1.9)	47.9 (1.8)	60.3 (2.7)	58.6 (1.6)	48.1 (2.2)	45.2 (5.1)
Moderate	All	50.1 (1.7)	45.2 (1.2)	45.7 (1.2)	59.7 (2.1)	55.0 (1.2)	42.9 (1.3)	41.2 (2.1)
Slow	All	51.3 (1.8)	42.0 (1.2)	45.6 (1.2)	62.3 (2.1)	54.8 (1.1)	42.2 (1.2)	36.8 (1.6)
Eddies	All	48.7 (2.2)	50.0 (2.1)	50.8 (2.2)	63.2 (2.8)	58.1 (1.9)	48.3 (2.8)	38.9 (6.4)
Interstitial	All	-	-	54.0 (3.9)			56.5 (4.3)	-
Intermittent	All	-	-	-			45.9 (11.6)	-
		F=0.35 P=0.790 NS	**F=5.67 P<0.001 ***	**F=1.388 P=0.236 NS**	**F=.456 P=0.713 NS**	**F=1.38 P=0.239 NS**	**F=3.23 P=0.006 ***	**F=1.87 P=0.114 NS**

Table 39. Mean MIBI values (SE) for MSHA current velocity attributes. Attributes with <5 samples are not included. Highest values are highlighted in blue (+) or red (-). Darker shades are significant (Tukey) and light shades are near significant and biologically meaningful. ANOVA results are at bottom. Tests with asterisks are significant at P<0.05 were followed with a Tukey multiple comparison test.

Depth Variability Attribute	*Reach Type*	*Northern Forests Rivers (1)*	*Prairie Forest Rivers (2)*	*Northern Streams Riffle-Run (3)*	*Northern Streams Glide-Pool (4)*	*Southern Streams Riffle-Run (5)*	*Southern Streams Glide-Pool (6)*	*Prairie Streams Glide-Pool (7)*
Torrential	All	-	-	-	-	-	-	-
Fast	All	67.5 (2.5)	29.3 (1.6)	69.0 (1.7)	68.3 (3.2)	39.7 (1.2)	42.7 (1.8)	39.5 (2.4)
Moderate	All	66.0 (2.4)	30.7 (1.3)	67.1 (1.3)	61.4 (1.4)	38.1 (1.1)	42.0 (1.2)	32.6 (1.2)
Slow	All	66.5 (2.1)	30.9 (1.3)	66.7 (1.3)	57.5 (1.1)	38.0 (1.2)	39.5 (1.1)	29.4 (1.1)
Eddies	All	69.1 (2.7)	30.6 (1.4)	66.8 (2.3)	65.8 (2.3)	39.4 (1.6)	47.8 (2.5)	32.6 (2.3)
Interstitial	All	-	-	57.3 (5.6)	-	-	-	-
Intermittent	All	-	-	-	-	-	-	-
		F=0.237 P=0.870 NS	**F=0.206 P=0.892 NS**	**F=1.206 P=0.307 NS**	**F=5.843 P>0.001 ***	**F=0.505 P=0.679 NS**	**F=3.568 P=0.014 ***	**F=5.48 P=0.001 ***

Current Velocity Cumulative Score

Outside of rivers, wadeable streams showed higher FIBIs (Table 40) and MIBIs (Table 41) in most stream strata with current scores of 4 (fish) or scores of 3-4 (macroinvertebrates) and generally lower scores with current scores of only 1 in most strata. In most strata, sites with intermittent or interstitial flow (only) were uncommon. These results are consistent with the ecological literature which shows an increase in biodiversity with an increasing diversity of current types (Gorman and Karr 1978).

Table 40. Mean FIBI values (SE) for MSHA current velocity scores. Attributes with <5 samples are not included. Highest values are highlighted in blue (+) or red (-). Darker shades are significant (Tukey) and light shades are near significant and biologically meaningful. ANOVA results are at bottom. Tests with asterisks are significant at P<0.05 were followed with a Tukey multiple comparison test.

Current Velocity Score	*Reach Type*	*Southern Rivers*	*Southern Streams*	*Southern Headwaters*	*Northern Rivers*	*Northern Streams*	*Northern Headwaters*	*Low Gradient Streams*
-2	All	-	-	-		-	45.9 (12.9)	
-1	All	-	-	-		-	-	27.0 (7.1)
0	All	-	-	-	-	-	45.4 (3.6)	28.5 (4.2)
1	All	40.8 (8.5)	34.9 (2.1)	36.7 (2.1)	58.3 (5.0)	48.3 (2.4)	38.3 (2.1)	32.9 (2.4)
2	All	50.1 (3.0)	38.1 (1.7)	47.1 (1.6)	61.4 (3.5)	50.3 (1.9)	40.1 (1.7)	41.2 (2.3)
3	All	53.7 (3.0)	48.5 (2.1)	47.1 (2.1)	61.3 (3.8)	58.2 (1.7)	46.6 (2.7)	39.4 (6.5)
4	All	48.7 (2.9)	52.9 (3.1)	53.5 (2.8)	61.4 (3.7)	59.5 (2.7)	50.4 (3.9)	-
		F=1.21 P=0.307 NS	**F=13.637 P<0.001 ***	**F=8.242 P<0.001 ***	**F=.104 P=0.957 NS**	**F=6.36 P<0.001 ***	**F=2.39 P=0.037 ***	**F=2.38 P=0.085 NS**

Table 41. Mean MIBI values (SE) for individual MSHA current velocity scores. Attributes with <5 samples are not included. Highest values are highlighted in blue (+) or red (-). Darker shades are significant (Tukey) and light shades are near significant and biologically meaningful. ANOVA results are at bottom. Tests with asterisks are significant at P<0.05 were followed with a Tukey multiple comparison test.

Current Velocity Score	*Reach Type*	*Northern Forests Rivers (1)*	*Prairie Forest Rivers (2)*	*Northern Streams Riffle-Run (3)*	*Northern Streams Glide-Pool (4)*	*Southern Streams Riffle-Run (5)*	*Southern Streams Glide-Pool (6)*	*Prairie Streams Glide-Pool (7)*
-2	All	-	-	55.8 (5.0)	-	-	-	22.0 (3.1)
-1	All	-	-	55.8 (5.0)	44.7 (9.9)	-	-	22.0 (3.1)
0	All	-	-	70.4 (3.5)	55.9 (4.7)	35.1 (1.6)	39.2 (3.0)	32.6 (2.4)
1	All	59.9 (4.9)	36.6 (3.8)	60.8 (3.6)	50.9 (1.6)	25.9 (3.2)	31.4 (1.6)	25.3 (1.4)
2	All	65.5 (4.5)	34.0 (3.6)	64.8 (2.4)	58.7 (1.6)	33.7 (1.6)	40.8 (1.6)	30.6 (1.7)
3	All	64.6 (5.3)	28.6 (1.8)	67.6 (1.9)	70.8 (2.9)	39.4 (1.9)	43.6 (2.1)	37.1 (2.5)
4	All	69.3 (2.6)	30.6 (1.9)	70.6 (2.9)	65.2 (3.4)	40.7 (1.8)	48.1 (3.0)	37.3 (4.2)
		F=0.584 P=0.628 NS	**F=1.256 P=0.297 NS**	**F=1.726 P=0.163 NS**	**F=13.33 P<0.001 ***	**F=5.39 P=0.001 ***	**F=10.26 P<0.001 ***	**F=7.75 P<0.001 ***

Table 42. Theoretical and data-driven “good” and “poor” habitat attributes for the channel metric for fish assemblages in Minnesota rivers and streams. “Good” attributes are those expected to be associated with higher FIBI scores and “poor” attributes are those expected to be associated with lower FIBI scores.

Sub-Metric	***Theoretical Attributes***	***Data Driven Attributes***						
		Southern Rivers (1)	***Southern Streams (2)***	***Southern Headwaters (3)***	***Northern Rivers (4)***	***Northern Streams (5)***	***Northern Headwaters (6)***	***Low Gradient Streams (7)***
Channel Metric								
Good Sinuosity	Excellent	-	Excell.[1] Good[2] Fair[1]	Excell.[1] Good[2] Fair[1]	-	Excell.[2] Good[2] Fair[2]	Excell.[2] Good[2] Fair[1]	Excel2] Good[1]
Poor Sinuosity	Poor	-	Poor[2]	Poor[2]	-	Poor[2]	Poor[2]	Poor[2]
Good Pool Width/Riffle Width	PW>RW	-	PW>RW[2] PW=RW[2]	PW>RW[2]	-	-	PW>RW[1]	PW>RW[1]
Poor Pool Width/Riffle Width	No Riffle, Impounded	-	No Riffle[2]	No Riffle[2]	-	-	No Riffle[1]	No Riffle[1]
Good Channel Development	Excellent	-	Excell.[2] Good[2]	Excell.[.5] Good[2]	-	Excell.[2] Good[1]	Excell.[2] Good[1]	Excell.[.5] Good[2]
Poor Channel Development	Poor	-	Fair[1] Poor[2]	Poor[2]	-	Fair[1] Poor[2]	Fair[1] Poor[2]	Poor[2]
Good Channel Stability	High	High[.5]	-	-	-	High[2]	High[2]	High[.5]
Poor Channel Stability	Poor	Low[.5]	Low[.5]	-	-	Mod.[1] Low[2]	Mod.[2] Low[1]	Low[.5]
Good – Depth Variation	>4X	>4X[.5]	>4X[2]	>4X[2]		>4X[2]	>4X[2]	>4X[2]
Poor – Depth Variation	<2X	<2X[.5]	<2X[2]	<2X[2]		<2X[2]	<2X[2]	<2X[2]
Good – Current Types	Fast, Eddies	-	Fast[1] Eddies[1]	Eddies[.5]		Fast[.5] Eddies[.5]	Fast[.5] Eddies[.5] Interstit.[1]	Fast[.5]
Poor – Current Types	Intermittent	-	Slow[1]	-	-	-	-	-
Good – Current Score	4	-	4[2] 3[2]	4[1] 3[1]		4[1] 3[1]	4[.5]	-
Poor – Current Score	≤1	-	2[1] 1[2]	1[1]	-	2[1] 1[1]	1[.5]	1[1] -1[.5]

Table 43. Theoretical and data-driven “good” and “poor” habitat attributes for the channel metric for macroinvertebrate assemblages in Minnesota rivers and streams. “Good” attributes are those expected to be associated with higher MIBI scores and “poor” attributes are those expected to be associated with lower MIBI scores.

Sub-Metric	***Theoretical Attributes***	***Data Driven Attributes***						
		Northern Forests Rivers (1)	***Prairie Forest Rivers (2)***	***Northern Streams Riffle-Run (3)***	***Northern Streams Glide-Pool (4)***	***Southern Streams Riffle-Run (5)***	***Southern Streams Glide-Pool (6)***	***Prairie Streams Glide-Pool (7)***
Channel Metric								
Good Sinuosity	Excellent	-	-	Good[1]	Excell.[1] Good[1]	Excell.[2] Good[2]	Excell.[2] Good[1] Fair[1]	Excell.[1] Good[2]
Poor Sinuosity	Poor	-	-	Fair[1] Poor[1]	Poor[1]	Poor[2]	Poor[2]	Fair[1] Poor[2]
Good Pool Width/Riffle Width	PW>RW	-	-	-	-	-	PW=RW[1]	PW>RW[1] PW=RW[1]
Poor Pool Width/Riffle Width	No Riffle, Impounded	-	-	-	-	-	PW>RW[1] No Riffle[1]	No Riffle[1]
Good Channel Development	Excellent	Excell.[.5]	-	Excell.[1]	Excell.[1[Good[1]	Excell.[1[Good[1]	Excell.[.5] Good[1] Fair[1]	Excell.[2] Good[2]
Poor Channel Development	Poor	-	-	-	Poor[1]	Poor[1]	Poor[2]	Poor[2]
Good Channel Stability	High	-	-	High[1]	-	-	Mod.[1]	-
Poor Channel Stability	Poor	-		-	-	-	-	-
Good – Depth Variation	>4X	-	-	-	>4X[1] 2-4X[.5]	>4X[2] 2-4X[1]	>4X[2] 2-4X[1]	>4X[2]
Poor – Depth Variation	<2X	-	-	-	<2X[1]	<2X[2]	<2X[2]	<2X[2]
Good – Current Types	Fast, Eddies	-	-	-	Fast[1] Eddies[1]	-	Eddies[1]	Fast[2]
Poor – Current Types	Intermittent	-	-	-	Slow[1]	-	-	Slow[2]
Good – Current Score	4	-	-	-	4[1] 3[2]	4[1] 3[1]	4[2] 3[2]	4[1] 3[2]
Poor – Current Score	≤1	1[.5]	-	1[.5]	1[2]	1[1]	1[2]	1[2]

Riparian Metric

Riparian zones are integral to stream ecosystems and numerous studies have identified the importance of natural riparian vegetation at multiple spatial scales, although its influence may vary with the relative impact types in a watershed (*e.g.*, agricultural versus urban versus least disturbed, Wang *et al*. 2003). There was little correlation between the riparian metrics scores and the FIBI (Figure 20) or MIBI (Figure 21) for any classification strata. The riparian metric of the MSHA includes a riparian width submetric, a bank erosion submetric and a shade submetric.

Riparian Width

Although there was no relationship between riparian width in rivers and FIBI or MIBI (Tables 44 and 45), there was an association between extensive or wide-to-extensive riparian zones and FIBI and MIBI for most wadeable strata and narrow-to-no riparian zones and low IBI scores (Tables 44 and 45).

Table 44. Mean FIBI values (SE) for average MSHA riparian width attribute. Attributes with <5 samples are not included. Highest values are highlighted in blue (+) or red (-). Darker shades are significant (Tukey) and light shades are near significant and biologically meaningful. ANOVA results are at bottom. Tests with asterisks are significant at P<0.05 were followed with a Tukey multiple comparison test.

Average Riparian Attribute	*Reach Type*	*Southern Rivers*	*Southern Streams*	*Southern Headwaters*	*Northern Rivers*	*Northern Streams*	*Northern Headwaters*	*Low Gradient Streams*
Extensive	All	50.4 (4.7)	49.7 (2.8)	50.0 (3.6)	65.9 (2.3)	57.5 (1.5)	54.3 (1.9)	49.0 (2.5)
Wide	All	52.9 (3.6)	41.2 (2.5)	42.8 (3.0)	58.2 (4.6)	53.4 (2.2)	46.7 (2.2)	40.5 (3.5)
Moderate	All	49.0 (2.4)	44.5 (2.1)	47.6 (1.9)	52.4 (5.0)	52.1 (2.6)	32.0 (2.1)	29.8 (3.0)
Narrow	All	53.7 (5.6)	38.9 (2.3)	42.4 (1.9)	61.5 (6.5)	35.4 (4.7)	28.3 (2.8)	18.2 (2.5)
V. Narrow	All	47.3 (6.5)	40.2 (6.1)	37.4 (3.4)	-	46.7 (2.9)	21.1 (3.1)	15.3 (4.6)
None	All	-	34.7 (1.3)	42.0 (2.4)	-	50.6 (2.3)	44.5 (3.0)	33.8 (4.4)
		F=0.35 P=0.84 NS	**F=1.91 P=0.091 NS**	**F=2.173 P=0.057 NS**	**F=2.429 P=0.07 NS**	**F=4.22 P<0.001 ***	**F=25.27 P<0.001 ***	**F=19.8 P<0.001 ***

Table 45. Mean MIBI values (SE) for average MSHA riparian width attribute. Attributes with <5 samples are not included. Highest values are highlighted in blue (+) or red (-). Darker shades are significant (Tukey) and light shades are near significant and biologically meaningful. ANOVA results are at bottom. Tests with asterisks are significant at P<0.05 were followed with a Tukey multiple comparison test.

Average Riparian Attribute	*Reach Type*	*Northern Forests Rivers (1)*	*Prairie Forest Rivers (2)*	*Northern Streams Riffle-Run (3)*	*Northern Streams Glide-Pool (4)*	*Southern Streams Riffle-Run (5)*	*Southern Streams Glide-Pool (6)*	*Prairie Streams Glide-Pool (7)*
Extensive	All	70.1 (2.4)	32.3 (3.3)	68.2 (1.7)	59.3 (1.4)	43.2 (2.2)	42.3 (2.4)	37.5 (3.1)
Wide	All	60.2 (5.8)	27.9 (3.2)	68.0 (2.2)	55.2 (2.1)	37.9 (1.9)	44.7 (2.4)	36.7 (2.9)
Moderate	All	61.0 (4.1)	32.6 (1.7)	58.3 (3.4)	55.7 (3.5)	36.5 (2.0)	39.5 (1.8)	30.6 (1.8)
Narrow	All	-	27.7 (2.5)	42.8 (5.8)	47.3 (3.8)	30.9 (1.9)	34.8 (1.9)	25.5 (1.4)
V. Narrow	All	-	-	-	54.3 (11.0)	33.5 (6.3)	30.8 (2.7)	21.2 (2.6)
None	All	-	-	-	-	35.1 (1.5)	37.1 (2.6)	32.6 (2.3)
		F=2.28 P=0.11 NS	**F=0.995 P=0.401 NS**	**F=4.376 P<0.001 ***	**F=2.006 P=0.114 NS**	**F=2.58 P=0.028 ***	**F=4.090 P=0.001 ***	**F=6.22 P<0.001 ***

Bank Erosion Submetric

The bank erosion submetric showed little association with the FIBI or MIBI in most of the classification strata (Tables 46 and 47). In fact where results were significant statistically they were somewhat confounding biologically. For fish in the Southern Streams and Headwaters strata the FIBI scores were low where there was no erosion. This can occur where a heavily grassed bank shows little active erosion, even though very large storms can occasion cause bank failures in such reaches. There was little association between bank erosion and the MIBI (Table 47).

Table 46. Mean FIBI values (SE) for individual MSHA bank erosion score. Attributes with <5 samples are not included. Highest values are highlighted in blue (+) or red (-). Darker shades are significant (Tukey) and light shades are near significant and biologically meaningful. ANOVA results are at bottom. Tests with asterisks are significant at P<0.05 were followed with a Tukey multiple comparison test.

Erosion Score	*Reach Type*	*Southern Rivers*	*Southern Streams*	*Southern Headwaters*	*Northern Rivers*	*Northern Streams*	*Northern Headwaters*	*Low Gradient Streams*
Severe [0]	All	50.3 (1.7)	38.0 (1.3)	33.2 (1.8)	-	-	-	-
Heavy [1]	All	52.7 (3.8)	43.5 (4.2)	30.2 (6.9)	-	51.1 (6.0)	40.1 (5.7)	-
Moderate [3]	All	46.3 (3.1)	46.2 (3.1)	50.2 (3.0)	64.0 (5.8)	52.7 (2.9)	41.6 (5.1)	22.5 (6.5)
Little [4]	All	51.6 (4.0)	46.1 (1.9)	46.2 (1.9)	65.5 (3.3)	54.8 (1.7)	46.8 (2.7)	39.3 (3.5)
None [5]	All	56.0 (5.1)	35.5 (2.5)	36.2 (2.2)	64.5 (2.7)	57.4 (1.7)	42.5 (1.6)	36.4 (2.0)
		F=1.55 P=0.191 NS	**F=2.785 P=0.027 ***	**F=7.111 P<0.001 ***	**F=0.036 P=0.964 NS**	**F=1.16 P=0.325 NS**	**F=0.789 P=0.501 NS**	**F=1.49 P=0.227 NS**

Table 47. Mean MIBI values (SE) for MSHA bank erosion score. Attributes with <5 samples are not included. Highest values are highlighted in blue (+) or red (-). Darker shades are significant (Tukey) and light shades are near significant and biologically meaningful. ANOVA results are at bottom. Tests with asterisks are significant at P<0.05 were followed with a Tukey multiple comparison test.

Erosion Score	*Reach Type*	*Northern Forests Rivers (1)*	*Prairie Forest Rivers (2)*	*Northern Streams Riffle-Run (3)*	*Northern Streams Glide-Pool (4)*	*Southern Streams Riffle-Run (5)*	*Southern Streams Glide-Pool (6)*	*Prairie Streams Glide-Pool (7)*
Severe	All	-	39.9 (2.7)	-	-	-	-	32.9 (2.4)
Heavy	All	-	29.7 (3.1)	76.0 (6.1)	-	39.2 (3.7)	42.4 (2.5)	37.6 (3.4)
Moderate	All	55.8 (5.6)	30.7 (2.6)	66.8 (5.0)	70.0 (3.2)	38.1 (2.0)	44.0 (3.1)	33.7 (3.2)
Little	All	67.5 (3.6)	31.0 (1.6)	62.8 (2.3)	58.8 (2.0)	36.2 (1.7)	40.9 (1.6)	30.6 (1.7)
None	All	68.0 (2.9)	31.3 (6.0)	67.4 (1.6)	55.0 (1.4)	37.6 (2.4)	36.4 (1.6)	27.3 (1.4)
		F=1.609 P=0.211 NS	**F=0.19 P=0.94 NS**	**F=1.537 P=0.207 NS**	**F=7.977 P<0.001 ***	**F=0.521 P=0.72 NS**	**F=2.29 P=0.078 NS**	**F=2.34 P<0.055 NS**

Stream Shade

Unlike bank erosion, the amount of shade showed some association with the FIBI and MIBI scores (Tables 48 and 49). For fish assemblages Southern and Northern Streams and Southern Rivers had lower FIBI scores when shade was absent or light and higher FIBI scores with moderate or substantial shade. For macroinvertebrates a similar pattern occurred in Southern Streams (Riffle/Run and Glide Pool) and for Prairie Glide/Pool streams (Table 49). Thus shading was more of an issue in Southern Streams where stream modifications were more prevalent and temperatures generally higher; in such cases lack of shade may be a surrogate for channelization.

Table 48. Mean FIBI values (SE) for individual MSHA shade score. Attributes with <5 samples are not included. Highest values are highlighted in blue (+) or red (-). Darker shades are significant (Tukey) and light shades are near significant and biologically meaningful. ANOVA results are at bottom. Tests with asterisks are significant at P<0.05 were followed with a Tukey multiple comparison test.

Shade Score	*Reach Type*	*Southern Rivers*	*Southern Streams*	*Southern Headwaters*	*Northern Rivers*	*Northern Streams*	*Northern Headwaters*	*Low Gradient Streams*
None [0]	All	50.0 (1.8)	37.3 (1.2)	33.4 (1.7)	-	48.6 (1.8)	39.0 (2.1)	23.1 (2.7)
Light [1]	All	47.4 (2.4)	37.0 (1.7)	39.3 (2.4)	63.3 (2.9)	52.8 (2.0)	39.6 (2.5)	38.1 (2.3)
Moderate [2]	All	58.6 (3.3)	51.3 (2.6)	43.5 (2.9)	64.5 (3.1)	59.3 (1.9)	48.2 (2.5)	39.1 (3.3)
Substantial [4]	All	50.1 (6.8)	51.2 (3.7)	46.9 (2.3)	56.3 (7.8)	56.4 (2.5)	49.3 (2.3)	41.5 (6.3)
Heavy [5]	All	-	40.0 (5.9)	40.2 (4.2)	-	56.2 (2.0)	35.6 (3.3)	29.3 (7.7)
		F=4.799 P=0.004 *	**F=8.65 P<0.001 ***	**F=1.29 P=0.272 NS**	**F=0.50 P=0.609 NS**	**F=4.107 P=0.003 ***	**F=4.249 P=0.002 ***	**F=1.89 P=0.113 NS**

Table 49. Mean MIBI values (SE) for MSHA shade score. Attributes with <5 samples are not included. Highest values are highlighted in blue (+) or red (-). Darker shades are significant (Tukey) and light shades are near significant and biologically meaningful. ANOVA results are at bottom. Tests with asterisks are significant at P<0.05 were followed with a Tukey multiple comparison test.

Shade Score	*Reach Type*	*Northern Forests Rivers (1)*	*Prairie Forest Rivers (2)*	*Northern Streams Riffle-Run (3)*	*Northern Streams Glide-Pool (4)*	*Southern Streams Riffle-Run (5)*	*Southern Streams Glide-Pool (6)*	*Prairie Streams Glide-Pool (7)*
None	All	-	35.2 (3.0)	-	57.4 (4.0)	32.5 (1.3)	34.4 (1.8)	27.8 (1.4)
Light	All	65.7 (3.1)	29.6 (1.6)	67.2 (2.4)	54.0 (1.8)	31.3 (1.4)	35.5 (1.4)	27.7 (1.2)
Moderate	All	64.1 (2.8)	31.8 (1.6)	69.9 (2.1)	57.9 (1.8)	40.3 (1.5)	42.8 (1.7)	29.8 (1.6)
Substantial	All	-	35.1 (2.8)	61.4 (2.4)	56.8 (2.9)	38.1 (1.5)	44.0 (2.7)	32.9 (2.6)
Heavy	All	-	-	57.6 (2.8)	56.6 (3.9)	37.6 (2.4)	40.7 (2.8)	35.5 (4.2)
		F=0.04 P=0.841 NS	**F=1.38 P=0.34 NS**	**F=3.449 P=0.018 ***	**F=0.694 P=0.56 NS**	**F=7.85 P<0.001 ***	**F=6.47 P<0.001 ***	**F=3.001 P=0.019 ***

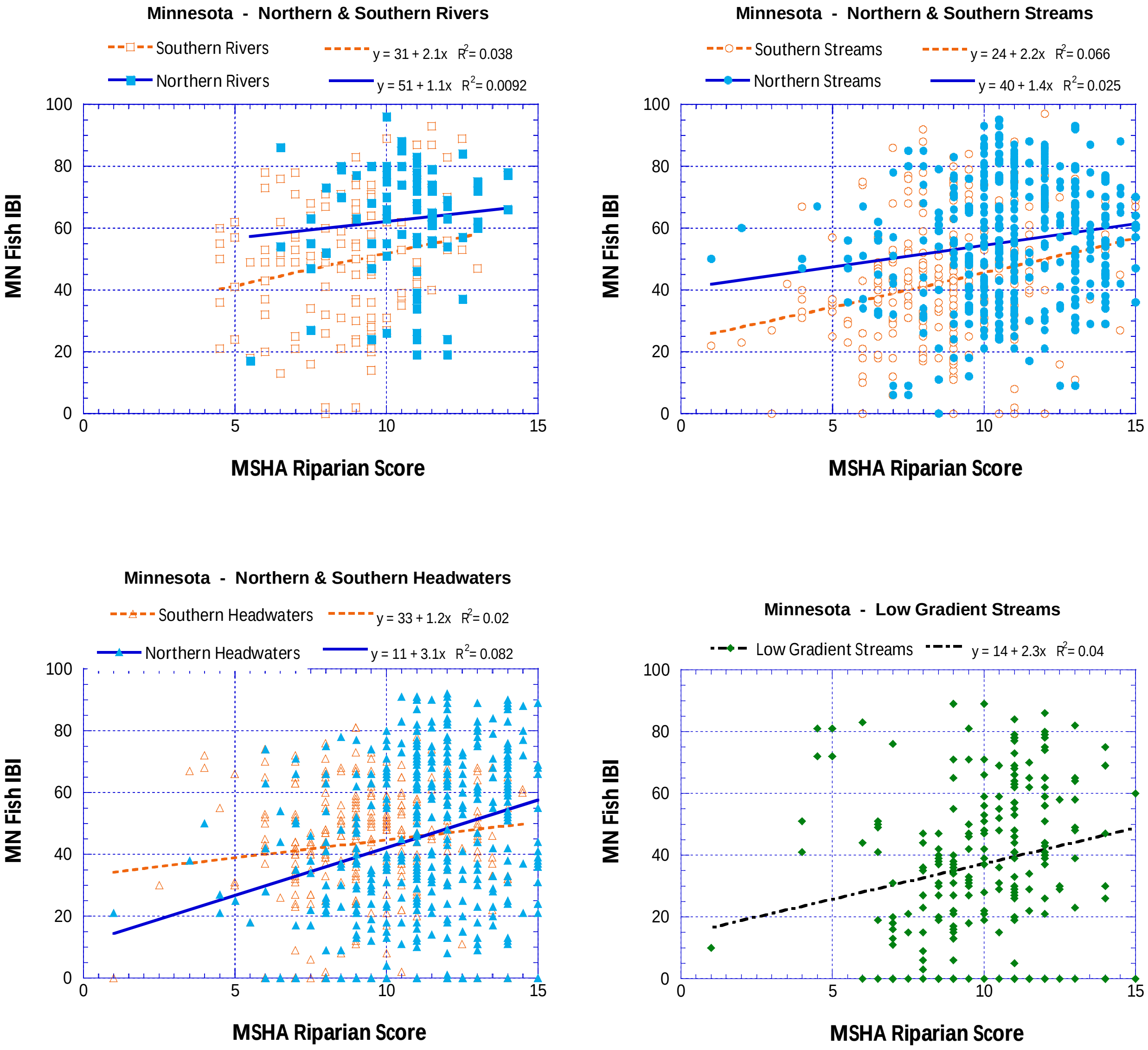

Figure 20. Plots of Fish IBI versus MSHA riparian score for Minnesota Northern and Southern rivers (top left), streams (top right), headwaters (bottom left) and statewide for low gradient streams (bottom right).

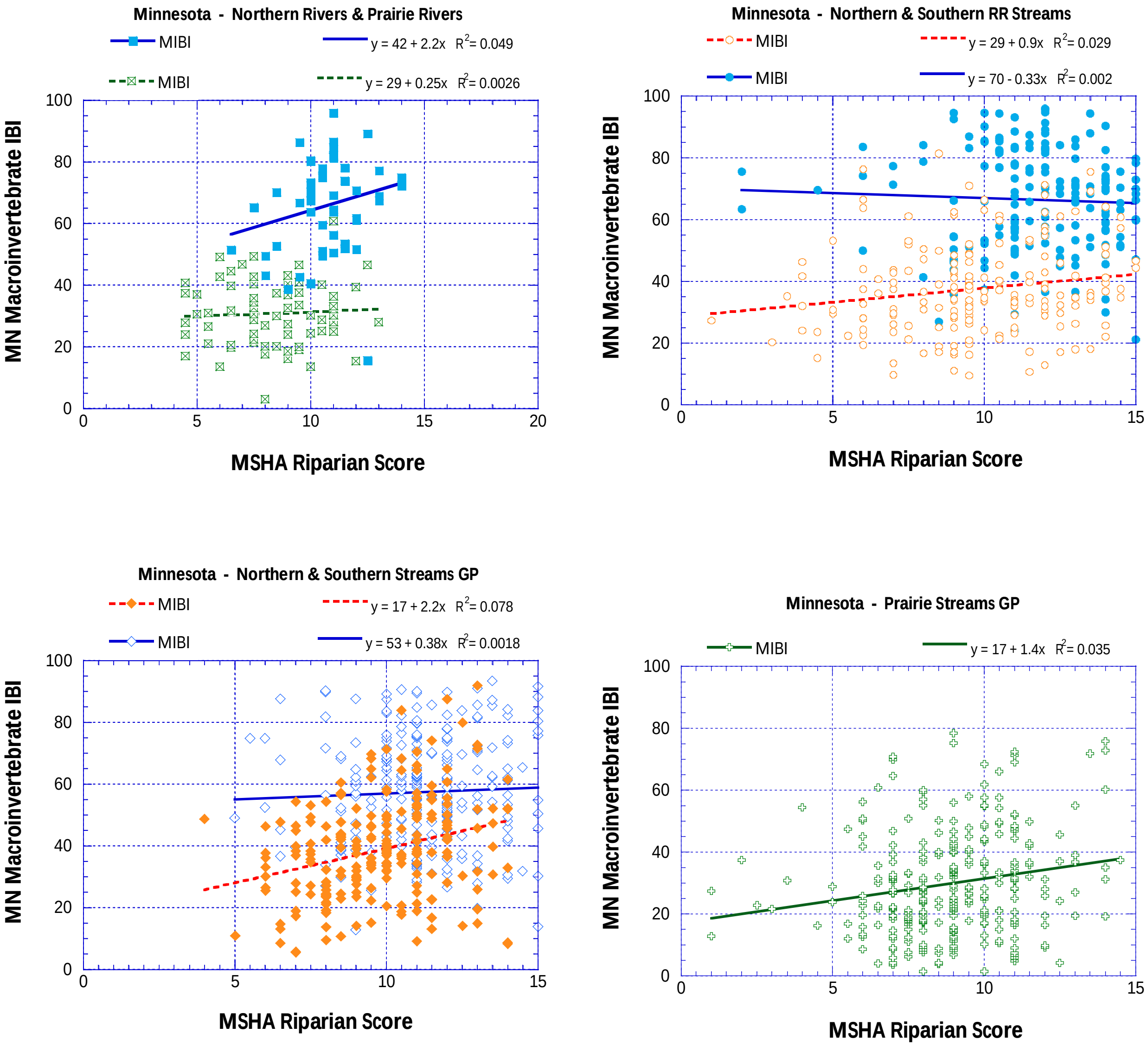

Figure 21. Plots of MIBI versus MSHA riparian score for Minnesota Northern and Prairie rivers (top left), Northern and Southern Riffle/Run streams (top right), Northern and Southern Glide/Pool streams (bottom left) and Prairie Glide/Pool streams (bottom right).

Table 50. Theoretical and data-driven “good” and “poor” habitat attributes for the riparian metric for fish assemblages in Minnesota rivers and streams. “Good” attributes are those expected to be associated with higher FIBI scores and “poor” attributes are those expected to be associated with lower FIBI scores.

Sub-Metric	***Theoretical Attributes***	***Data Driven Attributes***						
		Southern Rivers (1)	***Southern Streams (2)***	***Southern Headwaters (3)***	***Northern Rivers (4)***	***Northern Streams (5)***	***Northern Headwaters (6)***	***Low Gradient Streams (7)***
Riparian Metric								
Good Riparian Width	Extensive, Wide	-	Extens.[.5]	Extens.[.5]	Extens.[.5]	Extens.[1] Wide[1]	Wide[2] Extens.[2]	Wide[2] Extens.[2]
Good Riparian Width	None	-	None[.5]	V. Narrow[.5] None[.5]	-	Narrow[1] V. Narrow[1] None[1]	Mod.[2] Narrow[2] V. Narrow[2] None[2]	Mod.[1] Narrow[2] V. Narrow[2] None[1]
Good Bank Erosion	Little, None	-	-	-	-	None[.5]	-	-
Poor Bank Erosion	Heavy, Severe	-	None[.5]	Severe[.5] Heavy[.5] None[.5]	-	-	-	-
Good Shade	Substantial, Heavy	Mod.[1]	Mod.[2] Subst.[1]	Subst.[.5]	-	Mod.[1] Subst.[1] Heavy[1]	Mod.[.5] Subst.[1]	-
Poor Shade	Light, None	None[1] Light[1]	None[2] Light[2]	None[.5]	-	None[1]	None[.5] Light[.5]	None[.5] Subst.[.5]

Table 51. Theoretical and data-driven "good" and "poor" habitat attributes for the riparian metric for macroinvertebrate assemblages in Minnesota rivers and streams. "Good" attributes are those expected to be associated with higher MIBI scores and "poor" attributes are those expected to be associated with lower MIBI scores.

Sub-Metric	*Theoretical Attributes*	*Data Driven Attributes*						
		Northern Forests Rivers (1)	*Prairie Forest Rivers (2)*	*Northern Streams Riffle-Run (3)*	*Northern Streams Glide-Poo (4)*	*Southern Streams Riffle-Run (5)*	*Southern Streams Glide-Pool (6)*	*Prairie Streams Glide-Pool (7)*
Riparian Metric								
Good Riparian Width	Extensive, Wide	Extens.[.5]	-	Extens.[1] Wide[1]	-	Extens.[1]	Extens.[.5] Wide[1]	Extens.[2] Wide[1]
Good Riparian Width	None	-	-	Narrow[1]	Narrow[.5] V. Narrow[.5]	Narrow[1] V. Narrow[.5] None[.5]	Narrow[1] V. Narrow[1] None[.5]	Narrow[1] V. Narrow[2] None[.5]
Good Bank Erosion	Little, None	-	-	-	Mod.[2]	-	-	-
Poor Bank Erosion	Heavy, Severe	Mod.[.5]	-	-	-	-	-	-
Good Shade	Substantial, Heavy	-	-	-	-	Mod.[1] Subst[1] Heavy[1]	Mod.[1] Subst[1] Heavy[1]	Subst[.5] Heavy[.5]
Poor Shade	Light, None	-	-	Heavy[1]	-	None[2] Light[2]	None[2] Light[1]	None[.5] Light[.5]

Land Use

Land use in a watershed has been shown in a wide number of studies to have influence on aquatic assemblages related most often to polluted runoff and changes to hydrology compared to natural land cover types (*e.g.,* Wang et al. 1997, Allan 2004). Correlations between the overall metric score and the FIBI or MIBI scores were weak for most classification strata (Figures 22-23). For fish assemblages in most classification strata the occurrence of natural land uses was most often associated with higher FIBI and MIBI scores and row crop was most often associated with lower FIBI and MIBI scores (Tables 52 and 53). Certain land uses were purposely unrepresented in the data set to exclude impacts likely to confound the effects of habitat (*e.g.,* urban). We saw a similar pattern for most classification strata for macroinvertebrates except for Northern and Prairie Rivers and Northern Glide/Pool Streams (Table 53). Attributes selected as good and poor habitat attributes are summarized in Tables 54 and 55.

Table 52. Mean FIBI values (SE) for individual MSHA land use types (attributes). Attributes with <5 samples are not included. Highest values are highlighted in blue (+) or red (-). Darker shades are significant (Tukey) and light shades are near significant and biologically meaningful. ANOVA results are at bottom. Tests with asterisks are significant at P<0.05 were followed with a Tukey multiple comparison test.

Attribute	*Reach Type*	*Southern Rivers*	*Southern Streams*	*Southern Headwaters*	*Northern Rivers*	*Northern Streams*	*Northern Headwaters*	*Low Gradient Streams*
Natural	All	56.1 (3.0)	50.1 (2.4)	46.3 (3.1)	64.5 (2.2)	58.3 (1.2)	49.6 (1.5)	44.8 (1.9)
Old Field	All	-	32.2 (10.1)	39.5 (4.9)	-	58.1 (3.0)	34.9 (3.4)	37.7 (5.0)
Pasture	All	-	36.6 (7.9)	46.5 (7.3)	-	65.2 (4.0)	33.9 (6.4)	-
No Till	All	-	-	-	-	-	43.6 (7.0)	29.3 (7.4)
Park	All	-	-	47.1 (5.7)	-	56.3 (3.3)	31.7 (4.6)	21.9 (4.9)
Urban	All	-	-	-	-	-	49.4 (6.2)	-
Row Crop	All	48.3 (2.1)	41.8 (1.6)	43.0 (1.4)	59.6 (6.1)	42.4 (2.1)	30.0 (2.2)	24.7 (2.5)
		F=4..478 P=0.036 *	**F=3.25 P=0.022 ***	**F=0.574 P=0.681 NS**	**F=0.527 P=0.47 NS**	**F=10.56 P<0.001 ***	**F=12.023 P<0.001 ***	**F=9.69 P<0.001 ***

Table 53. Mean MIBI values (SE) for individual MSHA land use types (attributes). Attributes with <5 samples are not included. Highest values are highlighted in blue (+) or red (-). Darker shades are significant (Tukey) and light shades are near significant and biologically meaningful. ANOVA results are at bottom. Tests with asterisks are significant at P<0.05 were followed with a Tukey multiple comparison test.

Attribute	*Reach Type*	*Northern Forests Rivers (1)*	*Prairie Forest Rivers (2)*	*Northern Streams Riffle-Run (3)*	*Northern Streams Glide-Pool (4)*	*Southern Streams Riffle-Run (5)*	*Southern Streams Glide-Pool (6)*	*Prairie Streams Glide-Pool (7)*
Natural	All	66.3 (2.2)	31.3 (2.1)	67.4 (1.3)	57.7 (1.1)	44.7 (1.6)	45.5 (1.6)	38.6 (2.2)
Old Field	All	-	-	67.0 (2.8)	58.2 (2.8)	42.2 (5.0)	41.7 (4.1)	37.5 (6.8)
Pasture	All	-	-	68.4 (3.6)	59.2 (8.7)	36.4 (6.0)	37.3 (5.7)	-
No Till	All	-	-	-	-	-	-	37.5 (4.7)
Park	All	-	-	60.9 (4.8)	52.6 (4.2)	48.2 (5.1)	44.2 (3.1)	-
Urban	All	-	-	-	-)	-	45.6 (5.0)	20.7 (3.8)
Row Crop	All	-	30.3 (1.4)	48.7 (3.5)	50.3 (3.7)	33.8 (1.2)	36.7 (1.2)	28.1 (1.0)
		-	**F=0.161 P=0.689 NS**	**F=4.958 P<0.001 ***	**F=1.019 P=0.397 NS**	**F=8.345 P<0.001 ***	**F=4.40 P<0.001 ***	**F=7.946 P<0.001 ***

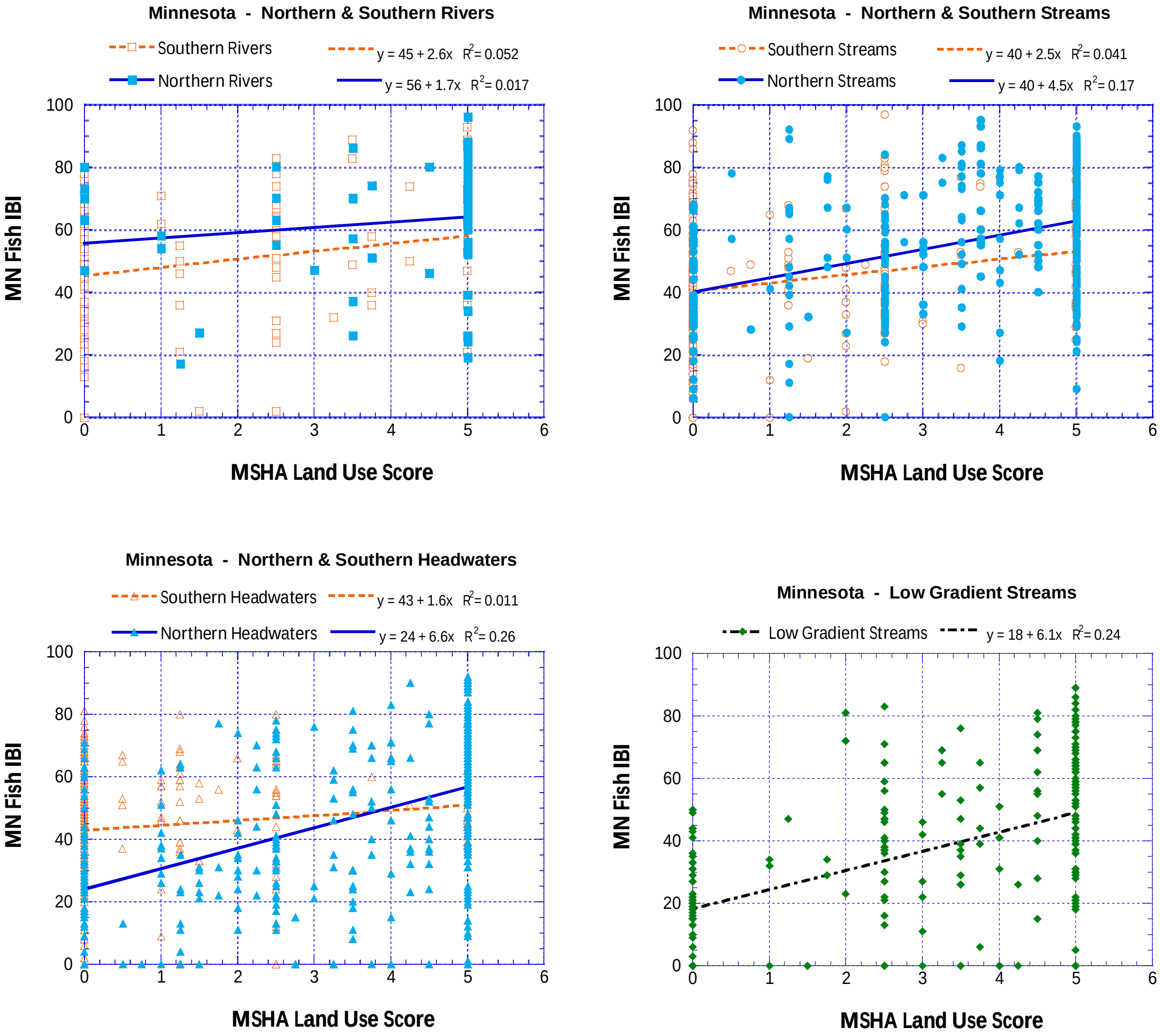

Figure 22. Plots of Fish IBI scores versus MSHA riparian score separately for Minnesota Northern and Southern rivers (top left), streams (top right), headwaters (bottom left) and statewide for low gradient streams (bottom right).

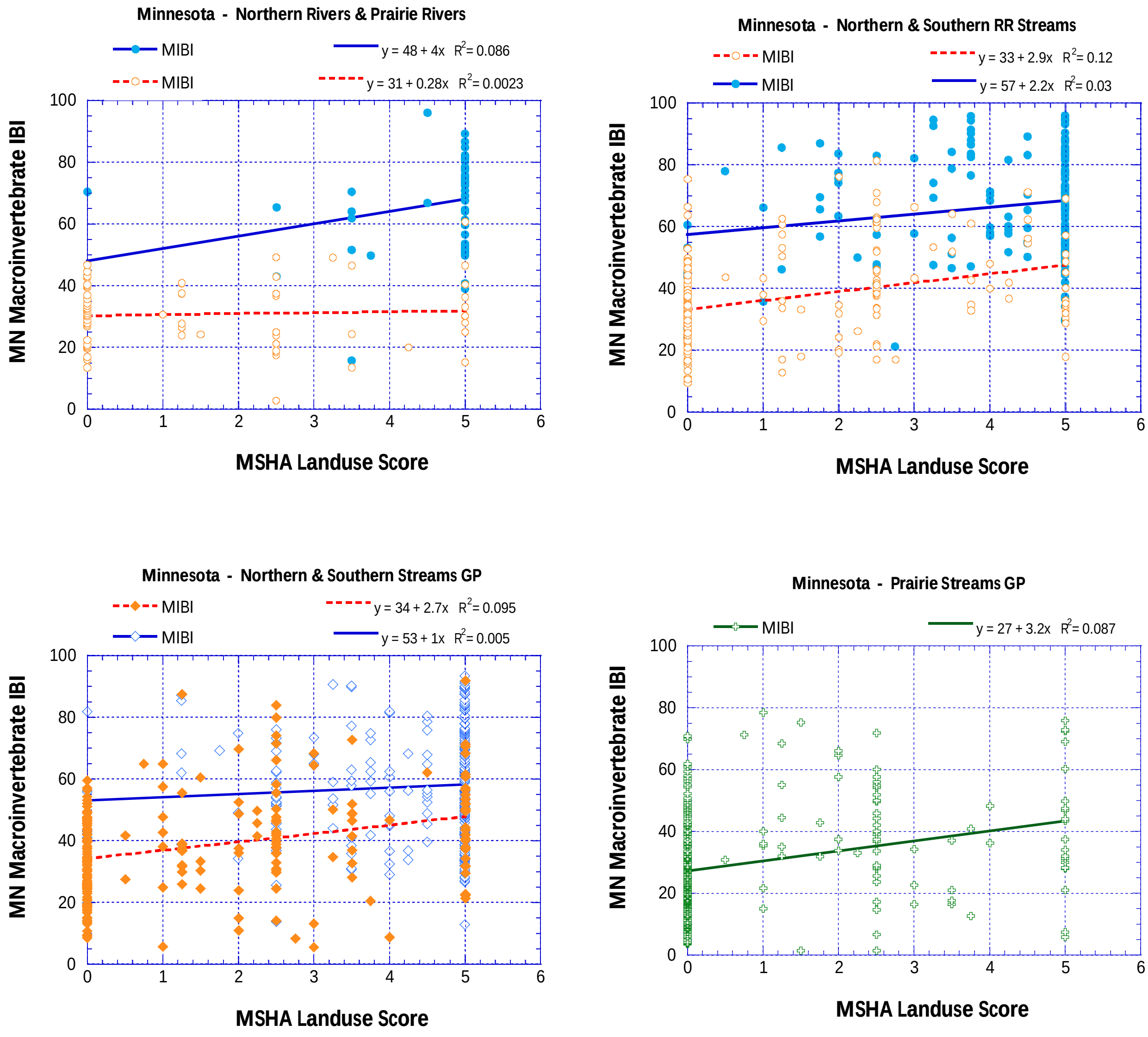

Figure 23. Plots of MIBI scores versus MSHA riparian score separately for Minnesota Northern and Prairie rivers (top left), Northern and Southern Riffle/Run streams (top right), Northern and Southern Glide/Pool streams (bottom left) and Prairie Glide/Pool streams (bottom right).

Table 54. Theoretical and data-driven “good” and “poor” habitat attributes for the land use metric for fish assemblages in Minnesota rivers and streams. “Good” attributes are those expected to be associated with higher FIBI scores and “poor” attributes are those expected to be associated with lower FIBI scores.

Sub-Metric	***Theoretical Attributes***	***Data Driven Attributes***						
		Southern Rivers (1)	***Southern Streams (2)***	***Southern Headwater (3)***	***Northern Rivers (4)***	***Northern Streams (5)***	***Northern Headwaters (6)***	***Low Gradient Streams (7)***
Land Use Metric								
Good Land uses	Natural	Natural[1]	Natural[1]	-	-	Natural2] Old Field[1] Park[1] Pasture[.5]	Natural[2] No Till[.5]	Natural[2] Old Field[1]
Poor Land Uses	Urban, Row crop	Row crop[1]	Row crop[1]	-	-	Row crop[2]	Row crop[2]	Row crop[2]

Table 55. Theoretical and data-driven “good” and “poor” habitat attributes for the land use metric for macroinvertebrate assemblages in Minnesota rivers and streams. “Good” attributes are those expected to be associated with higher MIBI scores and “poor” attributes are those expected to be associated with lower MIBI scores.

Sub-Metric	***Theoretical Attributes***	***Data Driven Attributes***						
		Northern Forests Rivers (1)	***Prairie Forest Rivers (2)***	***Northern Streams Riffle-Run (3)***	***Northern Streams Glide-Pool (4)***	***Southern Streams Riffle-Run (5)***	***Southern Streams Glide-Pool (6)***	***Prairie Streams Glide-Pool (7)***
Land Use Metric								
Good Land uses	Natural	-	-	Natural[2], Old Field[1] Pasture[1]	-	Natural[2], Old Field[.5] Park[.5]	Natural[2] Park[.5]	Natural[2], Old Field[.5] No Till[.5]
Poor Land Uses	Urban, Row crop	-	-	Row crop[2]	Row crop[.5]	Row crop[2]	Row crop[2]	Row crop[2]

Sources of Variation in the MSHA-FIBI Relationship

Compared to correlations of a similar nature conducted in Ohio (**Error! Reference source not found.**, left), even though the trend of association between MSHA and the FIBI was positive, there was substantial variation in the relationship (**Error! Reference source not found.**, right). Of particular interest are situations where habitat is relatively poor (MSHA scores < 45) and biological performance would be attaining the threshold criteria for a region (Southern Streams = 43) (red boxed area of **Error! Reference source not found.**, right). In Ohio's Ohio River basin, a relationship among similar sized streams shows many fewer outliers (*i.e.,* good biology) at sites with poor habitat (**Error! Reference source not found.**, left). The importance of resolving the cause of these outliers is important because it affects the ease and accuracy of assigning a "modified" stream classification as was done for Ohio streams.

There are a number of possible explanations for the outliers in **Error! Reference source not found.**, right:

1) *Stream Temperature and/or Stream Flow*. Data from Ohio in the upper Great Miami River (Ohio EPA 2011) showed that sites with enhanced base flow were significantly more likely to attain their Warmwater (WWH) aquatic life use than sites without such flow, even when streams had been channelized. Streams with enhanced flows had more cool water fish and macroinvertebrate taxa, less variability in stream temperature, lower nutrients and higher dissolved oxygen levels than streams without enhanced flow (Ohio EPA 2011). The cooler temperatures are hypothesized to slow or minimize the effects of increased nutrients and maintain higher dissolved oxygen levels. These conditions would be important during typical summer "bottlenecks" of stress than can occur when temperatures and nutrients are high which can result in lower dissolved oxygen. In addition, higher flow rates can act to sweep riffle features free of silts and fine sediments. Finally, in small streams, risk of desiccation is lower where summer flows are more permanent.
2) Scale of Habitat Degradation. Streams are "open" systems and the biota that occurs at a site is a product of habitat conditions upstream and downstream of a reach in addition to habitat conditions within a reach. Outliers where habitat is poor and FIBI scores are good could be a

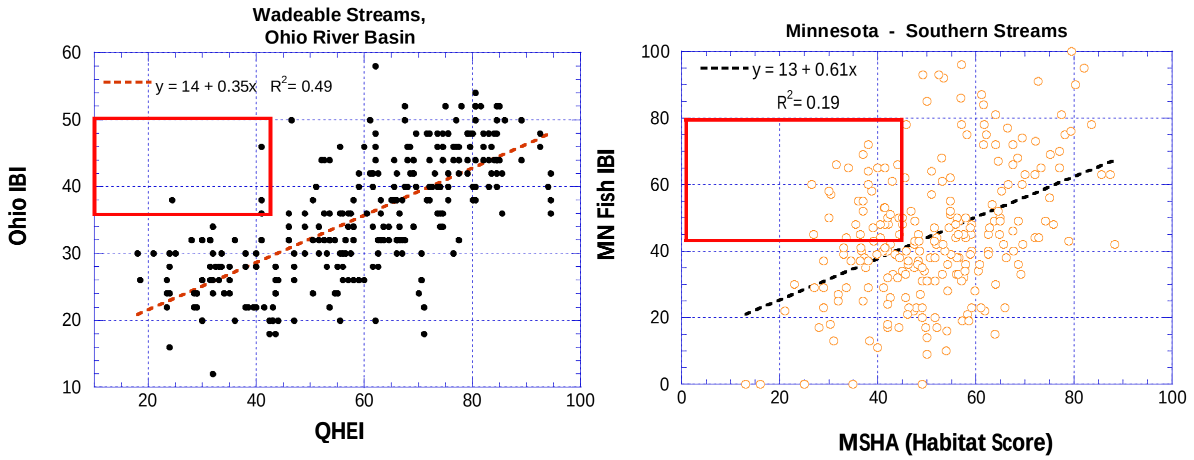

Figure 24. Scatter plots of QHEI versus Ohio wadeable Fish IBI scores (left) and MSHA Total Score versus MN Fish IBI scores in Minnesota Southern Streams. Red boxes encompass sites where sites achieve good biological conditions at sites with poor habitat.

result of nearby good habitats “propping” up assemblages in short habitat-degraded segments.

Correlation between Habitat Metrics

Many habitat features tend to co-occur, so an assessment of correlations between habitat metrics can be important to understand the possible mechanism of habitat effects on aquatic assemblages and individual species. This in turn can be useful when determining whether habitat limitations are feasibly restorable. The figures in this section depict correlations between individual major metrics and the final MSHA score. We also present similar correlations between metrics of the QHEI for the Lake Erie basin of Ohio to explore whether correlations differ among these regions.

The correlation between each individual metric and the total MSHA score is obviously dependent on the weighting of each metric towards the total score. The Land Use metric only comprises 5 points of the total score and is uncorrelated with other metrics other than the riparian metric (Figure 25) suggesting local land use does not limit or strongly influence other habitat attributes. This metric is correlated with the riparian metric because it reflects land use adjacent to the stream which is often a continuation of land uses further from the stream. The lack of a strong correlation between land use and stream habitat is important because it demonstrates that a land use type does not necessarily limit habitat quality in a stream. A heavily agricultural watershed can be comprised of streams with high quality habitats including MSHA scores that approach the maximum observed in Minnesota.

Unlike the Land Use metric, the Riparian metric does show a significant, but weak correlation and a threshold response to other MSHA metrics. The best performance of the substrate, cover and channel metrics only occur at sites with the best performing riparian metric scores (Figure 26). This pattern is similar to what was observed in Ohio with the QHEI (Figure 27). This association is likely related to the ability of intact riparian areas to reduce inputs of fines, reduce, bank erosion, provide high quality woody debris for cover, and allow evolution of channel form to enhance riffle/run/pool features. The substrate metric was not correlated with the cover metric, but did show a significant, but somewhat variable correlation and threshold response with the channel metric (Figure 28). Sites with low substrate scores generally also had only moderate or low channel scores. This may be attributable to more bank erosion in streams with modified or stressed channels and the accumulation of fines in entrenched channels. The Ohio data show similar correlations (Figure 29) although there was a weak correlation between substrate scores and cover scores perhaps related to sites where boulders are a characteristic substrate and cover type.

The cover score is only weakly correlated with the channel scores with a threshold evident at sites with low cover scores (*i.e.,* lack of association with sites with good channel conditions). Sites with stable, natural channel features are more likely to have good-excellent cover (Figure 30) and good-excellent substrate conditions (Figure 30). The channel metric comprises the largest component of the MSHA (36 of 100 points) and is, as expected most strongly correlated ($r^2 = 0.80$) with the total MSHA score. The channel metric of the QHEI is similarly correlated ($r^2 = 0.83$) with the total QHEI (Figure 31) even though it comprises only 20% of the potential scoring of the QHEI (20 of 100). Overall, the MSHA shows similar correlations between its component metrics as does QHEI. The process used elsewhere in this document to identify strong “positive” and “negative” habitat attributes is designed to extract those features that may be most limiting or most associated with aquatic life indicators.

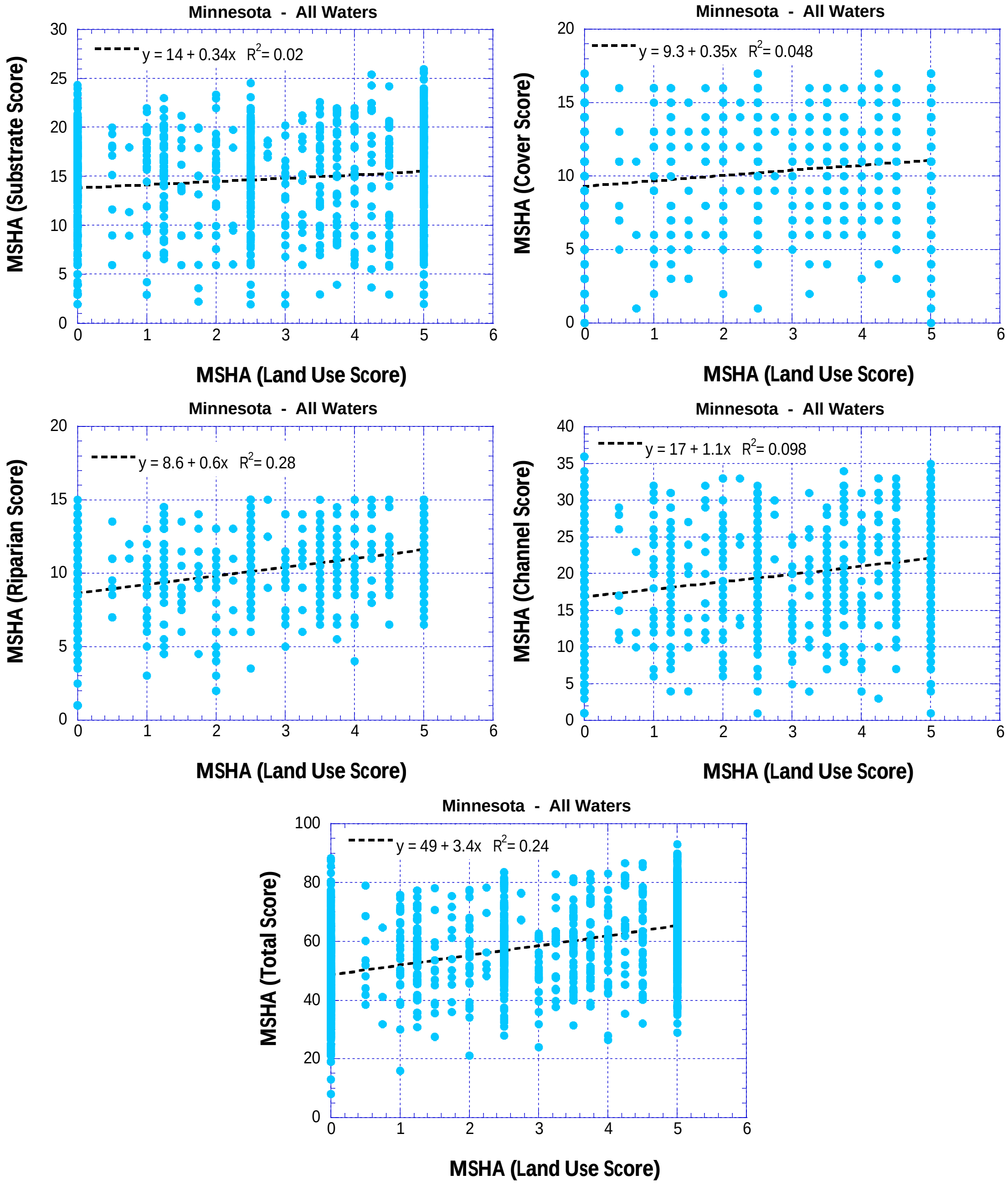

Figure 25. Correlations between the MSHA land use score and other MSHA metrics and the MSHA total score. All regions combined.

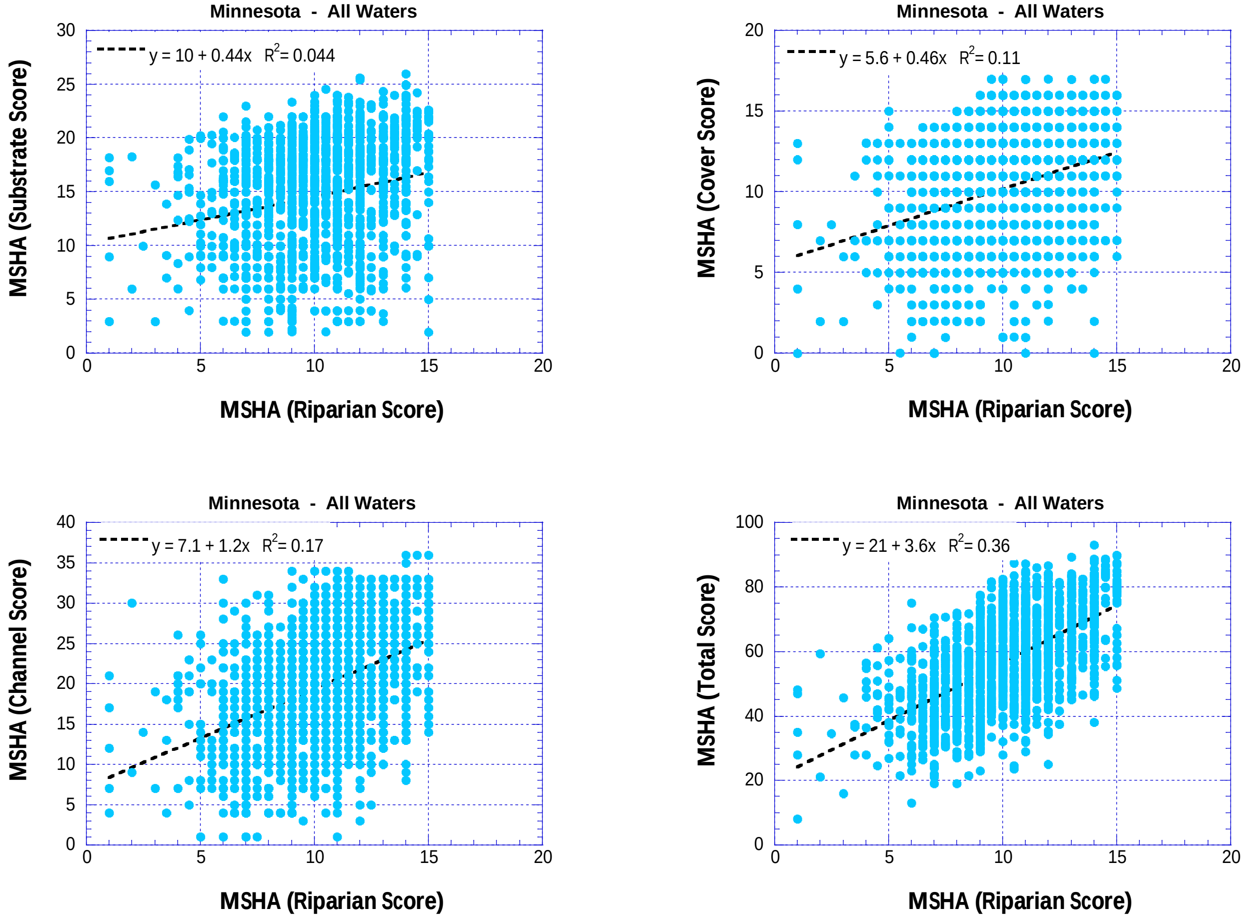

Figure 26. Correlations between the MSHA riparian score and other MSHA metrics and the MSHA total score. All regions combined.

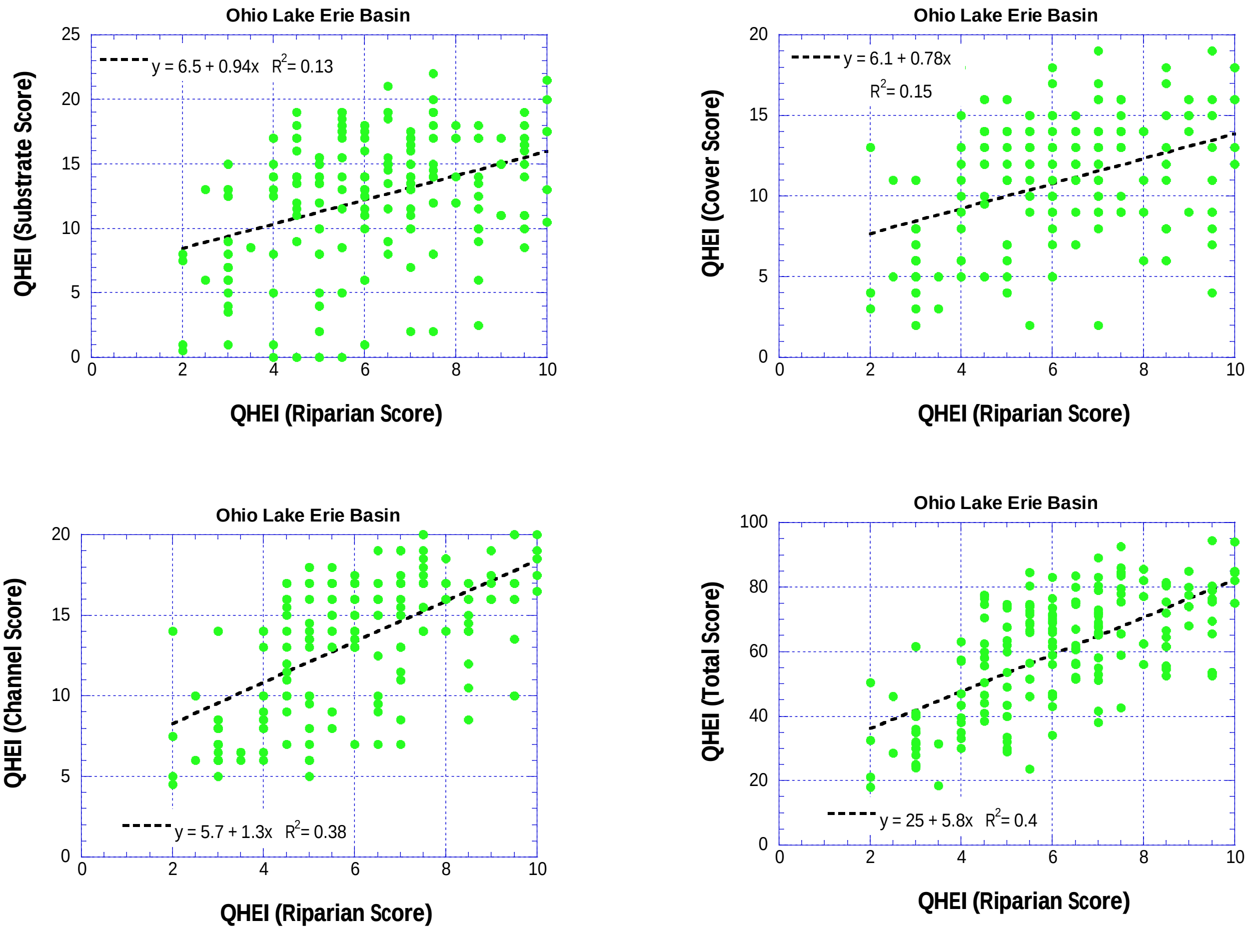

Figure 27. Correlations between the QHEI riparian score and other QHEI metrics and the QHEI total score. All regions combined.

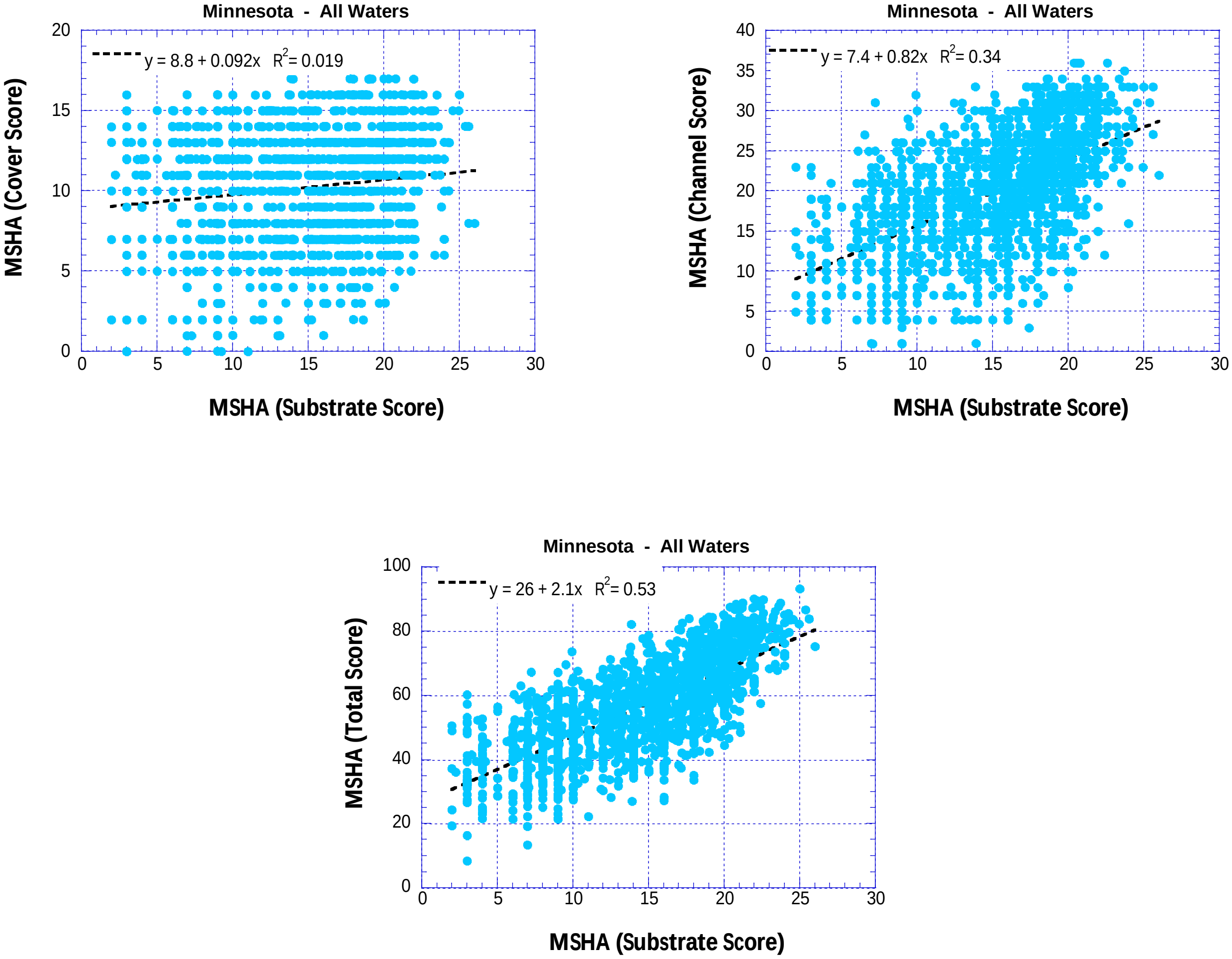

Figure 28. Correlations between the MSHA substrate score and other MSHA metrics and the MSHA total score.

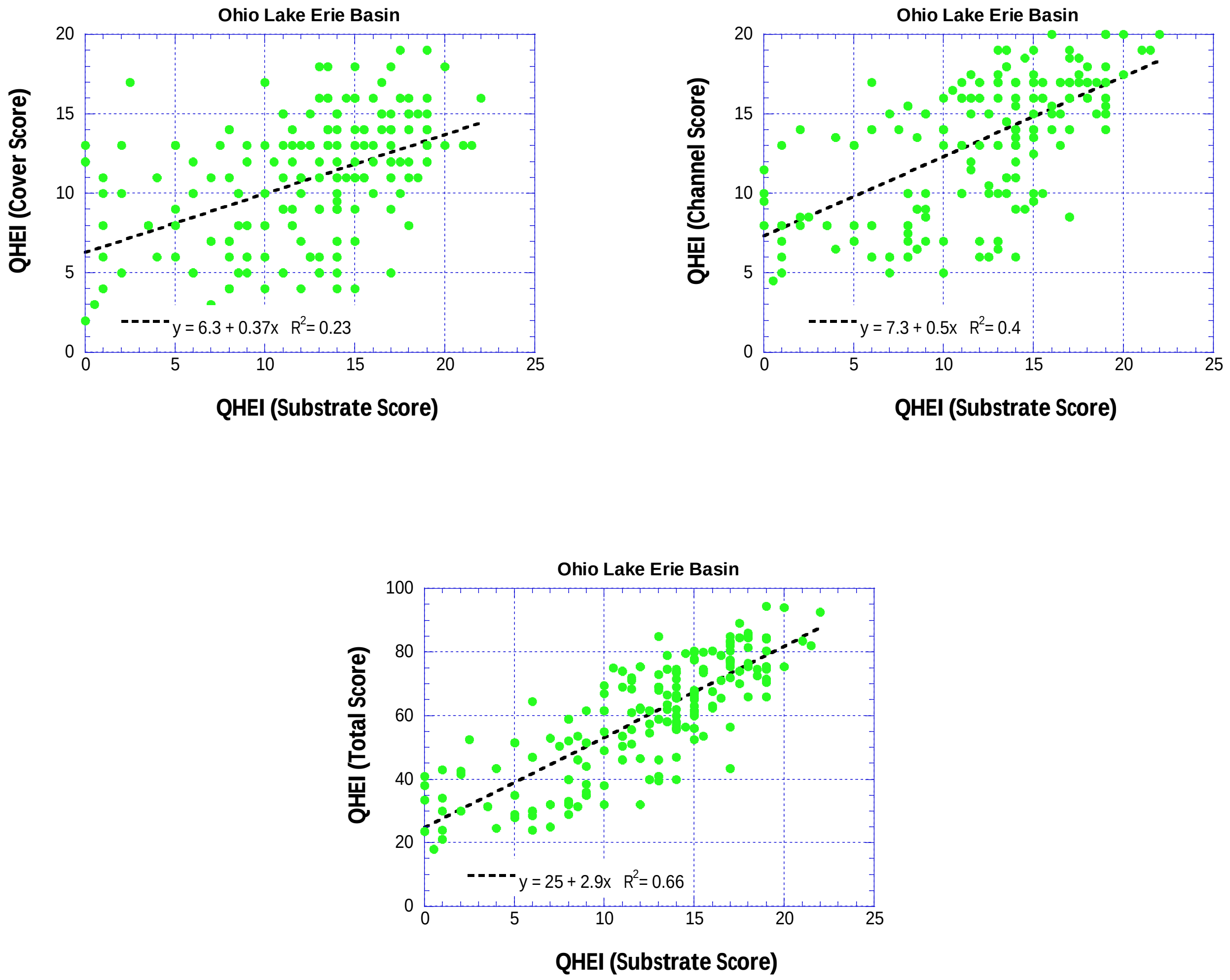

Figure 29. Correlations between the QHEI substrate score and other QHEI metrics and the QHEI total score for Ohio streams of the Lake Erie basin

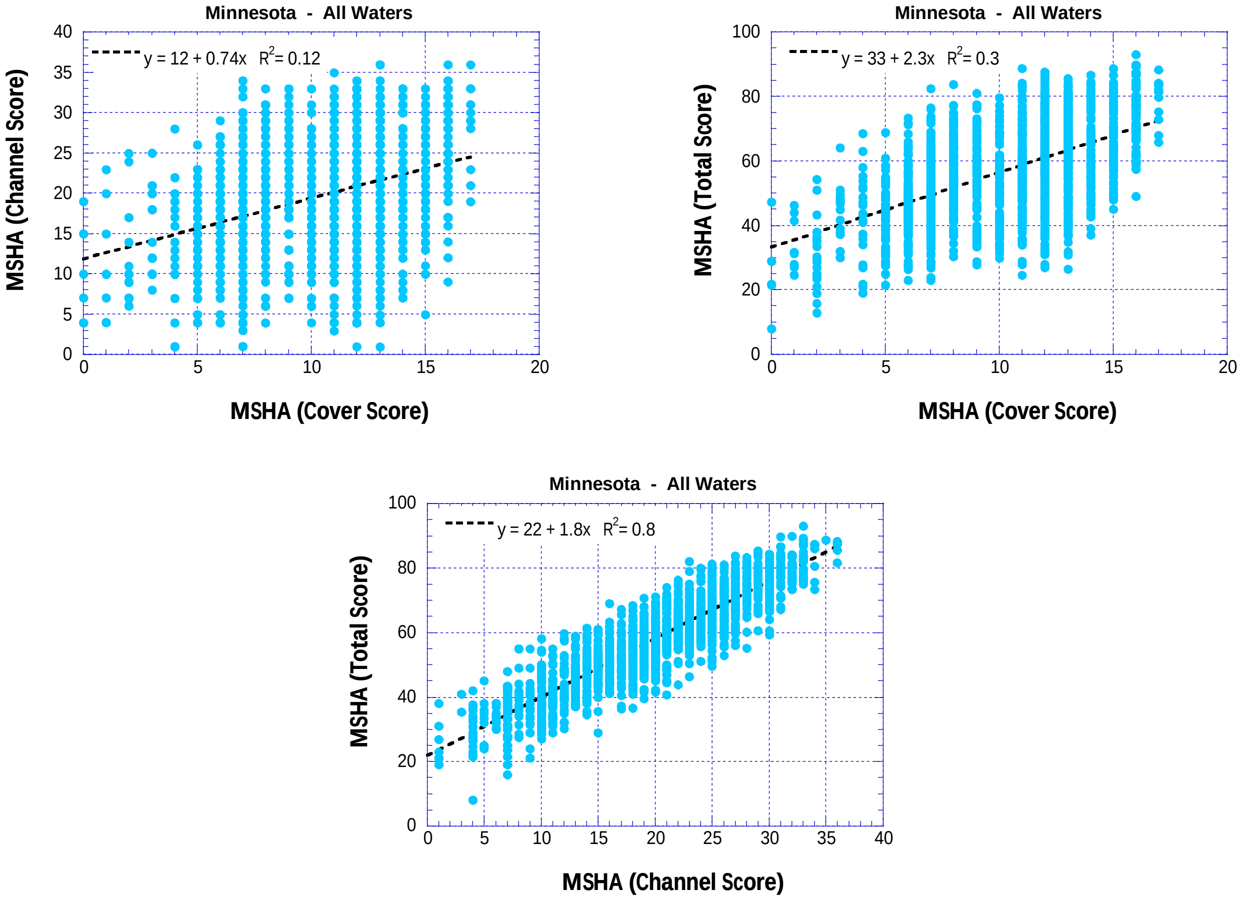

Figure 30. Correlations between the MSHA channel score and other MSHA metrics and the MSHA total score.

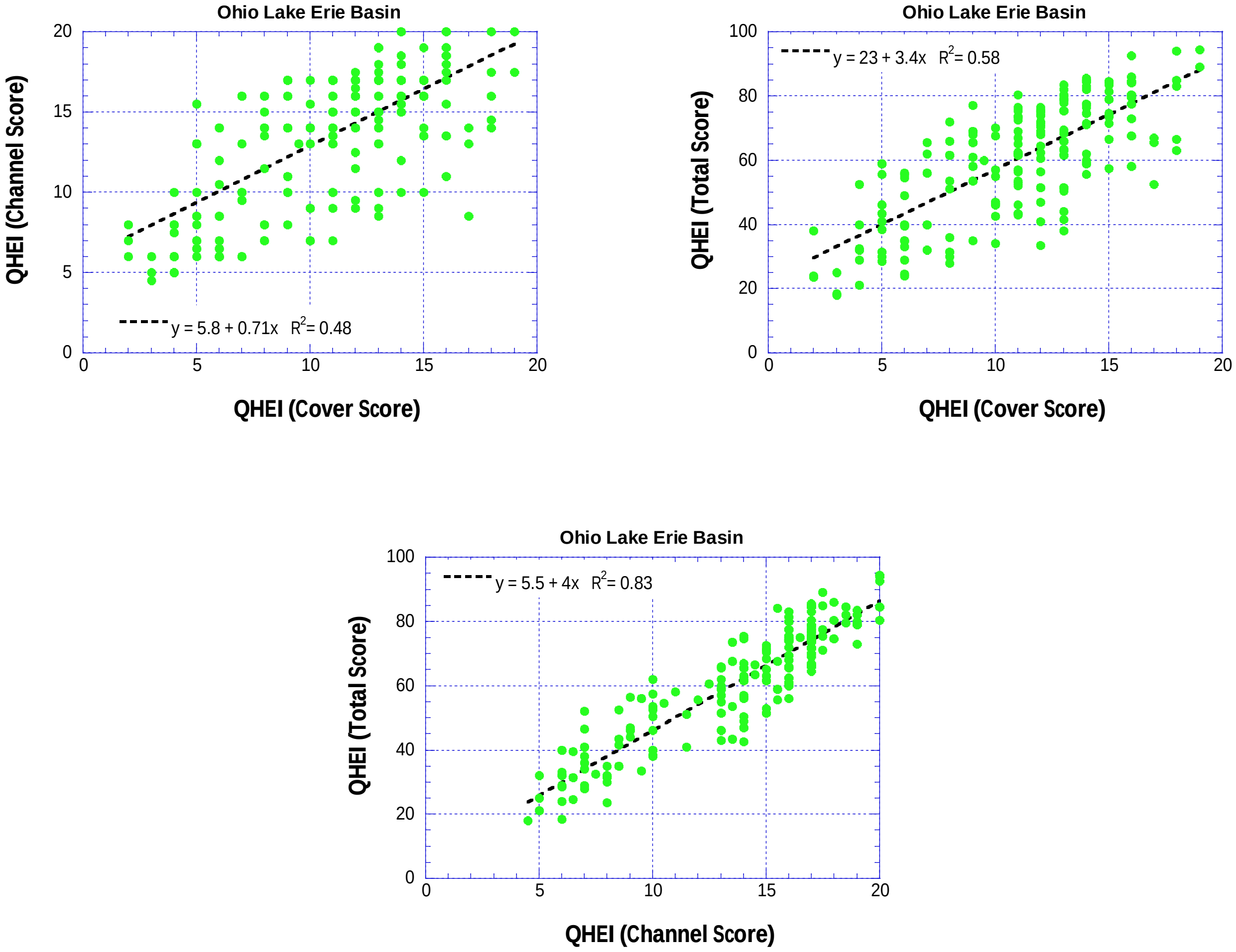

Figure 31. Correlations between the QHEI channel score and other QHEI metrics and the QHEI total score for Ohio streams of the Lake Erie basin

Good versus Poor Habitat Attributes

Rankin (1989, 1995) used the numbers of habitat attributes identified as associated with high IBIs ("good" attributes) or low IBIs ("poor" attributes) to explain variation in the Ohio fish IBI. These attributes were used as key factors in assigning aquatic life uses for streams that were deemed unable to attain the WWH or better aquatic life uses in Ohio because of essentially irretrievable[2] channel modifications. We attempted a similar approach in this study and in the preceding sections identified variables that would serve as "good" or "poor" habitat attributes for each metric for MN streams based on the analyses of which features were most strongly associated with low or high FIBIs and MIBIs within each of their classification strata.

Calculation of Weighted Poor and Good Habitat Attributes

The identification of "good" (or "Warmwater") and "poor" (or Modified Warmwater) habitat attributes with the Ohio QHEI and IBI distinguished between "high" influence and "moderate" influence habitat attributes based on the strength of the statistical correlation between the QHEI attribute and the Ohio IBI. After initially identifying good and poor habitat attributes for Minnesota streams based largely on statistical significance ($P<0.05$), we re-analyzed the data and distinguished among highly significant attributes ($P<0.001$) and those significant at $P<0.05$. We assigned a weight of 2 for highly significant attributes and 1 for those significant only at $P<0.05$, but less than $P<0.001$. In addition, because we analyzed each classification strata independently due to the non-equivalence of IBI scores we identified attributes that were trending towards significance where biological judgment suggested that low sample size may preclude certain attributes from being classified as significant attributes. These were assigned a weight of 0.5. Another difference with the Ohio method was additional weights given for watershed scale habitat conditions (or in several cases land use data) based on classification tree analyses and plots of watershed average MSHA versus IBI which identified a strong influence of watershed scale habitat condition on biological performance. These data were used to add 5 points to either the positive or negative attribute scores (Table 56). The strong influence of watershed scale habitat impacts on IBI in Ohio was quantified subsequent to the identification of good and poor habitat attributes. To further separate natural from channel modified sites an additional 5 points was added to the negative attribute score when a channel was identified as channelized (either old channelization or recent channelization). Although we added the extra points here to the attribute scores such factors could be considered separately as was done in the later effort by MPCA to fit attributes using logistic regression (MPCA 2015).

Once the "good" and "poor" habitat attribute scores were calculated they were plotted versus the IBI values, coded by channelization status, to help visualized the cumulative influence of habitat loss on aquatic life. As was discussed earlier, the Ohio dataset had sharp relationships between the QHEI and IBI with fewer "outliers" than observed in the Minnesota data. We attribute these differences to factors such as baseflow (lower in Ohio), summer stream temperatures (higher in Ohio) and the influence of these factors on nutrients (higher in Ohio) and nutrient processing and assimilation.

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[2] These were activities deemed not to be restorable with feasible restoration designs or where natural recovery was likely within the next 5+ years.

Table 56. Additional scoring modifications based on scale of habitat disturbance by HUC-8 for fish and macroinvertebrates

Fish	Southern Rivers (1)	Southern Streams (2)	Southern Headwaters (3)	Northern Rivers (4)	Northern Streams (5)	Northern Headwaters (6)	Low Gradient Streams (7)
Watershed Av. MSHA (5 pts)	>54.2	>53.8	>53	>54.9	>60.7	*	> 54.2
Watershed Av. MSHA (- 5 pts)	<50	<49.5	< 50	< 50	< 41.8	<50	< 50
Macros	Northern Forests Rivers (1)	Prairie Forest Rivers (2)	Northern Streams Riffle-Run (3)	Northern Streams Glide-Pool (4)	Southern Streams Riffle-Run (5)	Southern Streams Glide-Pool (6)	Prairie Streams Glide-Pool (7)
Watershed Av. MSHA (5 pts)	≥61.3	**	≥65.9	>60.5	>54.185	> 56.68	***
Watershed Av. MSHA (- 5 pts)	<50	<49.5	< 50	< 50	< 41.8	<50	< 50

*- Land Use Score > 3.6
**-Land Use Score > 2.875
***- Land Use Score > 0.375

To improve the visualization of the data we used both scatter plots of good attributes, poor attributes and the ratio of poor/good attributes versus the FIBI and MIBI. This assignment of tiered aquatic uses is a risk-based approach to stream management and we want to minimize the risk of designating a stream with a lower than CWA use (*e.g.,* channel modified use). To this end we converted the IBI data for ranges of MSHA weighted attributes to the probability of attainment of FIBI or MIBI thresholds and plotted these data by ranges of these attributes. Thus for a given range of weighted attributes (*e.g.,* good, poor, or poor/good ratio) we can calculate the probability that a site attains a use within a classification strata based on existing data. We then looked for ranges where the probability of attainment of a 2B use was low (*e.g.,* < 25%) to identify candidate reaches for a use attainability analysis (UAA).

Fish Data

Figures 32-38 present scatter and probability plots, by classification strata of good attribute scores (top), poor attribute scores (middle), and the ratio of poor-good attributer scores (bottom) for the FIBI. For most strata the probability of attaining an FIBI benchmark is strongly related to the attribute scores. In general the relationship is weakest for rivers and stronger for Southern strata and low gradient streams than Northern strata and for poor attributes versus good attributes or the ratio of poor/good attributes. Channelized versus natural stream channels separate most distinctly along the poor attribute scores and for streams, headwaters, and low gradient strata versus rivers. This data suggests that modified uses (*i.e.,* severe habitat limitations) would be most common in Southern streams and headwaters and low gradient streams and less likely in Northern strata and in river strata.

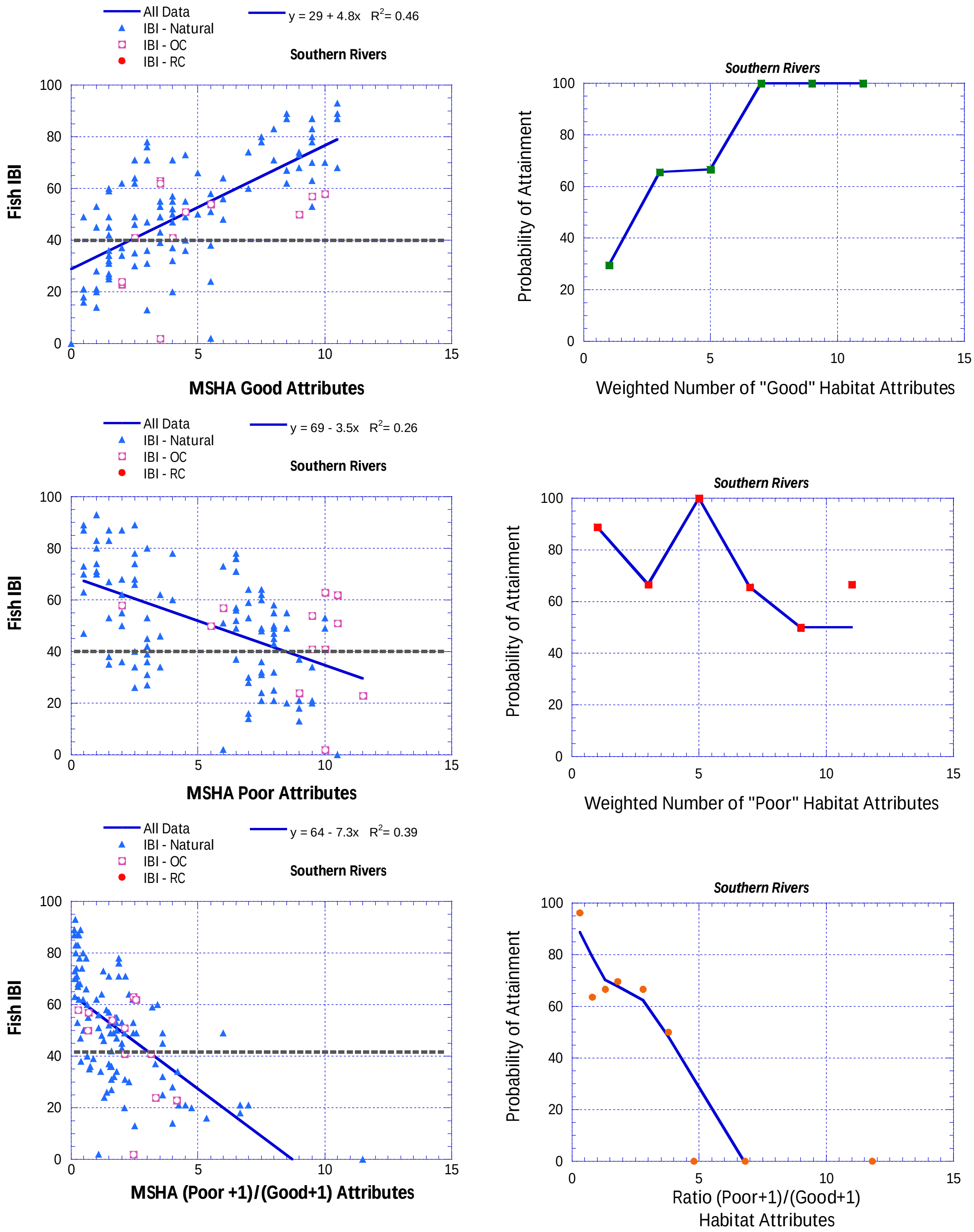


Figure 32. Plots of MSHA "good" habitat attributes (top left), "poor" habitat attributes (middle left) and a ratio (good+1/poor+1, bottom left) of attributes versus Fish IBI scores for the Southern Rivers classification. Plots on the right illustrate the percent of sites attaining the IBI threshold by ranges of the attribute measure. Sites are coded as natural and channelized (OC – old channelization, RC – recent channelization).

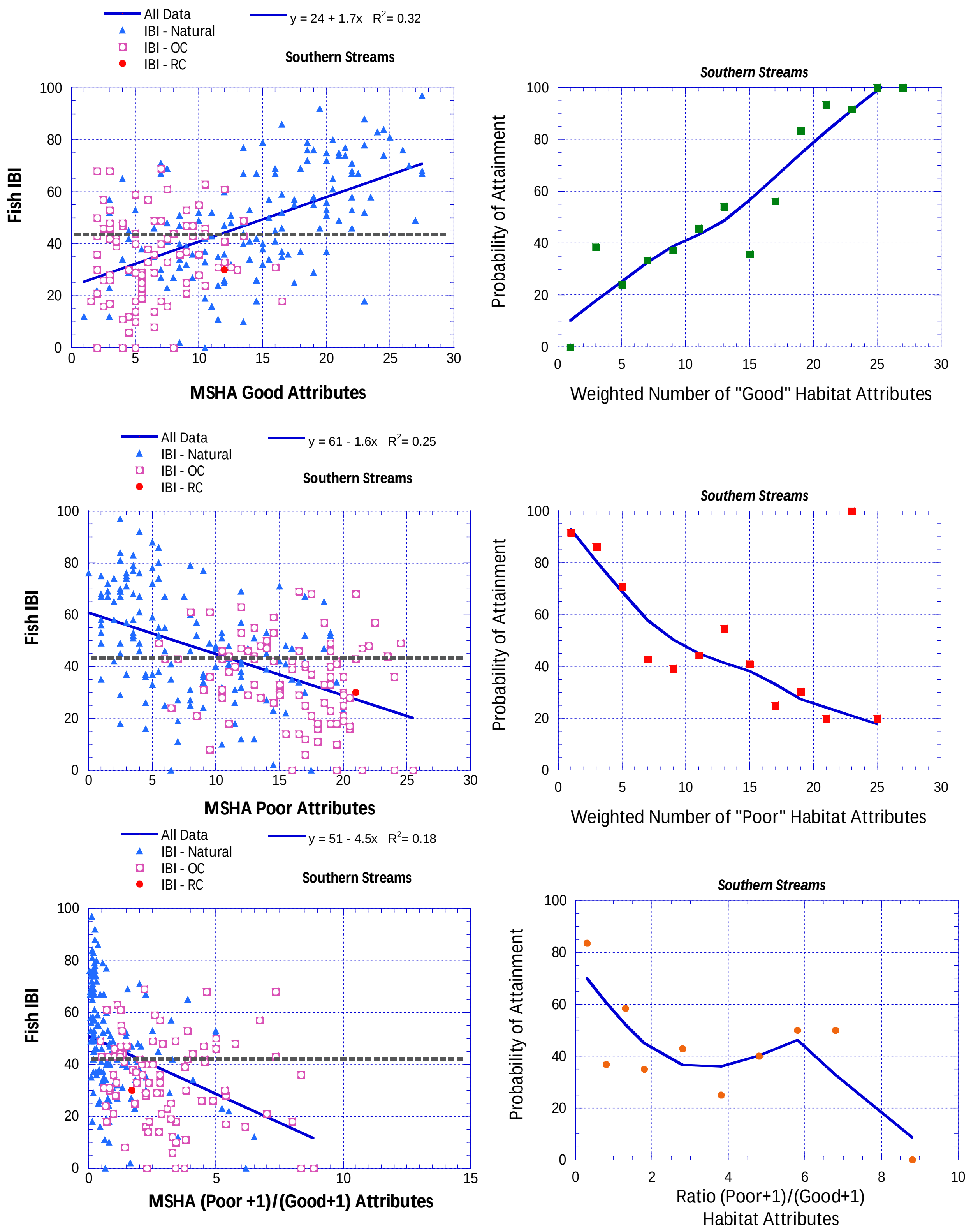


Figure 33. Plots of MSHA "good" habitat attributes (top left), "poor" habitat attributes (middle left) and a ratio (good+1/poor+1, bottom left) of attributes versus Fish IBI scores for the Southern Streams classification. Plots on the right illustrate the percent of sites attaining the IBI threshold by ranges of the attribute measure. Sites are coded as natural and channelized (OC – old channelization, RC – recent channelization).

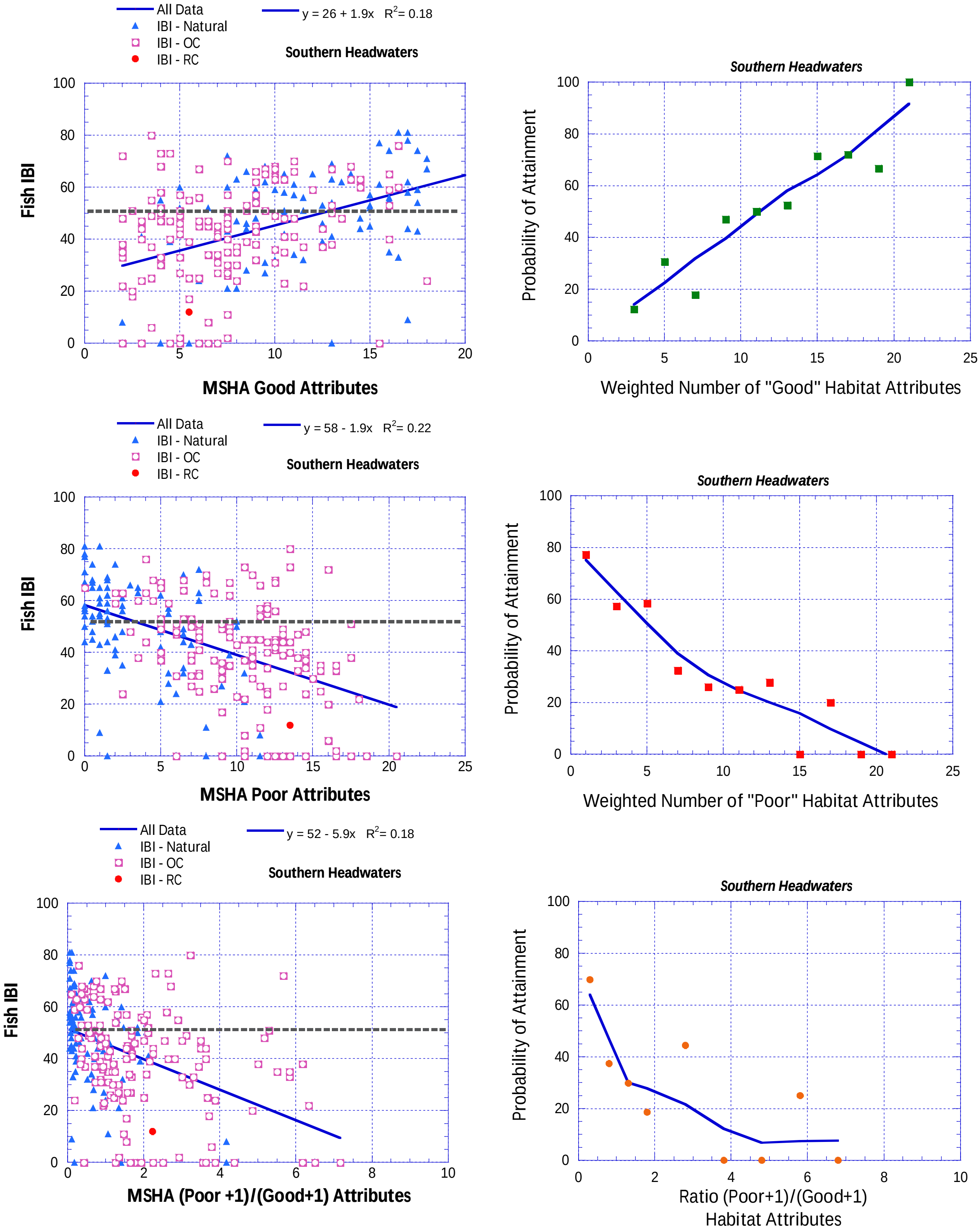


Figure 34. Plots of MSHA "good" habitat attributes (top left), "poor" habitat attributes (middle left) and the ratio (good+1/poor+1, bottom left) of attributes versus Fish IBI scores for the Southern Headwaters classification. Plots on the right illustrate the percent of sites attaining the IBI threshold by ranges of the attribute measure. Sites are coded as natural and channelized (OC – old channelization, RC – recent channelization).

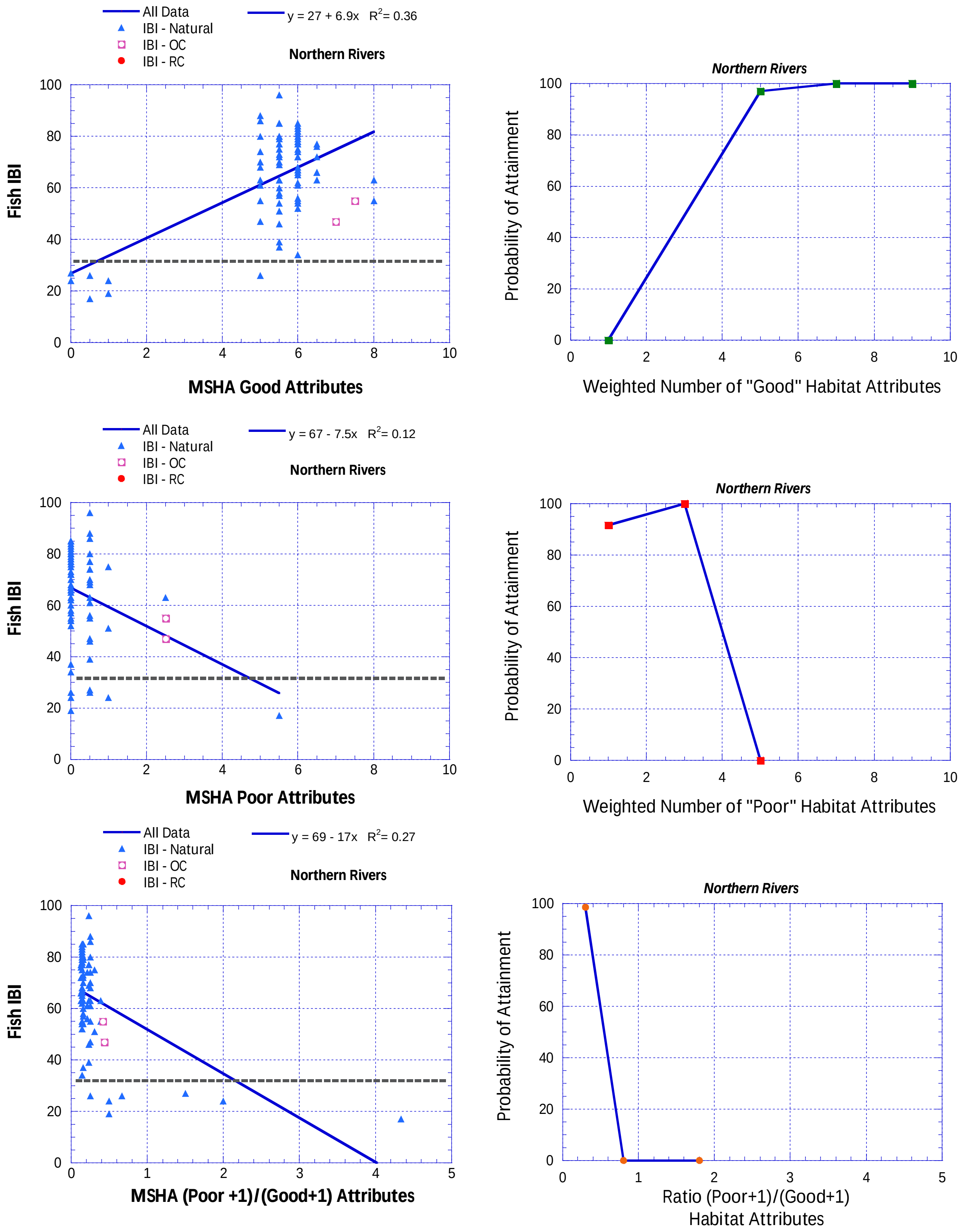


Figure 35. Plots of MSHA "good" habitat attributes (top left), "poor" habitat attributes (middle left) and the ratio (good+1/poor+1, bottom left) of attributes versus Fish IBI scores for the Northern Rivers classification. Plots on the right illustrate the percent of sites attaining the IBI threshold by ranges of the attribute measure. Sites are coded as natural and channelized (OC – old channelization, RC – recent channelization).

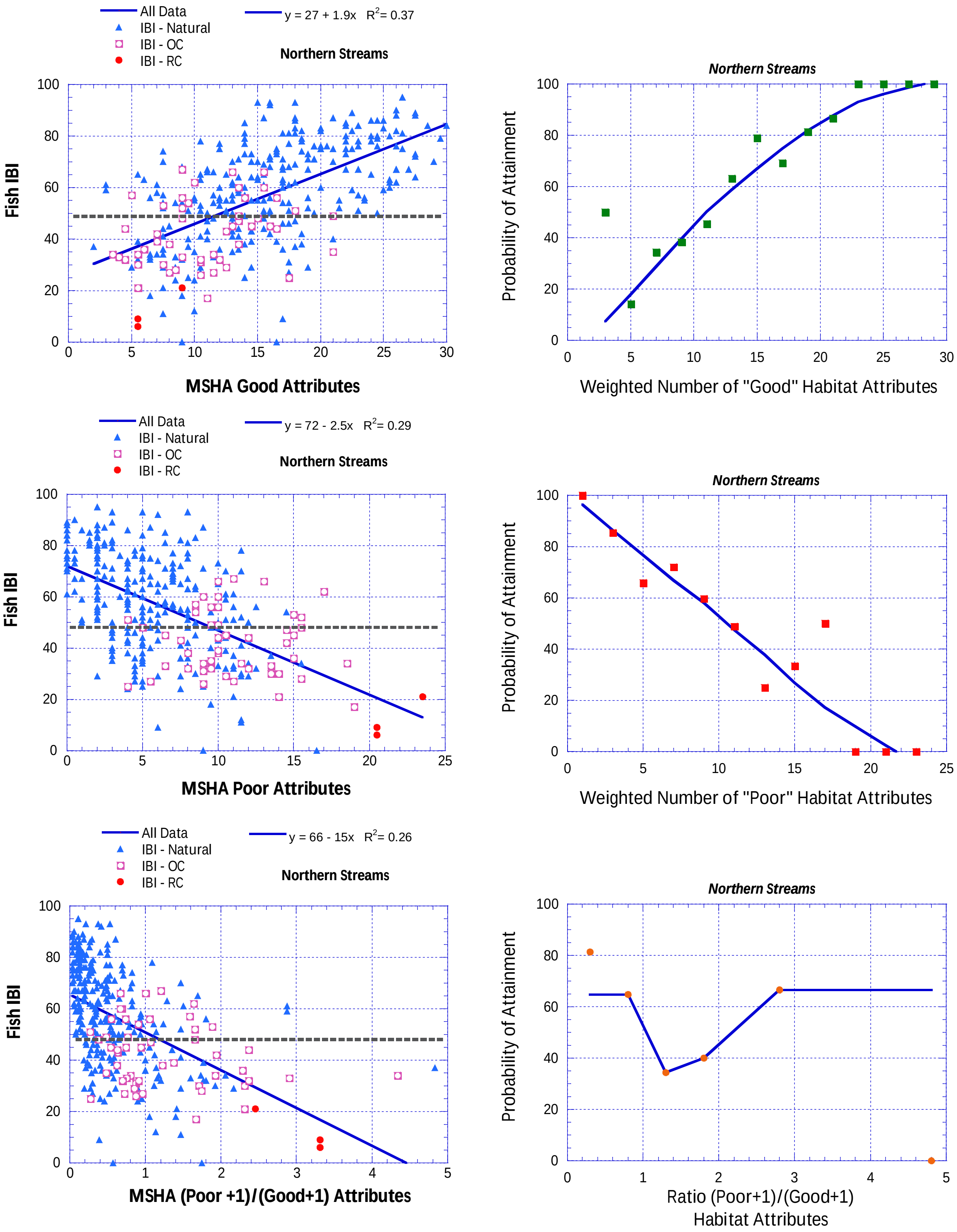


Figure 36. Plots of MSHA "good" habitat attributes (top left), "poor" habitat attributes (middle left) and the ratio (good+1/poor+1, bottom left) of attributes versus Fish IBI scores for the Northern Streams classification. Plots on the right illustrate the percent of sites attaining the IBI threshold by ranges of the attribute measure. Sites are coded as natural and channelized (OC – old channelization, RC – recent channelization).

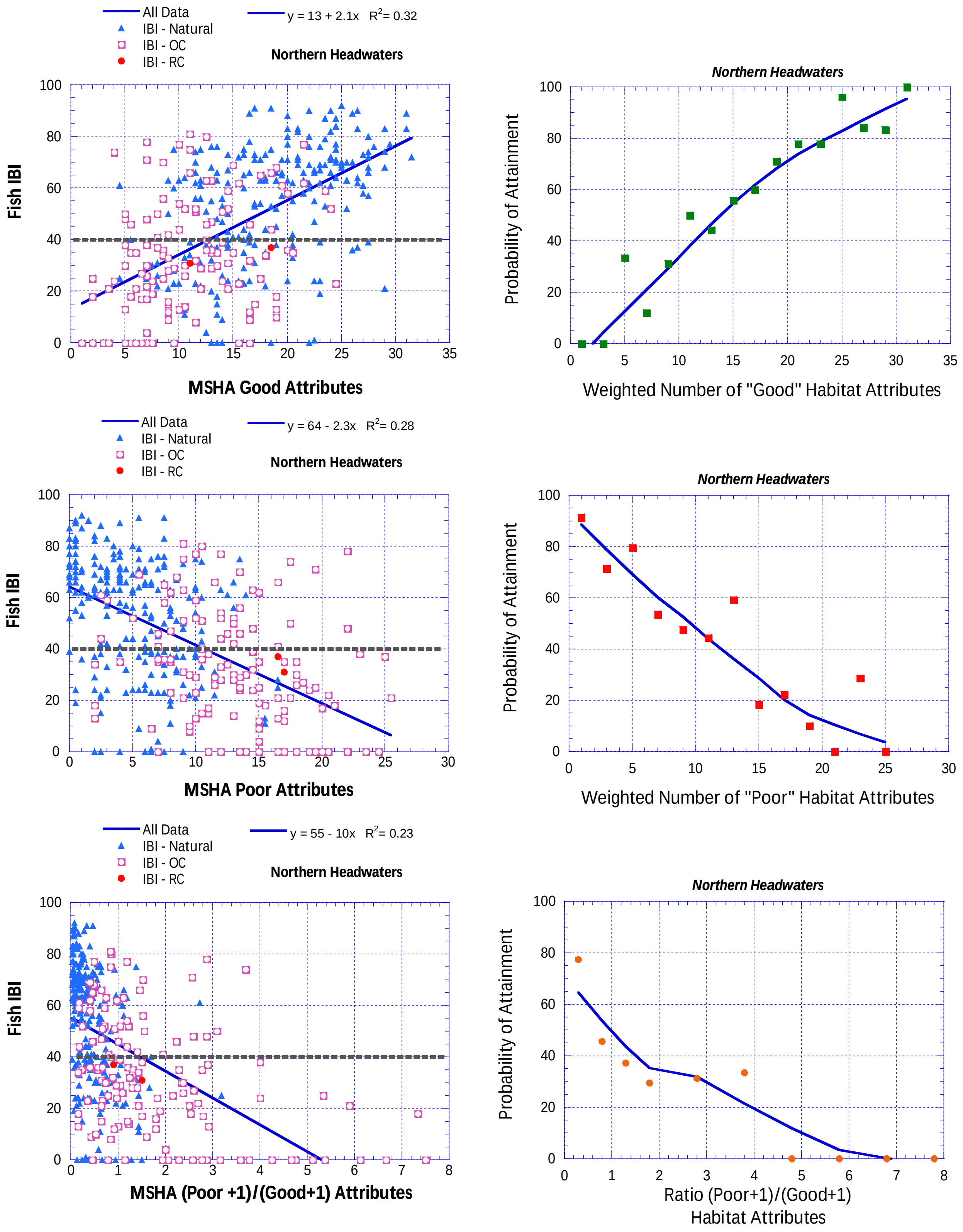


Figure 37. Plots of MSHA "good" habitat attributes (top left), "poor" habitat attributes (middle left) and the ratio (good+1/poor+1, bottom left) of attributes versus Fish IBI scores for the Northern Headwaters classification. Plots on the right illustrate the percent of sites attaining the IBI threshold by ranges of the attribute measure. Sites are coded as natural and channelized (OC – old channelization, RC – recent channelization).

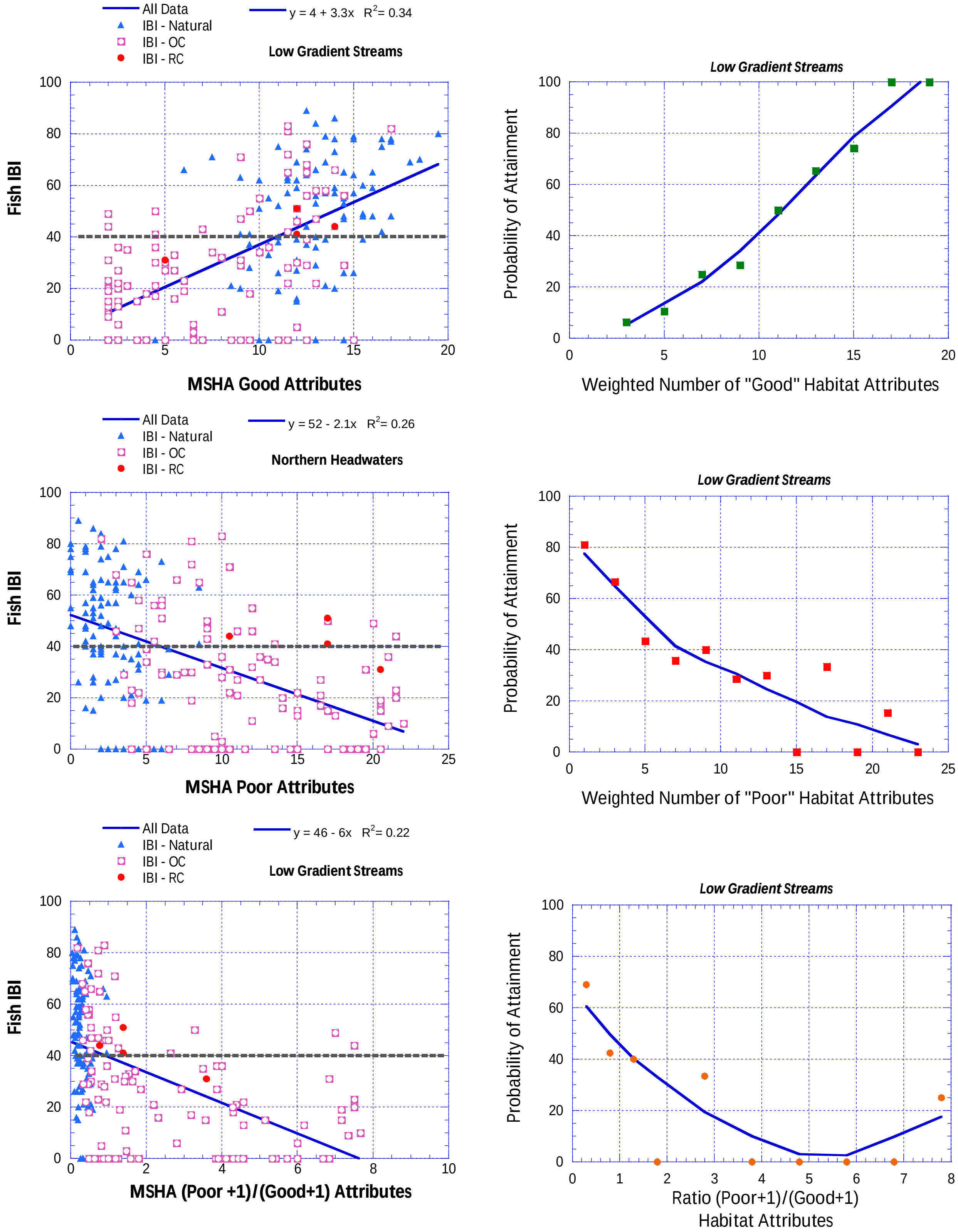


Figure 38. Plots of MSHA "good" habitat attributes (top left), "poor" habitat attributes (middle left) and a ratio (good+1/poor+1, bottom left) of attributes versus Fish IBI scores for the Low Gradient Streams classification. Plots on the right illustrate the percent of sites attaining the IBI threshold by ranges of the attribute measure. Sites are coded as natural and channelized (OC – old channelization, RC – recent channelization).

Macroinvertebrate Data

The classification strata for the MIBI differs from the classification scheme for the FIBI, but has some similarities in that it uses a North/South breakdown and the consideration of low gradient streams in distinguishing among riffle/run versus glide pool types habitat types in the classification strata. As with the fish assemblages there is a relationship between habitat and biological condition in rivers (Figures 39 and 40); however, habitat modifications are not widespread in the rivers sampled and a channel modified aquatic life use is not warranted.

Northern streams typified by riffle/run morphology had few sites that had been channelized and although there is a relationship between habitat attributes and the MIBI there are too few directly modified channels to consider a modified use within these macroinvertebrate classification strata (Figure 40). The macroinvertebrate classification strata where a modified aquatic life use would be considered include the Southern Riffle/Run streams, the Northern and Southern Glide/Pool streams and the Prairie Glide/Pool Streams (Figures 41-44).

Within the four classification strata where modified aquatic uses are a possibility, the weighted number of “poor” habitat attributes tends to separate modified from natural sites more clearly than the weighted number of “good” habitat attributes at a site (Figures 41-44). This pattern is similar to what we observed in the fish data (Figures 32-38). To help to convert these scatter plots into a more understandable pattern we plotted the probability of attaining the MIBI threshold by range of habitat attribute scores. These are located to the right of each attribute/IBI plot. (Figures 38-44)

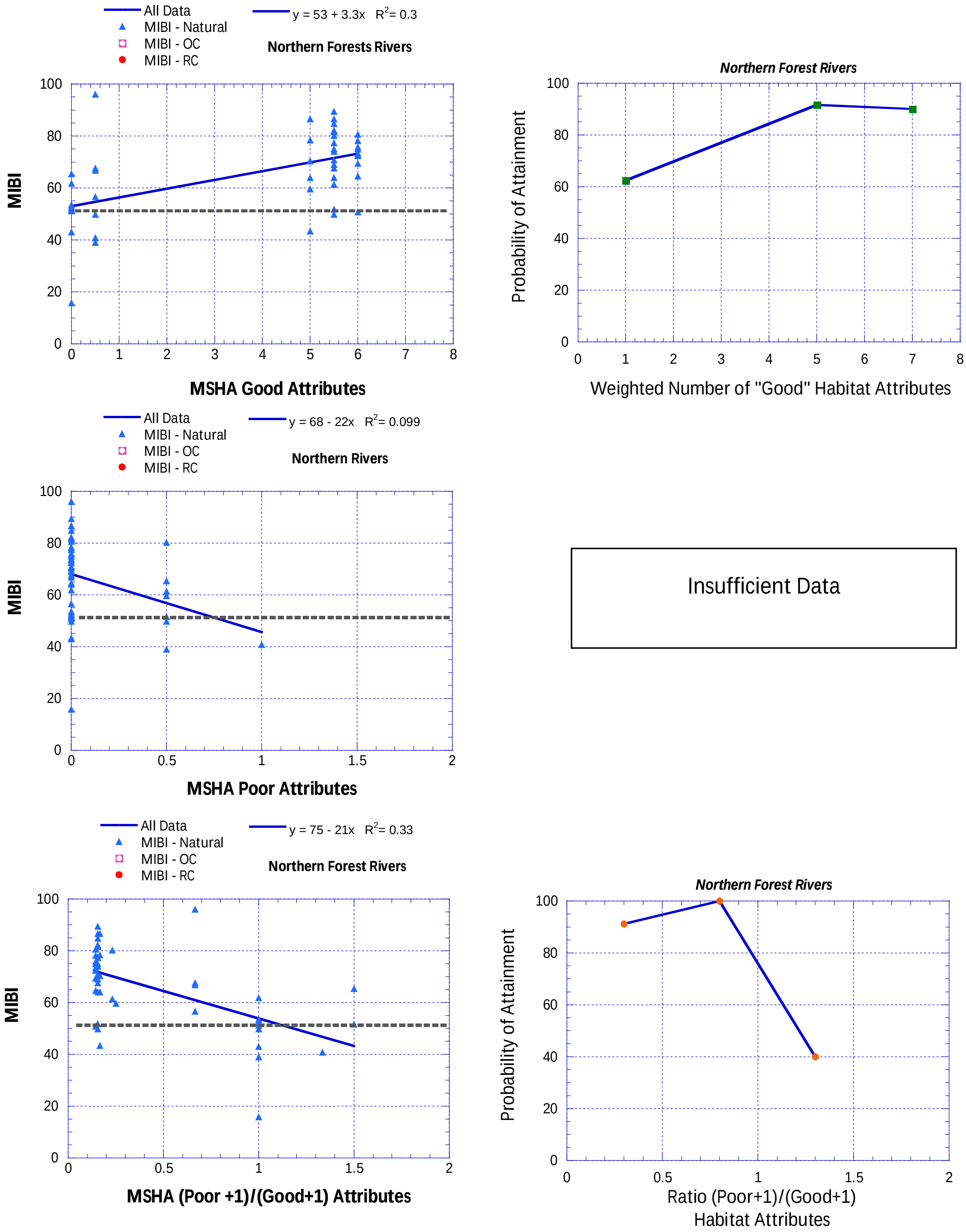


Figure 38. Plots of MSHA "good" habitat attributes (top left), "poor" habitat attributes (middle left) and the ratio (good+1/poor+1, bottom left) of attributes versus MIBI scores for the Northern Forest Rivers classification. Plots on the right illustrate the percent of sites attaining the MIBI threshold by ranges of the attribute measure. Sites are coded as natural and channelized (OC – old channelization, RC – recent channelization).

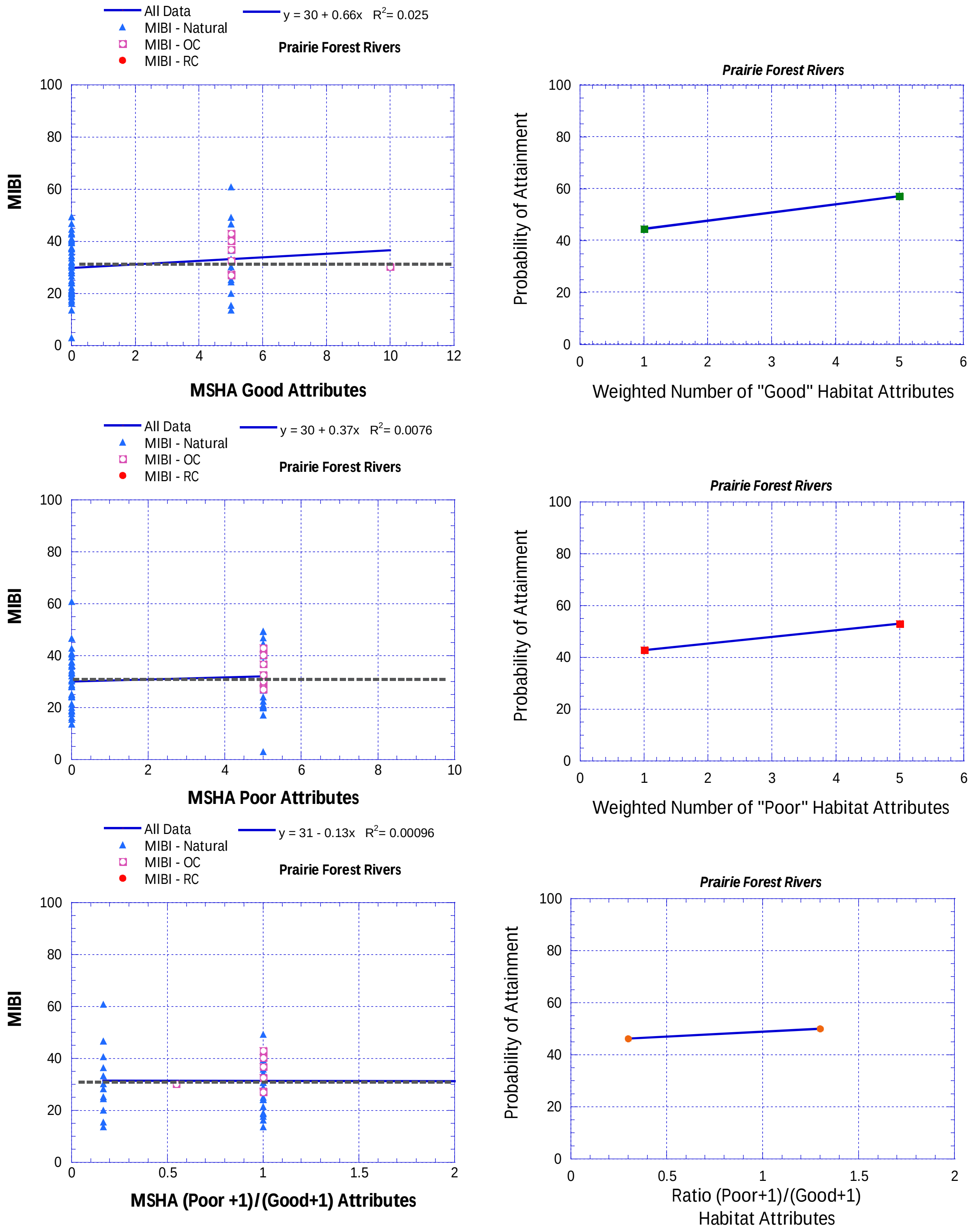


Figure 39. Plots of MSHA "good" habitat attributes (top left), "poor" habitat attributes (middle left) and the ratio (good+1/poor+1, bottom left) of attributes versus MIBI scores for the Prairie Forest Rivers classification. Plots on the right illustrate the percent of sites attaining the MIBI threshold by ranges of the attribute measure. Sites are coded as natural and channelized (OC – old channelization, RC – recent channelization).

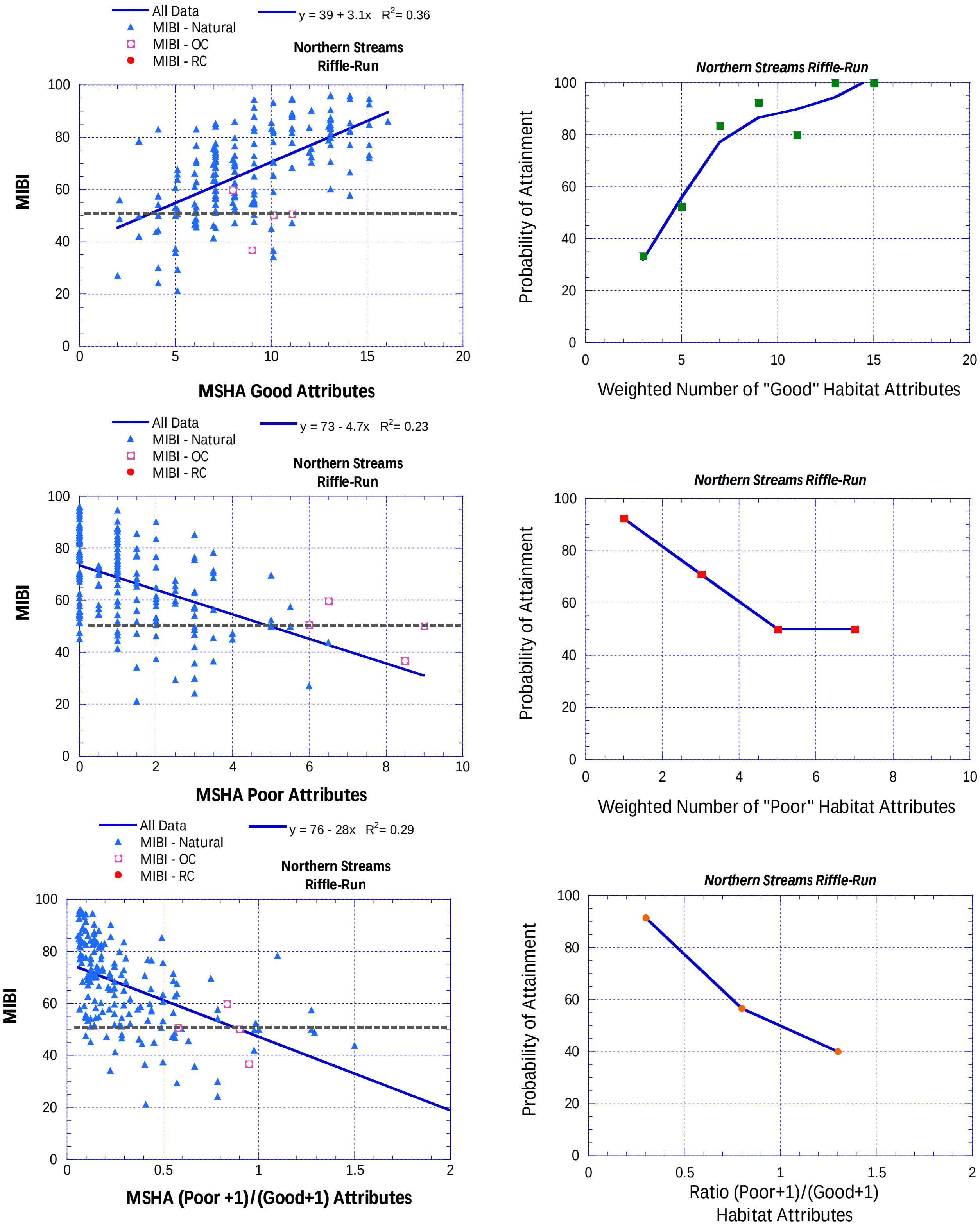


Figure 40. Plots of MSHA "good" habitat attributes (top left), "poor" habitat attributes (middle left) and a ratio (good+1/poor+1, bottom left) of attributes versus MIBI scores for the Northern Streams Riffle/Run classification. Plots on the right illustrate the percent of sites attaining the MIBI threshold by ranges of the attribute measure. Sites are coded as natural and channelized (OC – old channelization, RC – recent channelization).

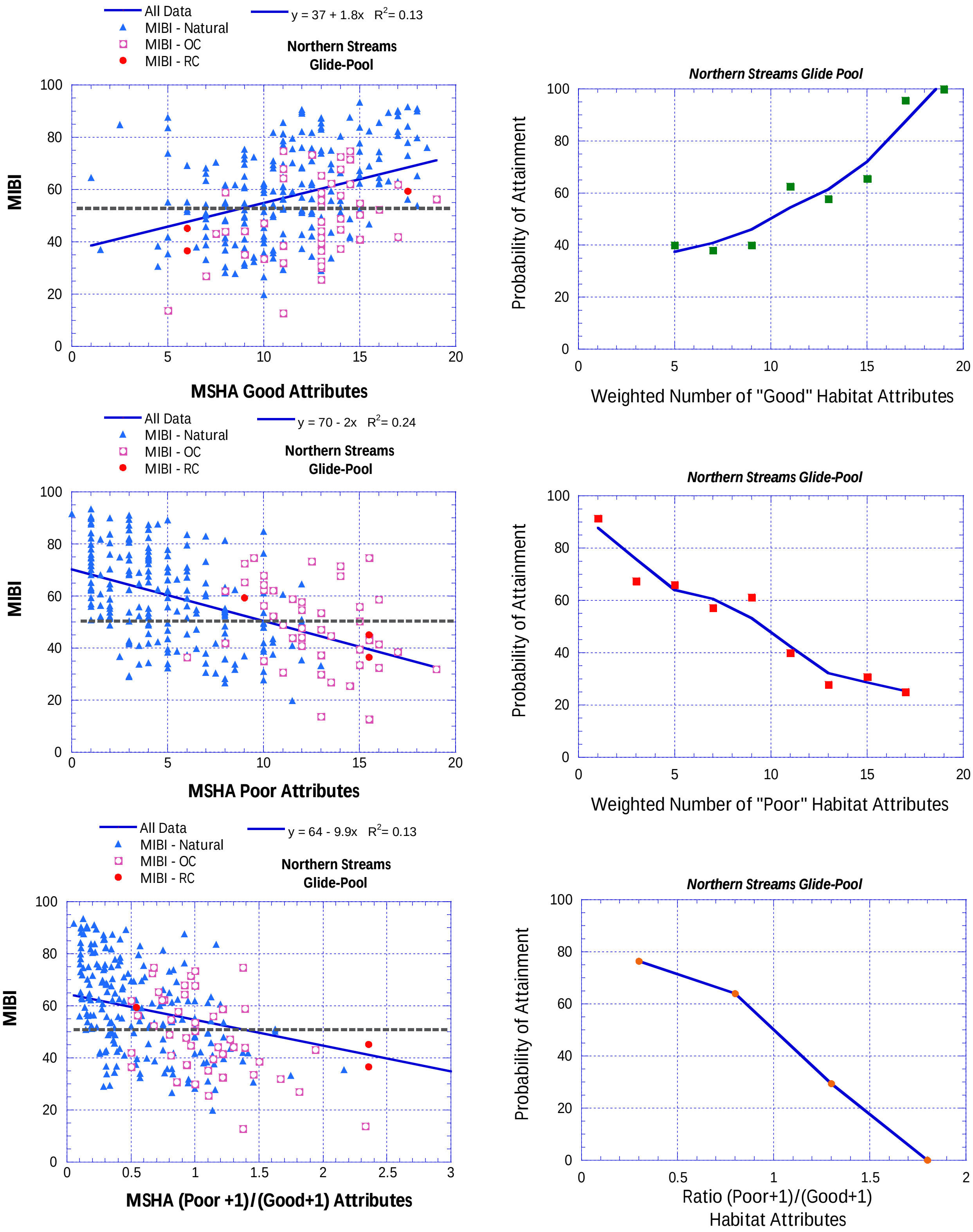


Figure 41. Plots of MSHA "good" habitat attributes (top left), "poor" habitat attributes (middle left) and a ratio (good+1/poor+1, bottom left) of attributes versus MIBI scores for the Northern Streams Glide/Pool classification. Plots on the right illustrate the percent of sites attaining the MIBI threshold by ranges of the attribute measure. Sites are coded as natural and channelized (OC – old channelization, RC – recent channelization).

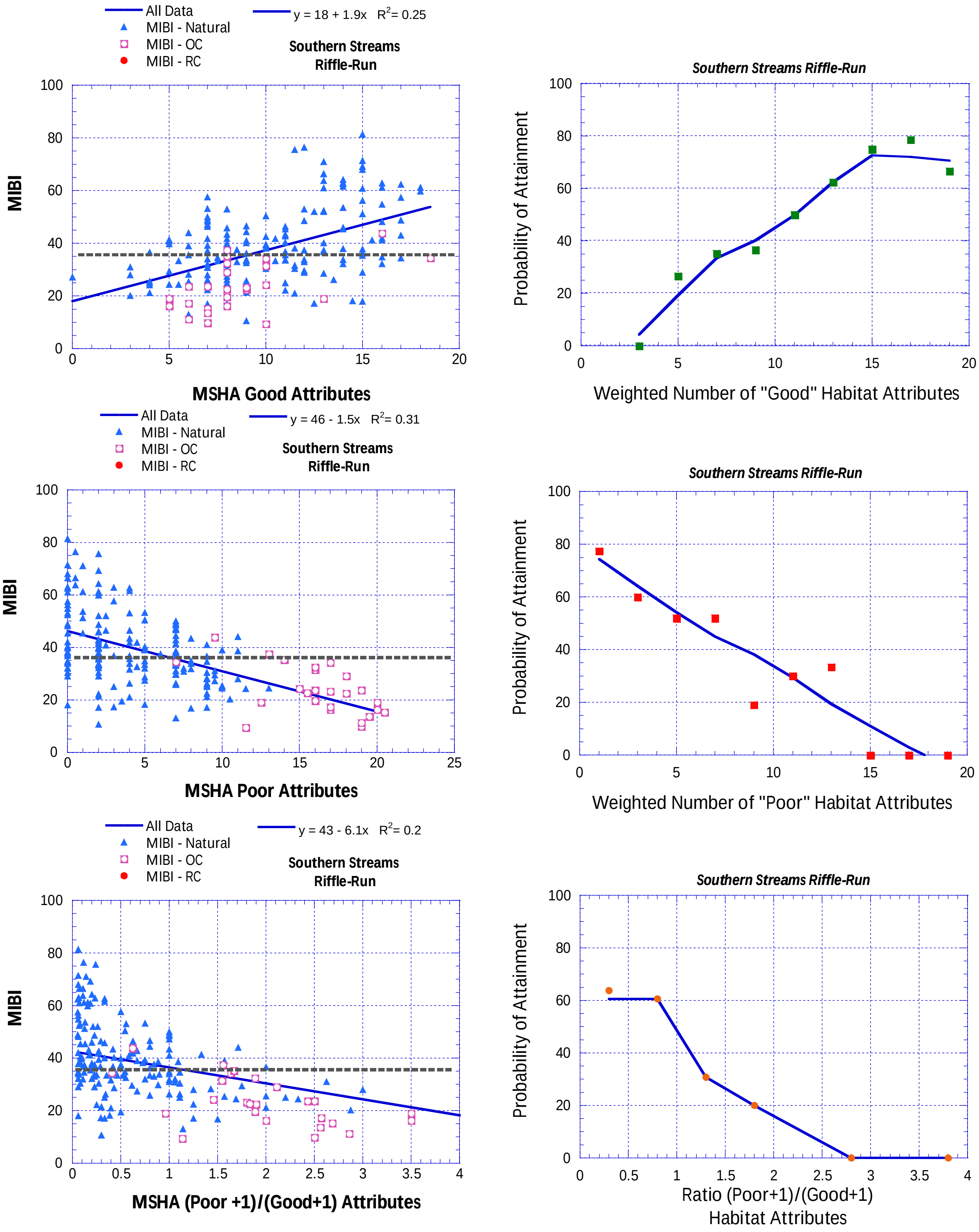


Figure 42. Plots of MSHA "good" habitat attributes (top left), "poor" habitat attributes (middle left) and a ratio (good+1/poor+1, bottom left) of attributes versus MIBI scores for the Southern Streams Riffle/Run classification. Plots on the right illustrate the percent of sites attaining the MIBI threshold by ranges of the attribute measure. Sites are coded as natural and channelized (OC – old channelization, RC – recent channelization).

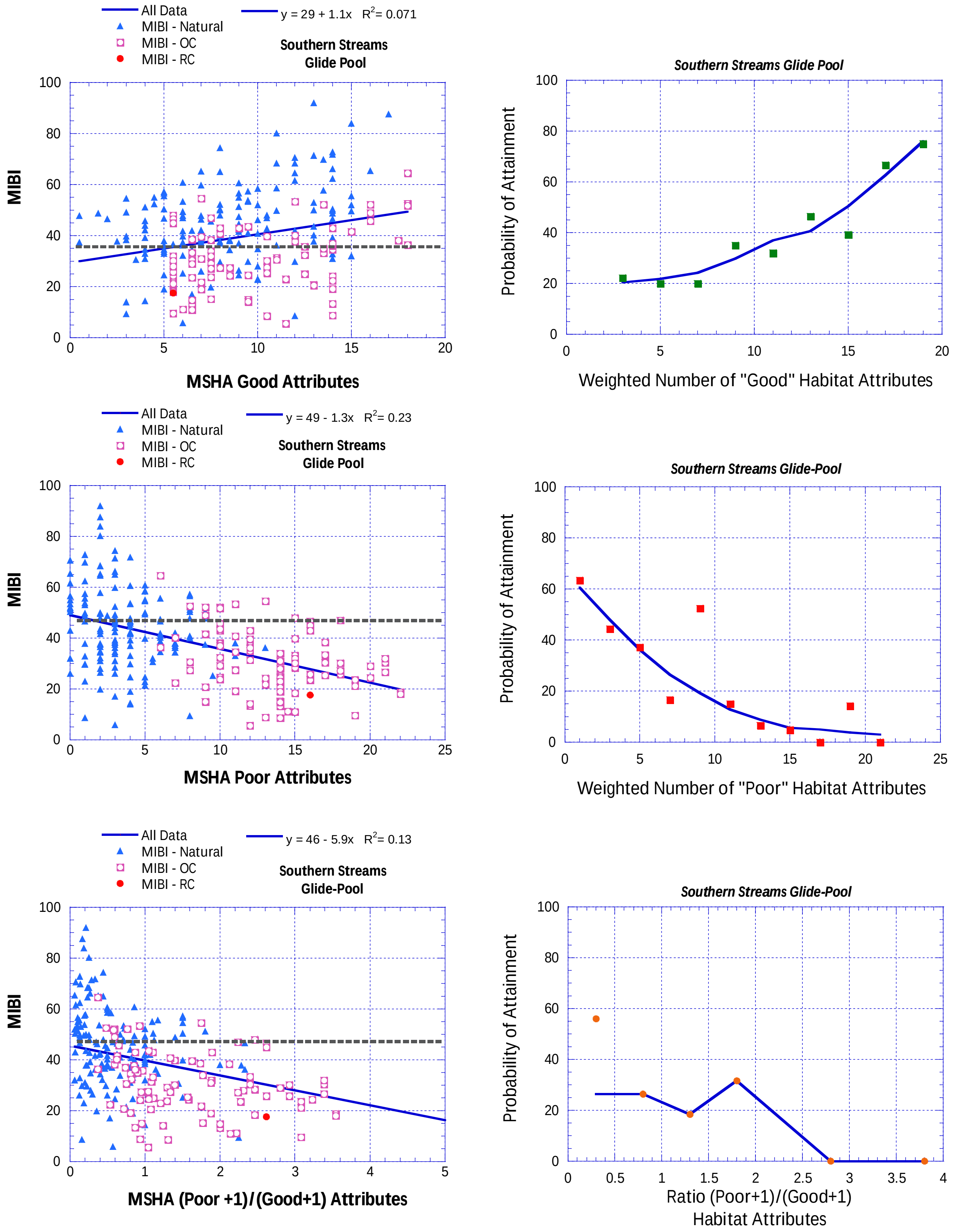


Figure 43. Plots of MSHA "good" habitat attributes (top left), "poor" habitat attributes (middle left) and a ratio (good+1/poor+1, bottom left) of attributes versus MIBI scores for the Southern Streams Glide/Pool classification. Plots on the right illustrate the percent of sites attaining the MIBI threshold by ranges of the attribute measure. Sites are coded as natural and channelized (OC – old channelization, RC – recent channelization).

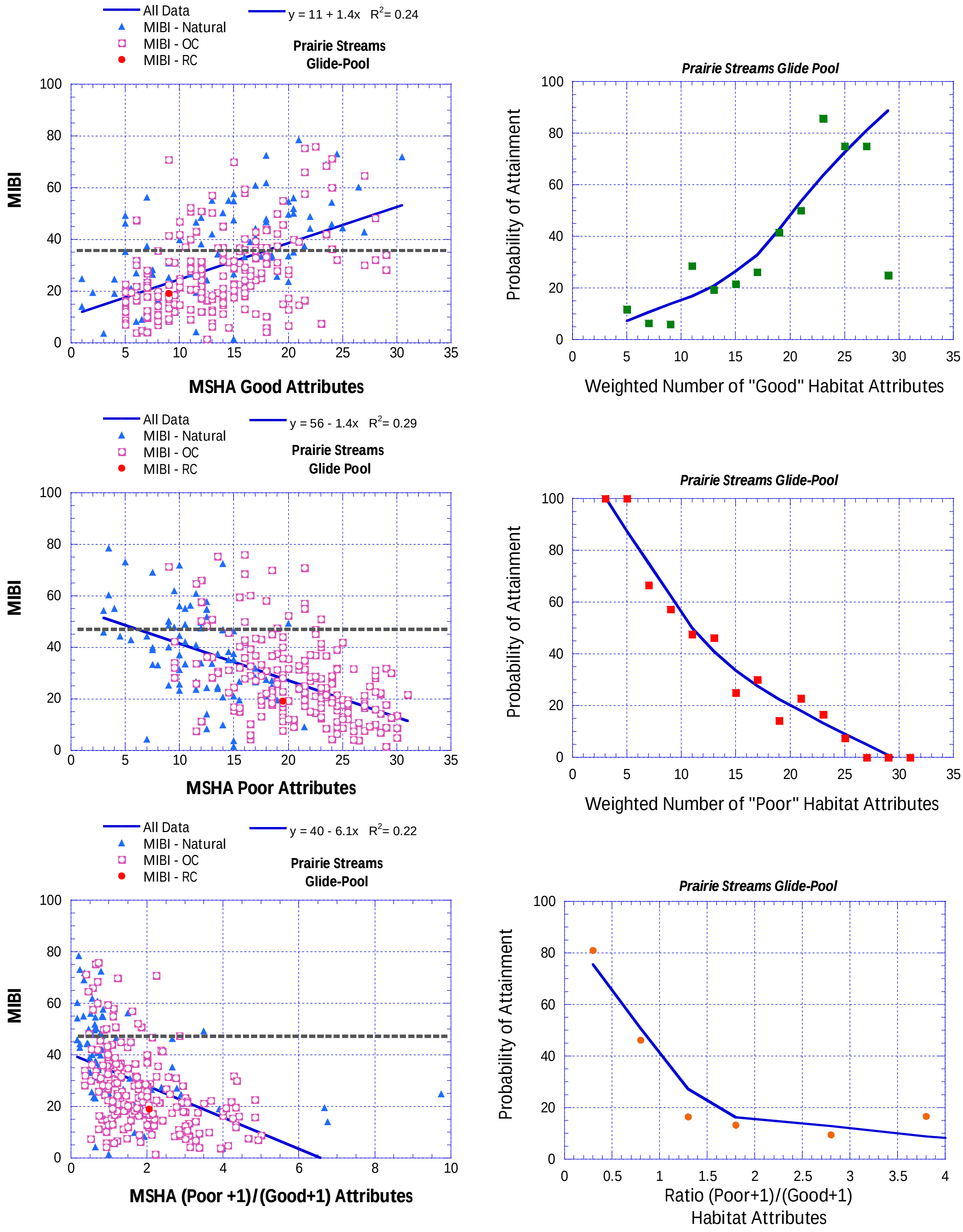


Figure 44. Plots of MSHA "good" habitat attributes (top left), "poor" habitat attributes (middle left) and a ratio (good+1/poor+1, bottom left) of attributes versus MIBI scores for the Prairie Streams Glide/Pool classification. Plots on the right illustrate the percent of sites attaining the MIBI threshold by ranges of the attribute measure. Sites are coded as natural and channelized (OC – old channelization, RC – recent channelization).

Figure 45. Map of "outliers' where MSHA habitat scores were < 50, but FIBI (top) or MIBI exceeded biological thresholds for each classification strata. Grey triangles are site with MSHA scores > 50 or with MSHA scores < 50 and impaired IBI or MIBI scores. Size of point increases with the magnitude IBIs above the thresholds.

Modified Stream Use Attainability analyses: Using the Good and Poor Habitat Attributes to Help Determine CWA Use Attainability

The presence of channelization is not by itself sufficient evidence that a stream cannot achieve an aquatic life use goal commensurate with the CWA interim goal (*i.e.,* fishable-swimmable). Some streams can attain a CWA use despite habitat losses due to channelization where activities are of a local nature and the biota is more strongly influenced by nearby reaches of good, productive habitat. In some places where habitat modification is more extensive biological assemblage impacts may be moderated by high base flows and lower summer stream temperatures. The modes of habitat effects on aquatic life are varied, but include more severe nutrient related impacts related to opening of the stream channel to unlimited sunlight, loss of buffers from adjacent land uses (*e.g.,* row crop), and geomorphic changes (*e.g.,* loss of flood prone areas) that act to concentrate nutrients and fine sediments within the wetted stream channel. Where base flows are high and/or stream temperatures are low these ecological processes can be slowed and effects on the biota moderated. In any case the attainment of CWA aquatic life use goals in channel modified streams is the best arbiter of "attainability" and the starting point for consideration of whether such goals are attainable. Figure 47 charts the first steps of the UAA process for consideration of a modified use which, assuming data is adequate, first asks whether CWA uses (2B or E2B) are attainable.

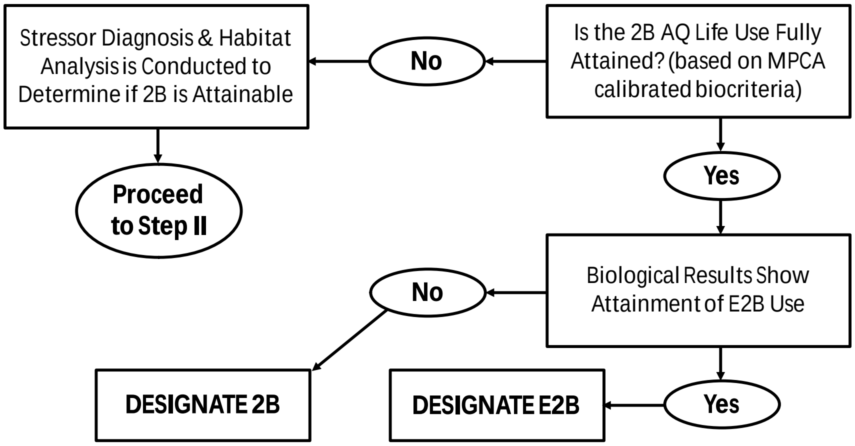


Figure 46. Initial steps in the UAA process for aquatic life uses.

The remainder of this section will focus on the decision points related to whether the weight of evidence is sufficient to conclude that a Class 2B CWA use is not attainable because of habitat limitations that are not ***feasibly restorable***. Part of this discussion is a "scientific" exercise that weighs data collected on habitat conditions at multiple spatial scales to assess the probability of attaining a CWA use after the adoption of reasonable best management practices on the landscape. This process also includes a socio-economic component that requires some definition of what "reasonable" best management practices are with regard to stream modification impacts. Stream that are considered feasibly restorable would not be candidates for a channel modified use, but if impaired would be placed on a state's TMDL list. This part of the decision making process is outlined in Figure 47. Sites that have not been directly modified by activities such as channelization would not be candidates for a channel modified use (Figure

47). Sites with poor habitat features that are the result of "natural" factors might be candidates for a site-specific criteria modification (see Figure 47). Modified streams that are expected to recover naturally within a relatively short time frame would also not be candidates for a channel modified use (Figure 47).

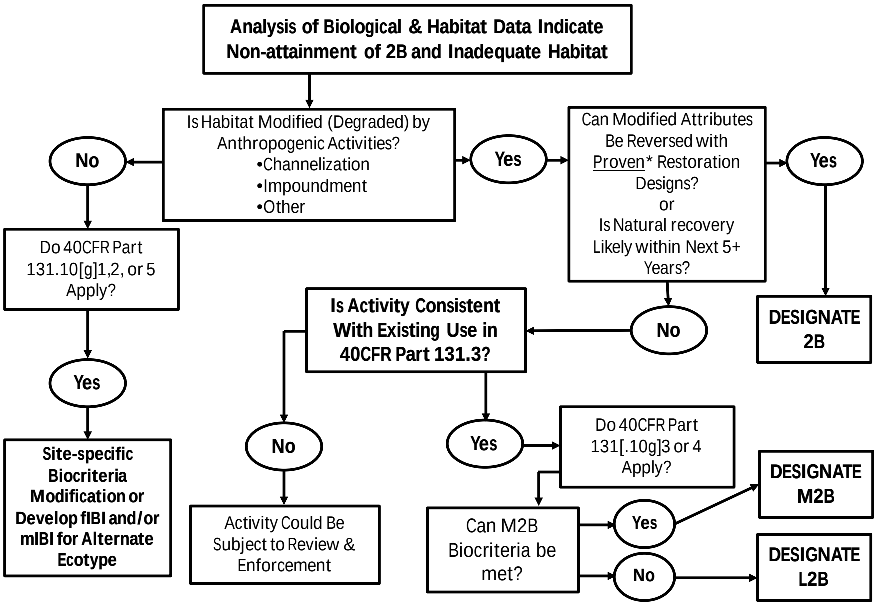


Figure 47. Flow chart illustrating decision points related to feasibility of restoration and assigning tiered aquatic life uses.

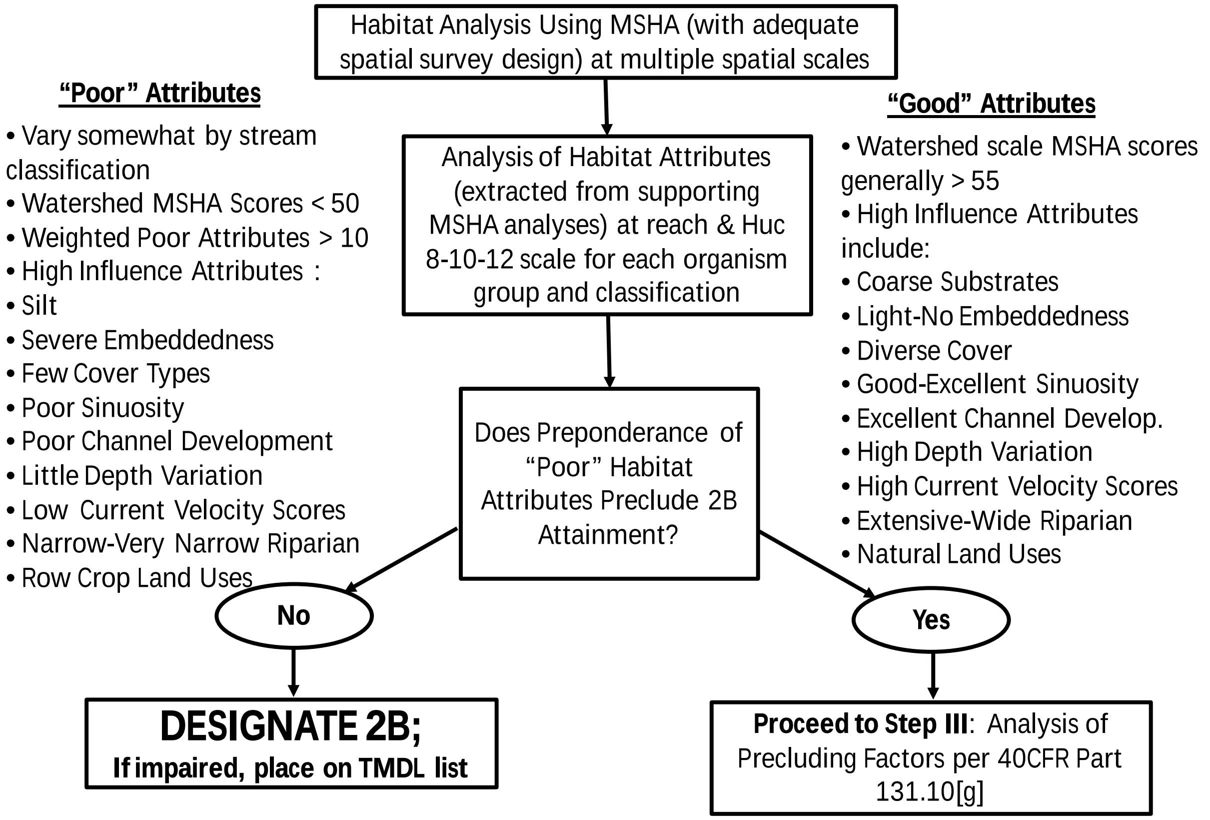


Figure 48. Flow chart summarizing the analysis of habitats attributes used in an UAA process for a channel modified aquatic life use

The list of attributes associated with assemblages' not attaining thresholds varied by classification strata by for both fish and macroinvertebrates as discussed in the sections for each habitat metric. The most frequently identified good and poor habitat attributes are summarized in Figure 48. For both fish and macroinvertebrates it does not appear that assemblages in river classifications are limited by habitat modifications to the extent that application of a channel modified use is warranted. Similarly for streams in the macroinvertebrates Northern Streams Riffle/Run classification strata do not have sufficient modified streams to justify consideration of a channel modified use.

Southern classifications (Fish Southern Streams and Southern Headwaters) and lower gradient classifications (Fish: Low Gradient streams; Macros Southern and Prairie Glide/Pool streams) have the greatest number of sites with high levels of poor attributes and sites that have non-attaining biological index scores. There were a substantial number of sites that reached an IBI threshold despite rather poor habitat, thus it will be important to address such streams up front in the process. The distribution of such outlier points was in some cases clustered within the same watershed (Figure 45) which should help focus on where modified uses are more or less likely. In addition, in many cases these clusters were similarly located for both fish and macroinvertebrates.

We transformed the data from the scatter plots of good and poor weighted attribute scores versus the FIBI and MIBI to plots of the percent of sites attaining thresholds within each classification to help in identifying candidates for channel modified uses. These plots represent a risk-based approach to identifying streams that are candidates for modified uses. Because of outliers few streams can be identified up front as with a single criterion (*e.g.,* weighted poor attribute score > 25) as likely channel modified streams, however the risk based probability data can identify groups of streams that are likely candidates which can then be subjected to a UAA analysis.

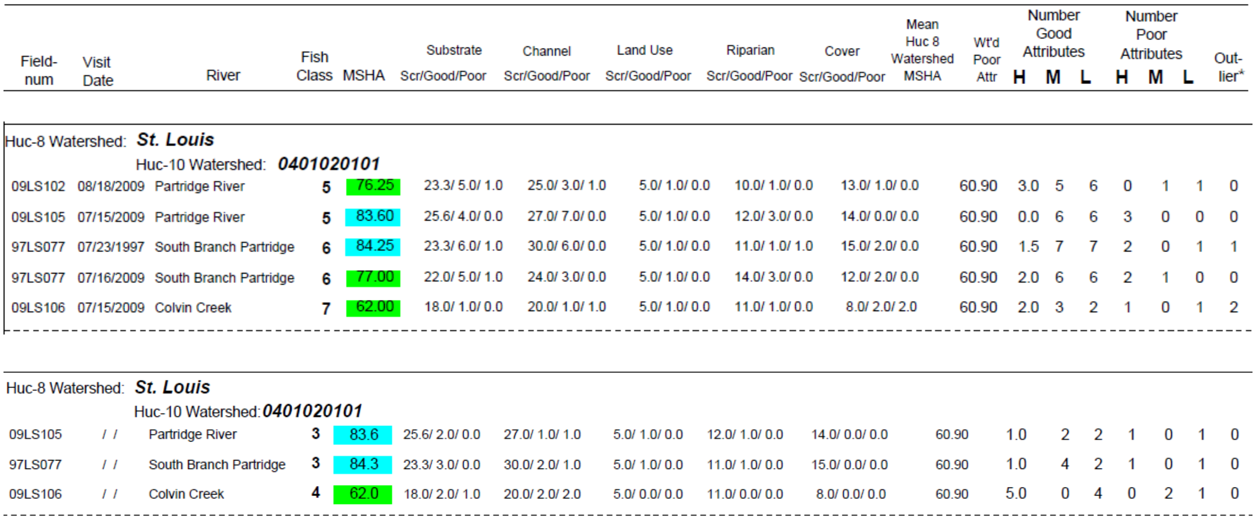
The watershed-based average MSHA and average IBI/MIBI data were strong classifying factors in identifying candidate streams for modified uses and clusters of streams where modifications of habitat may limit Class 2B uses. We produced an initial data printout organized by HUC-8 and HUC-10 watersheds that provide data on the MSHA scores, metric scores and metric attributes that will be useful in identifying candidate streams. In addition, these tables (Appendix 4 and 5) provide weighted poor habitat attribute scores and counts of the high, moderate and low influence good and poor habitat attributes. It also identified "outliers" up front where habitat scores were < 50, but FIBI or MIBI scores were above threshold values for their classification strata. **Error! Reference source not found.** provides a section of the printout for the Partridge River for the fish (top) and macroinvertebrates (bottom) and Table 57 summarized the FIBI and MIBI scores for these sites. These data represent good to excellent MSHA scores, few poor attributes, high average watershed habitat scores and have natural channels. They are in the Northern Streams and Headwater strata (fish) and the Northern Riffle/Run and Northern Glide/Pools strata (macroinvertebrates). These sites clearly have sufficient habitat to support the Class 2B aquatic life use and, without any channel modifications, would not be candidates for any modified use.

Table 57. Summary of FIBI, MIBI and MSHA scores for the Partridge River and So. Branch Partridge River in the St. Louis River basin in Minnesota.

Site Number Sample Year	Fish Classification Strata - Threshold	FIBI	Macro. Classification Strata - Threshold	MIBI	MSHA	Wt'd Negative Attributes
Partridge River						
09LS102 2009	No. Streams [48]	40[a]	-	-	76.25	3.0
09LS105 2009	No. Streams [48]	86	No. Streams Riffle/Run [50.3]	70.98	83.6	0.0
South Branch Partridge River						
97LS077 1997	No. Headw. [40]	61	No. Streams Riffle/Run [50.3]	78.26	84.3	1.0
97LS077 2009	No.Headw. [40]	61	-	-	-	-

[a] Low end scored

Figure 49. Habitat attribute table for sites in the Partridge River and South Branch Partridge, tributary in the St. Louis River watershed.



Huc-8 Watershed: **St. Louis**

Huc-10 Watershed: **0401020101**

Field-num	Visit Date	River	Fish Class	MSHA	Substrate Scr/Good/Poor	Channel Scr/Good/Poor	Land Use Scr/Good/Poor	Riparian Scr/Good/Poor	Cover Scr/Good/Poor	Mean Huc 8 Watershed MSHA	Wt'd Poor Attr	Number Good Attributes H	M	L	Number Poor Attributes H	M	L	Out-lier*
09LS102	08/18/2009	Partridge River	5	🟩 76.25	23.3/ 5.0/ 1.0	25.0/ 3.0/ 1.0	5.0/ 1.0/ 0.0	10.0/ 1.0/ 0.0	13.0/ 1.0/ 0.0	60.90	3.0	5	6	0	1	1	0	
09LS105	07/15/2009	Partridge River	5	🟦 83.60	25.6/ 4.0/ 0.0	27.0/ 7.0/ 0.0	5.0/ 1.0/ 0.0	12.0/ 3.0/ 0.0	14.0/ 0.0/ 0.0	60.90	0.0	6	6	3	0	0	0	
97LS077	07/23/1997	South Branch Partridge	6	🟦 84.25	23.3/ 6.0/ 1.0	30.0/ 6.0/ 0.0	5.0/ 1.0/ 0.0	11.0/ 1.0/ 1.0	15.0/ 2.0/ 0.0	60.90	1.5	7	7	2	0	1	1	
97LS077	07/16/2009	South Branch Partridge	6	🟩 77.00	22.0/ 5.0/ 1.0	24.0/ 3.0/ 0.0	5.0/ 1.0/ 0.0	14.0/ 3.0/ 0.0	12.0/ 2.0/ 0.0	60.90	2.0	6	6	2	1	0	0	
09LS106	07/15/2009	Colvin Creek	7	🟩 62.00	18.0/ 1.0/ 0.0	20.0/ 1.0/ 1.0	5.0/ 1.0/ 0.0	11.0/ 1.0/ 0.0	8.0/ 2.0/ 2.0	60.90	2.0	3	2	1	0	1	2	

Huc-8 Watershed: **St. Louis**

Huc-10 Watershed: **0401020101**

Field-num	Visit Date	River	Fish Class	MSHA	Substrate Scr/Good/Poor	Channel Scr/Good/Poor	Land Use Scr/Good/Poor	Riparian Scr/Good/Poor	Cover Scr/Good/Poor	Mean Huc 8 Watershed MSHA	Wt'd Poor Attr	Number Good Attributes H	M	L	Number Poor Attributes H	M	L	Out-lier*
09LS105	/ /	Partridge River	3	🟦 83.6	25.6/ 2.0/ 0.0	27.0/ 1.0/ 1.0	5.0/ 1.0/ 0.0	12.0/ 1.0/ 0.0	14.0/ 0.0/ 0.0	60.90	1.0	2	2	1	0	1	0	
97LS077	/ /	South Branch Partridge	3	🟦 84.3	23.3/ 3.0/ 0.0	30.0/ 2.0/ 1.0	5.0/ 1.0/ 0.0	11.0/ 1.0/ 0.0	15.0/ 0.0/ 0.0	60.90	1.0	4	2	1	0	1	0	
09LS106	/ /	Colvin Creek	4	🟩 62.0	18.0/ 2.0/ 1.0	20.0/ 2.0/ 2.0	5.0/ 0.0/ 0.0	11.0/ 0.0/ 0.0	8.0/ 0.0/ 0.0	60.90	5.0	0	4	0	2	1	0	

In contrast to the Partridge River is County Ditch # 6 in the Le Sueur watershed. Several of the sites have channel modifications (purple square next to MSHA score), high weighted poor habitat attributes and very poor MSHA scores and no outlier scores (Figure 50). Figure 50 provides a section of the printout for County Ditch #6 for the fish (top) and macroinvertebrates (bottom) and Table 58 summarized the FIBI and MIBI scores for these sites. Biological scores at the channelized sites are below the thresholds for the strata. The sites are classified for fish in the Southern Streams strata and for macroinvertebrates for Southern Glide/Pools strata. The modified sites on this table would be candidates for a channel modified use. As a confounding factor however, is a non-modified site also on County Ditch 6 which has a good

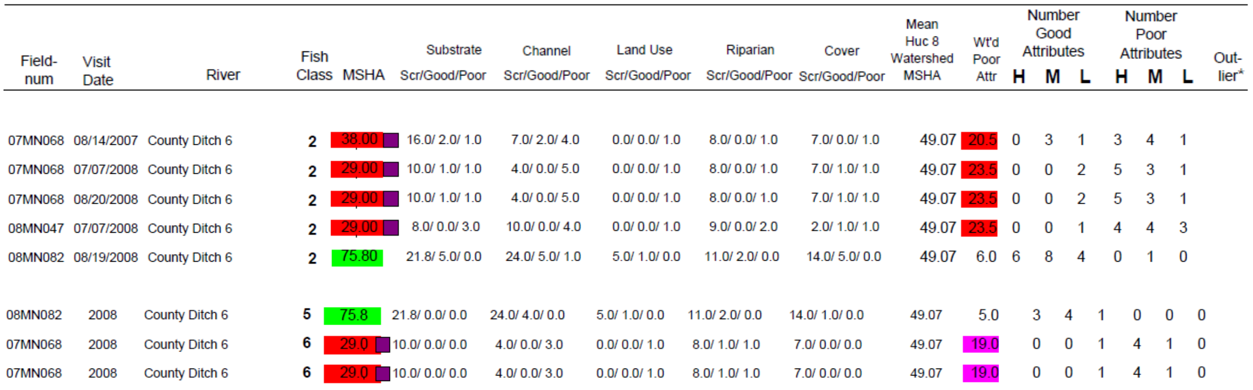
MSHA score, but is situated in fairly degraded watershed (Mean MSHA = 49). The site with good habitat has an IBI of 46 which is above the threshold [43], although the MIBI (33.36) is below the MIBI threshold [46.8].

Table 58. Summary of FIBI, MIBI and MSHA scores for the County Ditch # 6 in the Minnesota River basin in Minnesota. Underlined FIBI or MIBI scores are below the biological threshold.

Site Number Sample Year	Fish Classification Strata - Threshold	FIBI	Macro. Classification Strata - Threshold	MIBI	MSHA	Wt'd Negative Attributes
			Partridge River			
07MN068 2007	So. Streams [43]	34	-	-	38.0	20.5
07MN068 2008	So. Streams [43]	17	So. Streams Glide/Pool [46.8]	9.57	29.0	23.5
07MN068 2008	So. Streams [43]	28	-	-	29.0	23.5
08MN047 2008	So. Streams [43]	16	-	-	29.0	23.5
08MN082	So. Streams [43]	46	So. Streams Riffle/Run [46.8]	33.36	75.8	6.0

[a]Low end scored

Figure 50. Habitat attribute table for sites in County Ditch # 6, a tributary in the Le Sueur River watershed (Minnesota River basin). Upper block of data is for fish assemblage and bottom for macroinvertebrates.



Field-num	Visit Date	River	Fish Class	MSHA	Substrate Scr/Good/Poor	Channel Scr/Good/Poor	Land Use Scr/Good/Poor	Riparian Scr/Good/Poor	Cover Scr/Good/Poor	Mean Huc 8 Watershed MSHA	Wt'd Poor Attr	Number Good Attributes H	M	L	Number Poor Attributes H	M	L	Out-lier*
07MN068	08/14/2007	County Ditch 6	2	38.00	16.0/ 2.0/ 1.0	7.0/ 2.0/ 4.0	0.0/ 0.0/ 1.0	8.0/ 0.0/ 1.0	7.0/ 0.0/ 1.0	49.07	20.5	0	3	1	3	4	1	
07MN068	07/07/2008	County Ditch 6	2	29.00	10.0/ 1.0/ 1.0	4.0/ 0.0/ 5.0	0.0/ 0.0/ 1.0	8.0/ 0.0/ 1.0	7.0/ 1.0/ 1.0	49.07	23.5	0	0	2	5	3	1	
07MN068	08/20/2008	County Ditch 6	2	29.00	10.0/ 1.0/ 1.0	4.0/ 0.0/ 5.0	0.0/ 0.0/ 1.0	8.0/ 0.0/ 1.0	7.0/ 1.0/ 1.0	49.07	23.5	0	0	2	5	3	1	
08MN047	07/07/2008	County Ditch 6	2	29.00	8.0/ 0.0/ 3.0	10.0/ 0.0/ 4.0	0.0/ 0.0/ 1.0	9.0/ 0.0/ 2.0	2.0/ 1.0/ 1.0	49.07	23.5	0	0	1	4	4	3	
08MN082	08/19/2008	County Ditch 6	2	75.80	21.8/ 5.0/ 0.0	24.0/ 5.0/ 1.0	5.0/ 1.0/ 0.0	11.0/ 2.0/ 0.0	14.0/ 5.0/ 0.0	49.07	6.0	6	8	4	0	1	0	
08MN082	2008	County Ditch 6	5	75.8	21.8/ 0.0/ 0.0	24.0/ 4.0/ 0.0	5.0/ 1.0/ 0.0	11.0/ 2.0/ 0.0	14.0/ 1.0/ 0.0	49.07	5.0	3	4	1	0	0	0	
07MN068	2008	County Ditch 6	6	29.0	10.0/ 0.0/ 0.0	4.0/ 0.0/ 3.0	0.0/ 0.0/ 1.0	8.0/ 1.0/ 1.0	7.0/ 0.0/ 0.0	49.07	19.0	0	0	1	4	1	0	
07MN068	2008	County Ditch 6	6	29.0	10.0/ 0.0/ 0.0	4.0/ 0.0/ 3.0	0.0/ 0.0/ 1.0	8.0/ 1.0/ 1.0	7.0/ 0.0/ 0.0	49.07	19.0	0	0	1	4	1	0	

Several tributaries in the Whiteface River watershed provide examples of sites with multiple outlier points. Figure 51provides a section of the printout for tributaries in the Whiteface River watershed for the fish (top) and macroinvertebrates (bottom) and Table 59 summarized the FIBI and MIBI scores for these sites. These tributaries are modified and have high weighted poor habitat attribute scores and high numbers of high influence poor attributes, but three of the five sites for fish and two of four for macroinvertebrates have FIBI or MIBI sites well above the threshold. The sites are classified within the

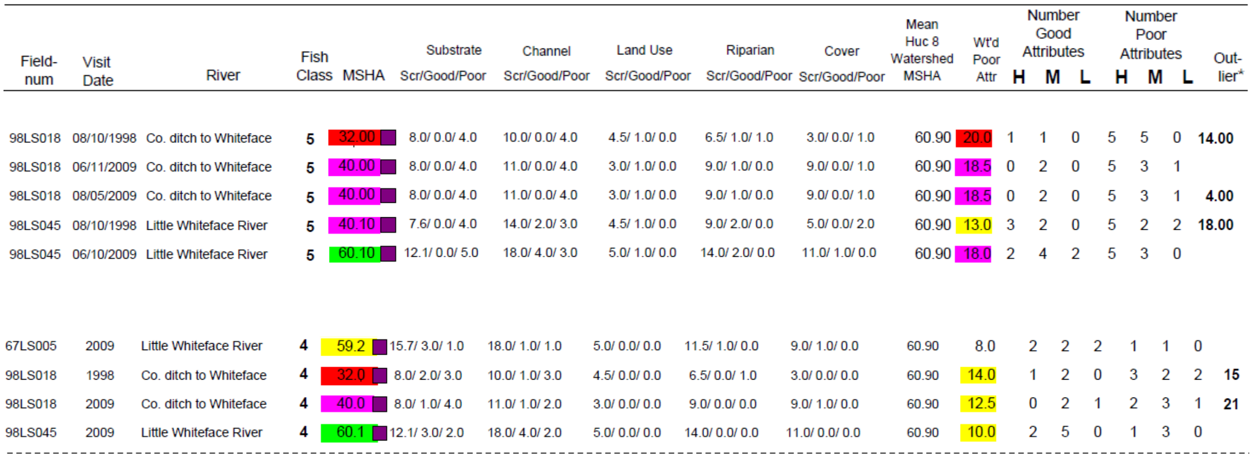
Northern Streams strata (fish) and the Northern Stream Glide/Pool strata (macroinvertebrates). Clearly some factor (*e.g.*, flow or temperature) is moderating the effects of the degraded habitat.

Table 59. Summary of FIBI, MIBI and MSHA scores for the Co. Ditch to the Whiteface River and the Little Whiteface River in Minnesota.

Site Number Sample Year	Fish Classification Strata - Threshold	FIBI	Macro. Classification Strata - Threshold	MIBI	MSHA	Wt'd Negative Attributes
Co. Ditch to the Whiteface River						
98LS018 1998	No. Streams [48]	62	No. Streams Glide/Pool [52.4]	67.9	32.0	20.0
98LS018 2009	No.Streams [48]	48	No. Streams Glide/Pool [52.4]	70.98	40	18.5
98LS018 2009	No.Streams [48]	52	-	-	40	18.5
Little Whiteface River						
98LS045 1998	No.Streams [48]	66	-	-	40.1	13.0
98LS045 2009	No.Streams [48]	45	No. Streams Glide/Pool [52.4]	56.39	60.1	18.0
98LS005 2009	-	-	No. Streams Glide/Pool [52.4]	42.06	59.2	8.0

[a] Low end scored

Figure 51. Habitat attribute table for sites in a County Ditch, and the Little Whiteface River, tributaries in the Whiteface River watersheds. Upper block of data is for fish assemblages and bottom for macroinvertebrates.



Field-num	Visit Date	River	Fish Class	MSHA	Substrate Scr/Good/Poor	Channel Scr/Good/Poor	Land Use Scr/Good/Poor	Riparian Scr/Good/Poor	Cover Scr/Good/Poor	Mean Huc 8 Watershed MSHA	Wt'd Poor Attr	Number Good Attributes			Number Poor Attributes			Out-lier*
												H	M	L	H	M	L	
98LS018	08/10/1998	Co. ditch to Whiteface	5	32.00	8.0/ 0.0/ 4.0	10.0/ 0.0/ 4.0	4.5/ 1.0/ 0.0	6.5/ 1.0/ 1.0	3.0/ 0.0/ 1.0	60.90	20.0	1	1	0	5	5	0	**14.00**
98LS018	06/11/2009	Co. ditch to Whiteface	5	40.00	8.0/ 0.0/ 4.0	11.0/ 0.0/ 4.0	3.0/ 1.0/ 0.0	9.0/ 1.0/ 0.0	9.0/ 0.0/ 1.0	60.90	18.5	0	2	0	5	3	1	
98LS018	08/05/2009	Co. ditch to Whiteface	5	40.00	8.0/ 0.0/ 4.0	11.0/ 0.0/ 4.0	3.0/ 1.0/ 0.0	9.0/ 1.0/ 0.0	9.0/ 0.0/ 1.0	60.90	18.5	0	2	0	5	3	1	**4.00**
98LS045	08/10/1998	Little Whiteface River	5	40.10	7.6/ 0.0/ 4.0	14.0/ 2.0/ 3.0	4.5/ 1.0/ 0.0	9.0/ 2.0/ 0.0	5.0/ 0.0/ 2.0	60.90	13.0	3	2	0	5	2	2	**18.00**
98LS045	06/10/2009	Little Whiteface River	5	60.10	12.1/ 0.0/ 5.0	18.0/ 4.0/ 3.0	5.0/ 1.0/ 0.0	14.0/ 2.0/ 0.0	11.0/ 1.0/ 0.0	60.90	18.0	2	4	2	5	3	0	
67LS005	2009	Little Whiteface River	4	59.2	15.7/ 3.0/ 1.0	18.0/ 1.0/ 1.0	5.0/ 0.0/ 0.0	11.5/ 1.0/ 0.0	9.0/ 1.0/ 0.0	60.90	8.0	2	2	2	1	1	0	
98LS018	1998	Co. ditch to Whiteface	4	32.0	8.0/ 2.0/ 3.0	10.0/ 1.0/ 3.0	4.5/ 0.0/ 0.0	6.5/ 0.0/ 1.0	3.0/ 0.0/ 0.0	60.90	14.0	1	2	0	3	2	2	**15**
98LS018	2009	Co. ditch to Whiteface	4	40.0	8.0/ 1.0/ 4.0	11.0/ 1.0/ 2.0	3.0/ 0.0/ 0.0	9.0/ 0.0/ 0.0	9.0/ 1.0/ 0.0	60.90	12.5	0	2	1	2	3	1	**21**
98LS045	2009	Little Whiteface River	4	60.1	12.1/ 3.0/ 2.0	18.0/ 4.0/ 2.0	5.0/ 0.0/ 0.0	14.0/ 0.0/ 0.0	11.0/ 0.0/ 0.0	60.90	10.0	2	5	0	1	3	0	

The number of poor attributes and the plots that identify the probability of attaining a Class 2B aquatic life use can be combined with data on watershed location and average MSHA scores to select candidates for channel modified uses. Examination of the biological attributes is also a useful tool in estimating the limitations of habitat impacts from channel modifications. In Ohio, channel modifications have a specific influence on populations of sensitive and intolerant fish species. While many of these species are sensitive to a wide range of stressors they are often particularly sensitive to habitat stressors. Many are fluvial specialists or fluvial dependents and decline where channelization has exacerbated low flow conditions. This may also explain why streams with high base flows may act as outliers from the effects of channel modifications. Other sensitive species are simple lithophilic spawners and are susceptible to siltation and sedimentation that often results from channel disturbance. High MSHA channel scores are typically associated with high MSHA substrates scores (Figure 28), but degraded channels can have poor substrates, a pattern we have also seen in Ohio streams (Figure 29).

The watershed average MSHA used in this system of weighted good and poor attribute scores was calculated at the HUC-8 watershed scale because this was the scale where data was most available. A perusal of Appendices 4 and 5 indicate variability within HUC-8 watersheds because of their size. We suggest that where data is available the spatial extent of habitat loss should be considered at the HUC-10 and HUC-12 scales.

The results presented here are meant as a coarse focus for conducting UAAs and expect that local stressor data and biological responses will be incorporated into a stressor identification process that is at the core of the UAA process. Performed in a “biocentric” manner, incorporating data on biological responses and on the feasibility of stream restoration should not create an onerous process for conducting UAAs. Minnesota has a mix of warmwater and coldwater systems which can be nearby one another and may confound this process and explain some of the variability in the relationships between habitat attributes and biological potential. We expect that applying the variables we derived here to specific streams and subwatersheds can help to refine thresholds for identifying modified aquatic life uses and exceptions or outliers to the process.

A companion effort to the identification of modified waters is the derivation of biocriteria for these waters. Modified aquatic life uses should have baseline biological expectations associated with managing such streams with best management practices for ditches. While this may seem to be an oxymoron, maximizing the ecological functions of even habitat limited waters can have downstream benefits related to control of erosion, nutrients and flow. Many states develop stream management guidelines that provide both minimum and better stream management practices that should be compatible with biological baselines developed for such streams. As stream restoration practice improves over time, such efforts can be used to improve ecological conditions in streams and to provide a basis for exploring new practices that can further enhance or perhaps even restore streams to CWA conditions while maintaining economic viability.

References

Aadland, L.P. 1993. Stream habitat types: Their fish assemblages and relationship to flow. North American Journal of Fisheries Management 13(4): 790-806.

Alford, J.B. 2014. Multi-scale assessment of habitats and stressors influencing stream fish assemblages in the Lake Pontchartrain Basin, USA. Hydrobiologia DOI 10.1007/s10750-014-1925-2.

Allan, J.D. 2004. Landscapes and riverscapes: the influence of land use on stream ecosystems. Annual Review of Ecology, Evolution, and Systematics. 35: 257-284.

Allan, J.D. 2007. Stream ecology: structure and function of running waters. Springer, New York, New York.

Angermeier, P.L. and J.R. Karr. 1984. Relationships between woody debris and fish habitat in a small warmwater stream. Transactions of the American Fisheries Society 113(6): 716-726.

Armitage, B.J., R. Mueller and E.T. Rankin. 2009. An Assessment of Threats to the Biological Condition of the Wabash River Aquatic Ecosystem of Indiana. In Two Parts. Prepared for The Indiana Nature Conservancy, Indianapolis, IN.

Arthington, A.H., S.E. Bunn, N.L. Poff, and R.J. Naiman. 2006. The challenge of providing environmental flow rules to sustain river ecosystems. Ecological Applications 16:1311-1318.

Bauer, S.B. and S.C. Ralph, 1999. Aquatic Habitat Indicators and their Application to Water Quality Objectives within the Clean Water Act. EPA-910-R-99-014, U.S. Environmental Protection Agency, Region 10, Seattle Washington.

Bauer, S.B. and S.C. Ralph. 2001. Strengthening the Use of Aquatic Habitat Indicators in the Clean Water Act Programs. Fisheries 26(6):14-25.

Baxter, R.M. 1977. Environmental effects of dams and impoundments. Annual Review of Ecology and Systematics 8:255-283.

Benke A.C. & J.B. Wallace. 2003. Influence of wood on invertebrate communities in streams and rivers. pp. 149-177. In The ecology and management of wood in world rivers. S. V. Gregory, K. L. Boyer & A. M. Gurnell (eds.). American Fisheries Society, Bethesda, MD.

Berkman, H.E., and F. Rabeni. 1987. Effect of siltation on stream fish communities. Environmental Biology of Fishes 18(4): 285 - 294.

Bernhardt, E.S., M.A. Palmer, J.D. Allan, G. Alexander, K. Barnas, S. Brooks, J. Carr, S. Clayton, C. Dahm, J. Follstad-Shah, D. Galat, S. Gloss, P. Goodwin, D. Hart, B. Hassett, R. Jankinson, S. Katz, G.M. Kondolf, P.S. Lake, R. Lave, J.L. Meyer, T.K. O'Donnell, L. Pagano, B. Powell, and E. Sudduth. 2005. Synthesizing U.S. river restoration efforts. Science 308:636–637.

Bey, C. and S.M.P. Sullivan. 2015. Associations between stream hydrogeomorphology and codependent mussel-fish assemblages: evidence from an Ohio, USA river system. Aquatic Conservation: Marine and Freshwater Ecosystems 25: 555-568.

Bond, N.R. and P.S. Lake. 2005. Ecological restoration and large-scale ecological disturbance: The effect of drought on the response by fish to a habitat restoration experiment. Restoration Ecology 13, no. 1:39-48.

Brazner, J.C., D.K. Tanner, N.E. Detenbeck, S.L. Batterman, S.L. Stark, L.A Jagger and V.M. Snarski.2005. Regional, watershed, and site-specific environmental influences on fish assemblage structure and function in western Lake Superior tributaries. Canadian Journal of Fisheries and Aquatic Sciences 62(6): 1254-1270.

Brooks, S.S., M.A. Palmer, B.J. Cardinale, C.M. Swan and S. Ribblett. 2002. Assessing stream ecosystem rehabilitation: limitations of community structure data. Restoration Ecology 10:156-168.

Christensen, V.G., K.E. Lee, J.M. McLees and S.L. Niemela. 2012. Relations between retired agricultural land, water quality, and aquatic-community health, Minnesota River Basin. Journal of Environmental Quality 41:1459-1472.

Cole, K.L., Guntenspergen, G., Davis, M.B. and K. Walker. 1998. Historical Landcover Changes in the Great Lakes Region, Chapter 6 in Sisk, T.D., editor. 1998. Perspectives on the land-use history of North America: a context for understanding our changing environment. U.S. Geological Survey, Biological Resources Division, Biological Science Report USGS/BRD/BSR-1998-0003. 104pp

Davidson, S.L. and B.C. Eaton. 2013. Modeling channel morphodynamic response to variations in large wood: Implications for stream rehabilitation in degraded watersheds. Geomorphology 202(15): 59–73.

Davies, S.P. and S.K. Jackson. 2006. The biological condition gradient: A descriptive model for interpreting change in aquatic ecosystems. Ecological Applications 16: 1251-1266.

De'ath, G. and K.E. Fabricius. 2000. Classification and regression trees: a powerful yet simple technique for ecological data analysis. Ecology 81(11): 3178–3192.

Emerson, J.W. 1971. Channelization: a case study. Science 173:325–326.

Engstrom, D.R., Almendinger, J.E., and J.A. Wolin. 2009. Historical changes in sediment and phosphorus loading to the upper Mississippi River: mass-balance reconstructions from the sediments of Lake Pepin. Journal of Paleolimnology 41:563–588.

Fischer, J.R., and P. Paukert. 2008. Habitat relationships with fish assemblages in minimally disturbed Great Plains regions. Ecology of Freshwater Fish 17(4): 597-609.

Gammon, J.R. 1998. The Wabash River Ecosystem. Indiana University Press, Bloomington: 250 pp.

Gerritsen, J., L. Zheng, E. Leppo, and C.O. Yoder. 2013. Calibration of the biological condition gradient for streams of Minnesota. Prepared for the Minnesota Pollution Control Agency, St. Paul, MN.

Gorman O.T., Karr J.R. 1978. Habitat structure and stream fish communities. Ecology 59: 507–515

Hannaford, M.J., M.T. Barbour, and V.H. Resh. 1997. Training reduces observer variability in visual-based assessments of stream habitat. Journal of the North American Benthological Society 16(4):853-860.

Heatherly I.I., T., M.R. Whiles, T.V. and M.B. David. 2007. Relationships between water quality, habitat quality, and macroinvertebrate assemblages in Illinois streams. Journal of Environmental Quality 36:1653–1660.

Hrodey, P.J., T.M. Sutton, E.A. Frimpong, and T.P. Simon. 2009. Land-use Impacts on Watershed Health and Integrity in Indiana Warmwater Streams. The American Midland Naturalist 161(1): 76-95.

Jennings, C.A., and J. Zigler. 2000. Ecology and biology of paddlefish in North America: historical perspectives, management approaches, and research priorities. Reviews in Fish Biology and Fisheries 10(2): 167-181.

Kaufmann, P.R., E.G. Levine, E.G. Robison, C. Seeliger, and D.V. Peck. 1999. Quantifying Physical Habitat in Wadeable Streams. EPA ⁄ 620 ⁄ R-99 ⁄ 003. U.S. Environmental Protection Agency, Washington, D.C., 102 pp.

Kennedy, T.L. and T.F. Turner. 2011. River channelization reduces nutrient flow and macroinvertebrate diversity at the aquatic terrestrial transition zone. Ecosphere 2(3): 1-13.

Lancaster, J. and A.G. Hildrew. 1993. Flow refugia and the microdistribution of lotic macroinvertebrates. Journal of the North American Benthological Society 12(4):385-393.

Lau, J.K., T.E. Lauer, and M.L. Weinman. 2006. Impacts of Channelization on Stream Habitats and Associated Fish Assemblages in East Central Indiana. The American Midland Naturalist 156(2): 319-330.

Lowe, W.H., G.E. Likens, M.E. Power. 2006. Linking Scales in Stream Ecology. BioScience 56(7):591-597.

Maddock, I. 1999. The importance of physical habitat assessment for evaluating river health. Freshwater Biology 41: 373–391.

Madejczyk, J.C., N.D. Mundahl, and R.M. Lehtinen. 1998. Fish Assemblages of Natural and Artificial Habitats within the Channel Border of the Upper Mississippi River. The American Midland Naturalist 139(2): 296-310.

Miltner, R.J. and E.T. Rankin. 2009. Analysis of National Wadeable Stream Survey Results in Region V: 2004-5. Prepared by: Midwest Biodiversity Institute for U.S. EPA, Region V, Water Division, 77

W. Jackson Blvd., Chicago, IL 60605 and U.S. EPA, Office of Wetlands, Oceans, and Watersheds, Ariel Rios Building, 1200 Pennsylvania Avenue, N. W., Washington, DC 20460.

MPCA. 2000. MPCA Invertebrate Sampling Procedures. Minnesota Pollution Control Agency. Division of Water Quality. EMAP-SOP4, Rev. 0. Minneapolis, MN.

MPCA. 2009a. MPCA stream habitat assessment (MSHA) protocol for stream monitoring sites. Minnesota Pollution Control Agency. Biological Monitoring Program, Minneapolis, MN.

MPCA. 2009b. Fish community sampling protocol for stream monitoring sites. Minnesota Pollution Control Agency. Biological Monitoring Program. Minneapolis, MN.

MPCA. 2014a. Development of fish indices of biological integrity (FIBI) for Minnesota rivers and streams. Minnesota Pollution Control Agency, St. Paul, MN (Available from: Minnesota Pollution Control Agency, 520 Lafayette Road North, St. Paul, MN 55155-4194, USA).

MPCA. 2014b. Development of macroinvertebrate indices of biological integrity (MIBI) for Minnesota streams. Minnesota Pollution Control Agency, St. Paul, MN (Available from: Minnesota Pollution Control Agency, 520 Lafayette Road North, St. Paul, MN 55155-4194, USA).

MPCA. 2015. Technical guidance for reviewing and designating tiered aquatic life uses in Minnesota streams and rivers – Draft. Minnesota Pollution Control Agency, 520 Lafayette Road North, St. Paul, MN 55155-4194.

MPCA. 2016. Development of a Human Disturbance Score (HDS) for Minnesota streams. Minnesota Pollution Control Agency, 520 Lafayette Road North, St. Paul, MN 55155-4194.

Pollution Control Agency Neff, B.P., S.M. Day, A.R. Piggott, and L.M. Fuller. 2005. Base Flow in the Great Lakes Basin: U.S. Geological Survey Scientific Investigations Report 2005-5217, 23 p.

Nerbonne, B.A. and B. Vondracek. 2001. Effects of local land use on physical habitat, benthic macroinvertebrates, and fish in the Whitewater River, Minnesota, USA. Environmental Management 28(1): 87-99.

Ohio EPA. 2011. Biological and water quality study of the upper Great Miami River and selected tributaries, 2008; Auglaize, Mercer, Logan, Shelby, Champaign, and Darke Counties, Ohio, Jan 1, 2011, Ohio Environmental Protection Agency, Division of Surface Water, OHIO EPA Technical Report EAS/ EAS/2011-1-1.

Palmer, M.A., H.L. Menninger and E. Bernhardt. River restoration, habitat heterogeneity and biodiversity: a failure of theory or practice? Freshwater Biology 55 (Suppl. 1): 205–222.

Pasternack G.B., Bounrisavong M.K., Parikh K.K. 2008. Backwater control on riffle – pool hydraulics, fish habitat quality, and sediment transport regime in gravel-bed rivers. Journal of Hydrology 357: 125 – 139. DOI: 10.1016/j.jhydrol.2008.05.014

Peacock, E., W.R. Haag, and M.L. Warren. 2005. Prehistoric Decline in Freshwater Mussels Coincident with the Advent of Maize Agriculture. Conservation Biology 19(2): 547-551.

Pease, A.A., J.M. Taylor, K.O. Winemiller and R.S. King. 2011. Multiscale environmental influences on fish assemblage structure in Central Texas streams. Transactions of the American Fisheries Society 140: 1409–1427.

Poole, G.C., C.A. Frissell, and S.C. Ralph. 1997. In-stream habitat unit classification: inadequacies for monitoring and some consequences for management. Journal American Water Resource Association 33(4):879-896.

Pulliam, H.R. 1988. Sources, sinks, and population regulation. American Naturalist 132: 652

Pyron, M. and K. Neumann. 2008. Hydrologic alterations in the Wabash River watershed. River Research and Applications 24:1175-1184.

Rabeni, C.F., and A. Smale. 1995. Effects of siltation on stream fishes and the potential mitigating role of the buffering riparian zone. Hydrobiologia 303(1-3): 211 - 219.

Radinger J., C. Wolter, and J. Kail. 2015. Spatial Scaling of Environmental Variables Improves Species-Habitat Models of Fishes in a Small, Sand-Bed Lowland River. PLoS ONE 10(11): e0142813. doi: 10.1371/journal.pone.0142813

Rankin E.T. 1986. Habitat selection by smallmouth bass in response to physical characteristics in a natural stream. Transactions of the American Fisheries Society 115: 322-334.

Rankin E. 1989. The Qualitative Habitat Evaluation Index [QHEI]: Rationale, methods, and application. Ohio Environmental Protection Agency, Columbus, OH.

Rankin E.T. 1995. Habitat indices in water resource quality assessments. pp. 181-208. In: Biological assessment and criteria: Tools for water resource planning and decision making. W. S. Davis & T. P. Simon (eds.) Lewis Publishers, Boca Raton, FL.

Rashleigh, B. and J.G. Kennen. 2003. Beyond the indices: relations of habitat and fish characteristics in the Georgia Piedmont. Proceedings of the 2003 Georgia Water Resources Conference, held April 23-24, 2003, at the University of Georgia.

Richards, C., L.B. Johnson and G.E. Host. 1996. Landscape-scale influences on stream habitats and biota. Canadian Journal of Fisheries and Aquatic Sciences 53(S1): 295-311.

Roni, P., K. Hanson, and T. Beechie. 2008. Global review of physical and biological effectiveness of stream habitat rehabilitation techniques. North American Journal of Fisheries Management 28:856–890.

Roper, B.B., and D.L. Scarnecchia. 1995. Observer variability in classifying habitat types in stream surveys: North American Journal of Fisheries Management 15(1): 49–53.

Sandberg, J. 2008 Draft. A Fish Community-Based Classification Framework For Minnesota's Streams and Rivers, MPCA Northern Biological Monitoring Unit, MPCA, December, 2008.

Schlosser, I.J 1982. Fish community structure and function along two habitat gradients in a headwater stream. Ecological Monographs 52(4): 395-414.

Schlosser, I.J. 1991. Stream fish ecology: A landscape perspective. BioScience 41(10): 704-712.

Schwendel, A.C., R.G. Death, I.C. Fuller and M.K. Joy. 2011. Linking disturbance and stream invertebrate communities: how best to measure bed stability. Journal of the North American Benthological Society 30(1): 11-24.

Smith, P.W. 1979. The Fishes of Illinois. Univ. Illinois Press, Urbana. 314 pp.

Santhi, C., P.M. Allen, R.S. Muttiah, J.G. Arnold, and P. Tuppad. 2008. Regional estimation of base flow for the conterminous United States by hydrologic landscape regions. Journal of Hydrology 351: 139–153.

Simon, T.P. and C.C. Morris. 2009. Associated use attainment response between multiple aquatic assemblage indicators for evaluating catchment, habitat, water quality, and contaminants. Journal of Ecosystems, Volume 2014: 1-15.

Sisk, T.D., editor. 1998. Perspectives on the land-use history of North America: a context for understanding our changing environment. U.S. Geological Survey, Biological Resources Division, Biological Science Report USGS/BRD/BSR-1998-0003. 104pp

Smock, L.A., G.M. Metzler, and J.E. Gladden. 1989. Role of debris dams in the structure and functioning of low gradient headwater streams. Ecology 70:764–775.

Somerville, D.E. and B.A. Pruitt. 2004. Physical Stream Assessment: A Review of Selected Protocols for Use in the Clean Water Act Section 404 Program. September 2004, Prepared for the U.S. Environmental Protection Agency, Office of Wetlands, Oceans, and Watersheds, Wetlands Division (Order No. 3W-0503- NATX). Washington, D.C. 213 pp.

Sutherland A.B., J.L. Meyer & E.P. Gardiner. 2002. Effects of land cover on sediment regime and fish assemblage structure in four southern Appalachian streams. Freshwater Biology 47: 1791-1805.

Stoddard, J.L., P. Larsen, C.P. Hawkins, R.K. Johnson, and R.H. Norris. 2006. Setting expectations for the ecological condition of running waters: the concept of reference condition. Ecological Applications 16:1267-1276.

Sullivan, S.M.P. and M.C. Watzin. 2010. Towards a functional understanding of the effects of sediment aggradation on stream fish condition. River Research and Application. 26:1298-1314.

Sutherland, A.B., J.L. Meyer, and E.P. Gardiner 2002. Effects of land cover on sediment regime and fish assemblage structure in four southern Appalachian streams. Freshwater Biology 47(9): 1791-1805.

Tiemann, J.S., H.R. Dodd, N. Owens, and D.H. Wahl 2007. Effects of lowhead dams on Unionids in the Fox River, Illinois. Northeastern Naturalist 14(1): 125-138.

Trautman, M.B., 1981. The Fishes of Ohio. The Ohio State University Press, Columbus: 782 pp.

Vandermeer, J., I. Perfecto, and N. Schellhorn. 2010. Propagating sinks, ephemeral sources and percolating mosaics: conservation in landscapes. Landscape Ecology 25(4): 509 - 518.

Waits, E.R., M.J. Bagley, M.J. Blum, F.H. McCormick and J.M. Lazorchak. 2006. Source–sink dynamics sustain central stonerollers (*Campostoma anomalum*) in a heavily urbanized catchment. Freshwater Biology 53: 2061–2075.

Waters, T.F. 1995. Sediment in streams: sources, biological effects, and control. American Fisheries Society, Monograph 7, Bethesda, Maryland.

Wallace, J.B., J.R. Webster, and J.L. Meyer. 1995. Influence of log additions on physical and biotic characteristics of a mountain stream. Canadian Journal of Fisheries and Aquatic Sciences 52: 2120–2137.

Wang, L., J. Lyons, P. Kanehl and R. Gatti. 1997. Influences of watershed land use on habitat quality and biotic integrity in Wisconsin streams. Fisheries 22(6): 6-12.

Wang, L., J. Lyons, P. Rasmussen, P. Seelbach, T. Simon, M. Wiley, P. Kanehl, E. Baker, S. Niemela and P. M. Stewart. 2003. Watershed, reach, and riparian influences on stream fish assemblages in the Northern Lakes and Forest Ecoregion, U.S.A. Canadian Journal of Fisheries and Aquatic Sciences 60(5): 491-505.

Wang, L., J. Lyons, and P. Kanehl. 2006. Habitat and fish responses to multiple agricultural best management practices in a warm water stream. Journal of the American Water Resources Association 42(4): 1047-1062.

Weigel, B.M., J. Lyons, and P.W. Rasmussen. 2006. Fish assemblages and biotic integrity of a highly modified floodplain river, the Upper Mississippi, and a large, relatively unimpacted tributary, the Lower Wisconsin. River Research and Applications 22(8): 923 - 936.

Wiens, J.A., N.C. Stenseth, B. Van Horne, and R.A. Ims. 1993. Ecological mechanisms and landscape ecology. Oikos 66: 369-380.

Whitacre, H.W., B.B. Roper, and J.L. Kershner. 2007. A Comparison of Protocols and Observer Precision for Measuring Physical Stream Attributes. Journal of the American Water Resources Association 43(4):923-937.

Yang C.T. 1971. Formation of riffles and pools. Water Resources Research 7: 1567–1574. DOI: 10.1029/WR007i006p01567

Yoder, C.O. and 9 others. 2005. Changes in fish assemblage status in Ohio’s nonwadeable rivers and streams over two decades, pp. 399-429. in R. Hughes and J. Rinne (eds.). Historical changes in fish assemblages of large rivers in the America’s. American Fisheries Society Symposium Series.

Yoder, C.O. and E.T. Rankin. 1999. Biological criteria for water resource management, pp. 227-259. in P.C. Schulze and R.A. Frosch (eds.). Measures of Environmental Performance and Ecosystem Condition. National Academy of Engineering, National Academy Press, Washington, DC.