Identifying Healthy Watersheds in Wisconsin

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1 Introduction

1.1 The Healthy Watersheds Initiative

The U.S. Environmental Protection Agency (US EPA) launched the Healthy Watersheds Initiative to protect and maintain our nation's remaining healthy watersheds having natural, intact aquatic ecosystems; prevent them from becoming impaired; and accelerate restoration successes. This initiative is being implemented by promoting a strategic, systems approach to identify and protect healthy watersheds based on integrated assessments of habitat, biotic communities, water chemistry, and watershed processes such as hydrology, fluvial geomorphology, and natural disturbance regimes. Once healthy watersheds or healthy components of watersheds are identified, priorities can be set for protection and restoration, with the best chances of recovery likely to be in waters near existing healthy aquatic ecosystems (Sundermann, Stol, & Haase, 2011).

A healthy watershed is defined as one in which natural land cover supports dynamic hydrologic and geomorphic processes within their natural range of variation; habitat of sufficient size and connectivity supports native aquatic and riparian species; and water quality supports healthy biological communities. An interconnected network of natural land cover throughout a watershed, and especially in the riparian zone, provides critical habitat and supports maintenance of the natural flow regime and fluctuations in water levels. It also helps to maintain natural geomorphic processes, such as sediment storage and deposition, which form the basis of aquatic habitats. Connectivity of aquatic and riparian habitats, in the longitudinal, lateral, vertical, and temporal dimensions helps to ensure that biotic refugia are available during floods, droughts, and other extreme events.

The oft-repeated objective of the Clean Water Act is "to restore and maintain the chemical, physical, and biological integrity of the nation's waters." The Healthy Watersheds Initiative expands these three domains to call explicit attention to the hydrologic, geomorphic, and habitat attributes, in addition to the traditional chemical and biological attributes. Further, it places all of these attributes in a landscape context. This is important because, in addition to climate, landscape condition is one of the fundamental drivers of aquatic ecosystem integrity and, from a practical standpoint, landscape condition is the primary driver that watershed managers are able to exert some influence on improving or maintaining.

A typical viewpoint of aquatic ecosystems is that biological condition is the ultimate integrator of all other processes occurring in a watershed. While this is true, it can lead to assessment and management practices that ignore or deemphasize the importance of other attributes. Geomorphic condition, for example, has importance beyond the role it plays in forming habitat suitable for macroinvertebrate or fish species. An unstable stream channel can have disastrous consequences for riparian property owners. Similarly, hydrologic alteration has far-reaching impacts on supply of drinking water and irrigation water, and on flood impacts to local communities. Landscape condition impacts not only aquatic ecosystems, but terrestrial ecosystems supporting a whole array of organisms not under the traditional purview of water resource agencies, as well as recreational pursuits entirely separate from aquatic resources. The Healthy Watersheds Initiative, while acknowledging the importance of biological integrity, also places emphasis on these other attributes that have inherent importance and value beyond their role in maintaining biological integrity.

1.2 Identifying Healthy Watersheds in Wisconsin

Wisconsin contains a diversity of land and water resources that support public health, recreation, and the local economy. Degradation of these ecological resources inevitably leads to a diminished capacity to support the many services they provide. In recognition of these ecosystem services, and presented with the challenge of repairing thousands of miles of impaired streams and rivers, Wisconsin has invested heavily in the restoration of its aquatic resources. Equally critical to Wisconsin's future, however, is protection of its remaining miles of healthy streams and rivers. Without adequate protection, these streams may also become impaired and add to the financial and ecological burden that has proven so difficult to escape.

The US EPA funded an effort to provide the State's Department of Natural Resources (DNR) with technical support in conducting an integrated assessment to identify healthy watersheds throughout Wisconsin. This integrated approach incorporates multiple elements of ecological integrity and their interconnections. These include: 1) landscape condition, 2) habitat, 3) hydrology, 4) geomorphology, 5) water quality, and 6) biological condition. The goal of the Wisconsin Healthy Watersheds Assessment is to produce an aggregated analysis of whole system conditions based on these six elements. The Wisconsin Healthy Watersheds Assessment builds on previous work and uses existing data to demonstrate the linkages between aquatic ecosystem components and the landscape of which they are a part.

In October 2012, a three-day workshop was held with members of the project team[1] to select indicators to be used in the assessment and to discuss methods of analysis and reporting. Some indicators, primarily those that are measured with remote sensing methods, have data available in every watershed while others, such as field data, have data at just a few hundred sites throughout the state. Therefore, statistical methods were used to identify those indicators of watershed condition that are most important for driving aquatic ecosystem health and to develop predictive models. A multimetric index of watershed health was then constructed along with a watershed vulnerability index to identify opportunities for protection and restoration across the state. A roadmap of the healthy watersheds assessment process is presented in Figure 1.

[1] The project team consists of staff from Wisconsin DNR, EPA, and The Nature Conservancy.

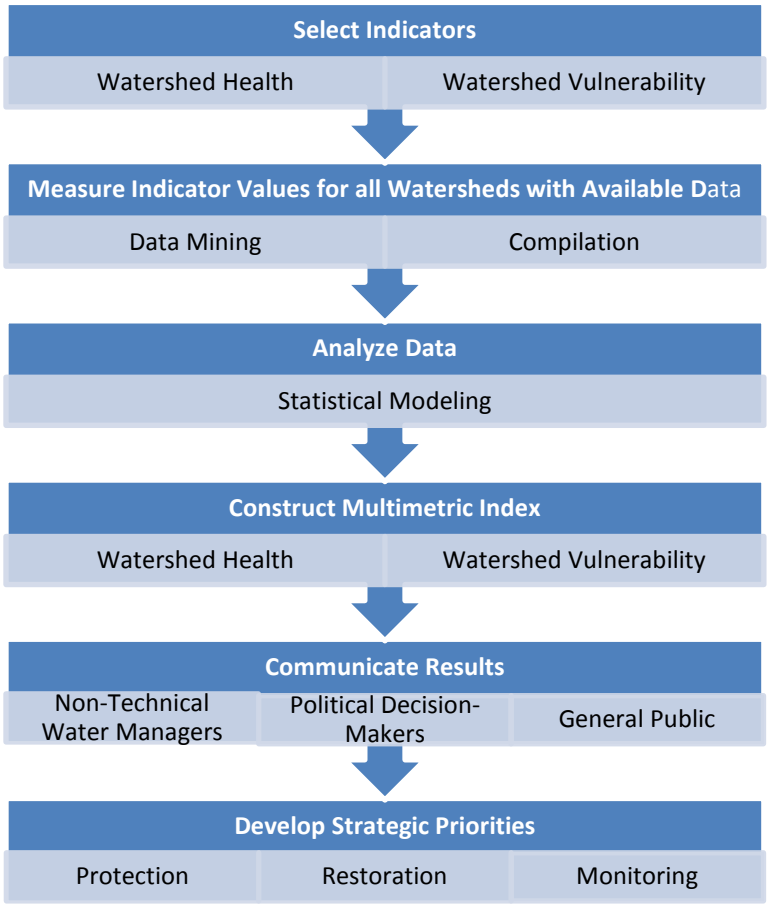

Figure 1 Roadmap of Wisconsin Healthy Watersheds Integrated Assessment.

2 Methods Overview

2.1 Indicator Selection & Modeling

A holistic evaluation of watershed health uses a framework that emphasizes the dynamic relationships between landscape drivers and aquatic responses. Landscape drivers are natural features of the earth's surface that respond to climatic effects (precipitation and temperature) to form streams, lakes, and wetlands. Critical landscape drivers of aquatic ecosystem conditions include:

- Slope
- Elevation
- Soils
- Geology
- Vegetation
- Drainage Area

The natural variability of these landscape drivers contribute to the diversity of aquatic ecosystems. They create the physical (i.e., hydrologic and geomorphic) and chemical conditions that biological organisms have evolved within and require for continued survival. Anthropogenic modifications to landscape drivers often result in changes to hydrologic, geomorphic, or chemical conditions, resulting in degradation of the biological community. Such modifications include:

- Impoundment of natural water courses (i.e., dam construction)
- Land cover alterations (i.e., urbanization and agricultural development)
- Surface and ground water withdrawals

Aquatic ecosystems exist within the context of landscape drivers and anthropogenic modifications. The health of aquatic ecosystems can be measured in terms of water chemistry, natural hydrologic regimes, geomorphic condition, habitat, and biological integrity. Measurement of these attributes often occurs at a specific point location on the landscape and represents a snapshot in space and time. Landscape condition, on the other hand, is most often evaluated using data collected via remote sensing techniques, and has data available for every watershed in the state. Indicators represent the relative condition of watershed and aquatic ecosystem attributes, and can be calculated from both remote sensing and field-collected data. Indicators that do not have data available statewide must have the potential to be potential to be modeled. Taking into consideration data availability, quality, and relevance to the project objective of identifying and characterizing healthy watersheds in Wisconsin, the project team selected the indicators of watershed health to be used in this assessment (Figure 2).

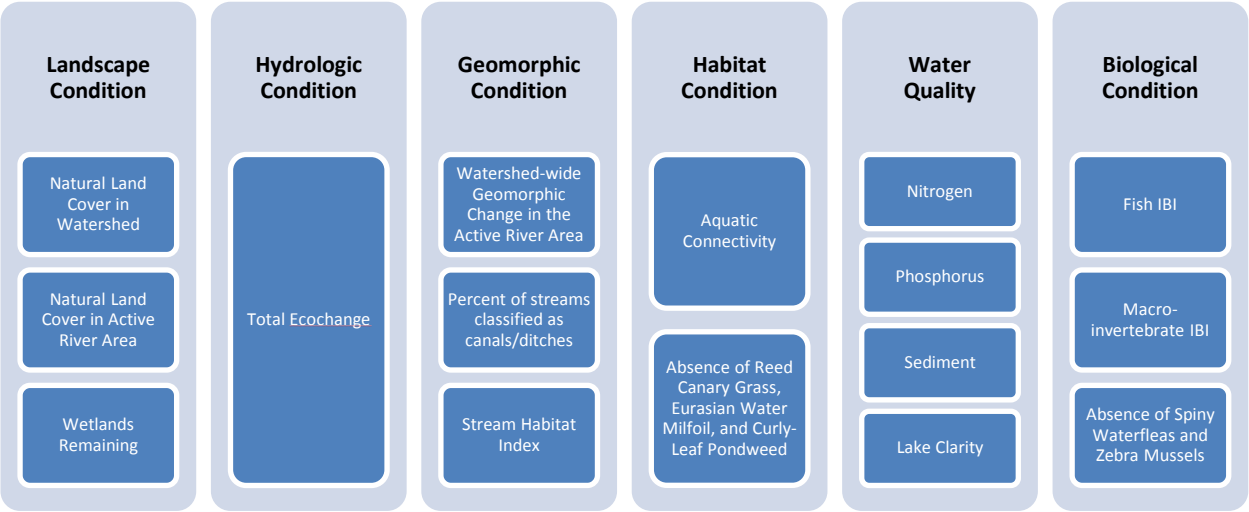

Figure 2 Indicators of Watershed Health.

Modeling is necessary because state monitoring programs do not have the resources necessary to monitor every single stream or watershed in their jurisdiction. In addition to helping to fill data gaps, models also allow us to examine the complex relationships between ecological characteristics. An example of a modeling approach is to use regression techniques to relate watershed characteristics for which data are available statewide to instream characteristics for which data are only available at discrete monitoring locations (e.g., water chemistry, fish, macroinvertebrates, streamflow). Previous

work in Wisconsin has used such approaches to estimate Indices of Biotic Integrity (IBI) for both fish (John Lyons, Personal Communication) and macroinvertebrates (Weigel, 2003) and to estimate sediment, nitrogen, and phosphorus loads across the state (Diebel, Freihoefer, Hook, Kirsch, Nelson, & Xiaochun, 2011). Similarly, modeled flow duration curves have recently been developed for streams and river in Wisconsin using multiple linear regression based on watershed characteristics (Matt Diebel, Personal Communication). For the Wisconsin Healthy Watersheds Assessment, landscape predictive models were developed using boosted regression tree (BRT) techniques to estimate specific parameters that cannot otherwise be represented at the watershed scale statewide. Biological, chemical, and habitat data from DNR's field monitoring sites were used to build the models, with 25% of the data set aside for model validation and 25% set aside for final model testing.

Modeling the biological, chemical, habitat, and hydrologic parameters provides estimates for evaluating watershed health, and quantifies the influence of watershed characteristics that drive aquatic ecosystem health. Ultimately, these watershed characteristics are the management targets for protecting and restoring aquatic ecosystems. Another advantage to statistical models is that they quantify the amount of error associated with the parameter being estimated.

In the absence of field-collected data, the landscape predictive models were used to generate predicted values of macroinvertebrate IBIs, fish IBIs, stream habitat, phosphorous, nitrogen, and sediment at the outlet of each catchment. In addition, Wisconsin DNR has recently developed predicted flow duration curves for both pre-settlement and current conditions at the outlet of each catchment. The relative influence of 'local' watershed characteristics and 'upstream' watershed characteristics on all predicted values are also quantified. Landscape, and other habitat and geomorphology indicators come from remotely sensed data and therefore do not require predictive models. The watershed health indicators for each of the six healthy watersheds attributes are summarized in Figure 2 and are discussed in greater depth below.

A database developed by Wisconsin DNR contains 997 stream, riparian, and watershed attributes for all 162,651 high resolution stream reaches and catchments in the state. An additional 70 attributes were calculated and added to this database for use in developing statistical models and calculating indicators of watershed health for use in the assessment. These indicators are listed in Appendix A. A high-resolution (1:24,000) stream network, and associated catchment delineations, were provided by DNR and are an essential dataset for conducting the analyses described in this report. Each catchment represents the direct, or local, drainage area for an individual stream reach and has a common identifier (CATCHID) assigned to it in the dataset. A separate table identifies the 'from' and 'to' CATCHID for every catchment in the dataset, giving a complete picture of the hydrologic relationships between every catchment in the stream network at the 1:24,000 scale. This information, in concert with a custom Python script, allows for rapid calculations of total upstream watershed characteristics for any stream reach in Wisconsin. The database of watershed attributes therefore contains both local catchment values and total upstream watershed values for each of these characteristics. This is valuable information for the statistical analyses, as some indicators of aquatic ecosystem health respond more strongly to local catchment characteristics, while others respond more strongly to upstream watershed characteristics.

A large dataset was constructed to contain the combined total of 1,067 instream, local catchment, and upstream watershed characteristics. The critical feature of this dataset is that every catchment that has a value for one of the instream indicators also has a corresponding value for each of the local catchment and upstream watershed characteristics. Many of the indicators of aquatic ecosystem health have data available for more than 1,000 locations, providing a powerful dataset for use in statistical modeling. Further, the resulting statistical models can be used to 'predict' the values of each of the instream indicators for all 162,651 stream reaches in the state, as the compiled dataset also contains the local catchment and upstream watershed characteristics for every unmonitored stream reach in Wisconsin.

2.1.1 Landscape Condition

Although the term landscape implies a focus on terrestrial features, aquatic systems are just as much landscape elements as forested patches and corridors. Rivers interact with other landscape elements through their natural floodplains, migrating meander belts, and riparian wetlands (The Nature Conservancy, 2008). Natural hydrology provides connectivity among aquatic habitats and between terrestrial and aquatic elements. Many aquatic organisms depend on being able to move through connected systems to habitats in response to variable environmental conditions. Furthermore, maintenance of natural land cover protects aquatic ecosystems from nonpoint sources of pollution, including urban and agricultural runoff, and helps maintain resilience in the face of climate change.

Recognizing the importance of connectivity, and with the view that aquatic ecosystems are embedded within the surrounding landscape, the Active River Area was delineated for the entire state of Wisconsin. The Active River Area includes not only the river channel but also floodplains, riparian wetlands, and other parts of the river corridor where key habitats and processes occur. It can be viewed as a more ecologically-relevant delineation of a riparian buffer, and in fact is sometimes referred to as a 'functional buffer zone'. The relative amount of natural land cover, defined as all land cover types other than urban, suburban, or agricultural, was quantified within the Active River Area and the entire watershed to derive two indicators of landscape condition: Percent Natural Land Cover in the Active River Area and Percent Natural Land Cover in the Watershed. These were combined with the percent wetlands remaining indicator to calculate the Landscape Condition Index presented in Section 3.1.1. Percent wetlands remaining was calculated as the difference between the current extent of wetlands as indicated by the Wisconsin Wetland Inventory (Wisconsin Department of Natural Resources, 2012), and the assumed historical extent of wetlands as indicated by hydric soils in the Natural Resource Conservation Service's SSURGO dataset (Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture, 2012).

2.1.2 Hydrologic Condition

The natural flow regime is considered one of the fundamental drivers of aquatic ecosystem condition. It can be characterized in terms of the magnitude, duration, timing, frequency, and rate of change of various flow metrics. Different components of the flow regime are responsible for regulating different aspects of biological community structure. For example, small, frequently occurring floods transport fine sediments, which maintain high benthic productivity and create spawning habitat for some fish species

(Poff, et al., 1997). Wisconsin DNR is currently in the process of building statistical models describing the flow regime for all Wisconsin streams and rivers (Matt Diebel, Personal Communication). Draft versions of these models were used to estimate the current and pre-settlement values for the following streamflow indicators:

- 5% exceedance flow
- 10% exceedance flow
- 25% exceedance flow
- 50% exceedance flow
- 75% exceedance flow
- 90% exceedance flow
- 95% exceedance flow

The mean absolute difference of all seven of these indicators was calculated for all catchments in Wisconsin and is used as a gross measure of hydrologic alteration. This is similar, in concept, to the total seasonal ecochange proposed by (Gao, Vogel, Kroll, Poff, & Olden, 2009).

2.1.3 Geomorphic Condition

Geomorphology and hydrology are intricately entwined and together with landscape characteristics, such as riparian vegetation, create the physical habitat upon which aquatic biota depend. Geomorphic condition refers to a "dynamic equilibrium" where sediment size and volume are in balance with stream slope and discharge. An absence of this dynamic equilibrium can result in degradation or aggradation of the stream channel and its floodplain. Assessments of geomorphic condition are typically conducted at the reach scale and require a substantial investment of field time and resources. While a limited number of such assessments have been conducted in Wisconsin, the data are not sufficient to extrapolate to a statewide scale with any reasonable degree of accuracy. Therefore, a relatively novel remote sensing approach was applied. This approach relies on digital elevation models (DEMs) from two different time periods (1960 and 2000) to create a "DEM of Difference". Typically, this procedure uses DEMs generated from high resolution LiDAR data to evaluate geomorphic change at the sub-reach scale. LiDAR data from multiple time periods are not yet available for the entire State of Wisconsin. However, since the uncertainty associated with the elevation data in DEMs is random (as opposed to systematic), and the number of individual elevation measurements in a catchment's Active River Area exceed 7,000, the same concept and methodology can be applied at the watershed scale with the following modifications:

1. A DEM of Difference created by the USGS based on 30 meter resolution elevation data (US Geological Survey, 2006) was clipped to the boundaries of the Active River Area for each catchment in the state.
2. The percent of the Active River Area within each catchment with a statistically significant geomorphic change was calculated. This approach cannot specify *where* in the catchment's Active River Area the change occurred; only the relative extent of the change.

The percent of streams classified as canals or ditches was also calculated for each catchment and is used as an additional indicator of geomorphic condition.

2.1.4 Habitat Condition

Habitat is, in many ways, an aggregate measure of the landscape, hydrologic, and geomorphic patterns and processes that are of most relevance to a given organism. Wisconsin DNR collects information on such characteristics to calculate a stream habitat index. Variables in the habitat index include riparian buffer width, bank erosion, pool area, width/depth ratio, fine sediments, fish cover, and riffle bend ratios. Stream habitat index data are available at 3,715 sites throughout the state (Figure 3). These data were compiled and BRT models were developed to predict stream habitat condition in all streams throughout the state. In addition, reed canary grass, Eurasian water milfoil, and curly-leaf pondweed data were used to calculate a presence/absence indicator of invasive species that are likely to impact habitat condition. The presence of dams was also included to represent aquatic connectivity.

Table 1 Summary statistics for stream habitat data in Wisconsin.

Statistic	Total Habitat Score
Sample Size	3715
Minimum	0
Maximum	100
Mean	58.7
Median	60

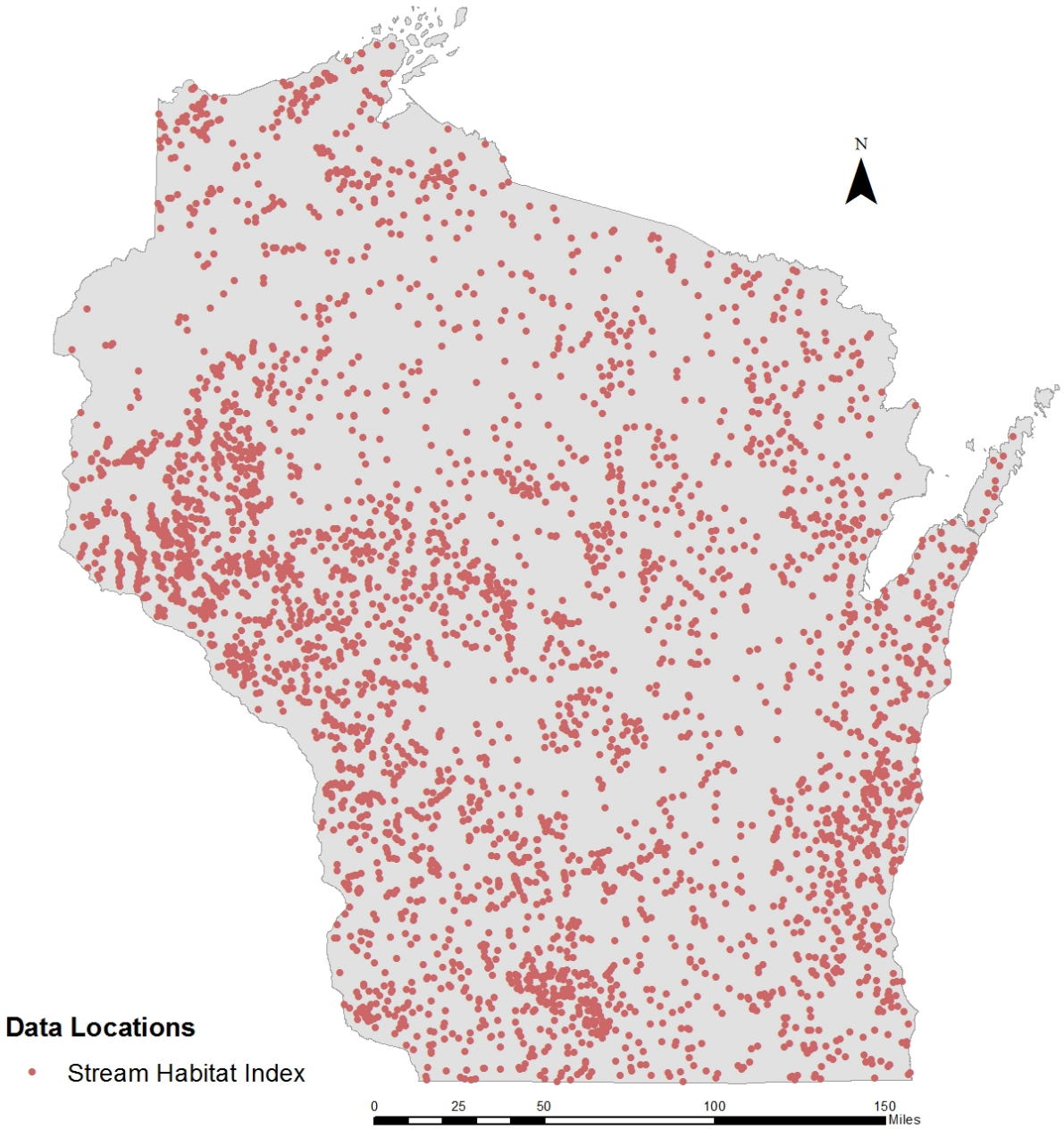

Figure 3 Map of monitoring locations with stream habitat index data.

2.1.5 Water Quality

Natural chemical characteristics of streams are typically within a certain range of variation at reference quality sites. Water quality, in the context of a healthy watersheds assessment, refers to the chemical and physical characteristics inherent in aquatic ecosystems such as nutrients, turbidity, temperature, dissolved oxygen, etc. Since water quality measured at a discrete monitoring location cannot be assumed to represent other locations within a watershed, it must first be related to upstream watershed characteristics in order to make a statement about watershed-wide conditions. Another approach for making statements about watershed-wide conditions would be to use a probabilistic monitoring design, but that is not practical for a statewide assessment at the subwatershed scale. BRT models were therefore developed to evaluate ammonia, nitrate-nitrite, total phosphorus, and suspended sediment levels in streams throughout the state. In addition, lake clarity is a response measure that is directly impacted by nutrient and sediment loadings and is used as an additional indicator of water quality.

Table 2 Summary statistics for water quality data in Wisconsin.

Statistic	Ammonia	Nitrate-Nitrite	Total Phosphorus	Suspended Sediment
Sample Size	1631	1859	2632	213
Minimum (mg/L)	0.1	0.1	0.1	1
Maximum (mg/L)	37.9	56.3	23.85	734
Mean (mg/L)	0.4047	1.395	0.4153	27.12
Median (mg/L)	0.25	0.394	0.28	6

2.1.6 Biological Condition

Wisconsin conducts both probabilistic and targeted monitoring of macroinvertebrate and fish communities for streams across the state. These data are used by the state to evaluate biological condition based on indices of biotic integrity (IBIs) at each site. Fish IBI data are available at 1,266 sites and macroinvertebrate IBI data are available at 5,600 sites throughout the state (Figure 5). These data were compiled and BRT models were developed to predict biological condition in all streams throughout the state. In addition, spiny waterflea and zebra mussel data were used to develop a presence/absence indicator of invasive species that are likely to directly impact biological condition.

Table 3 Summary statistics for Index of Biotic Integrity data in Wisconsin.

Statistic	Fish IBI	Macroinvertebrate IBI
Sample Size	1266	5600
Minimum	0	-8.332
Maximum	100	12.35
Mean	55.03	5.119
Median	52.75	5.054

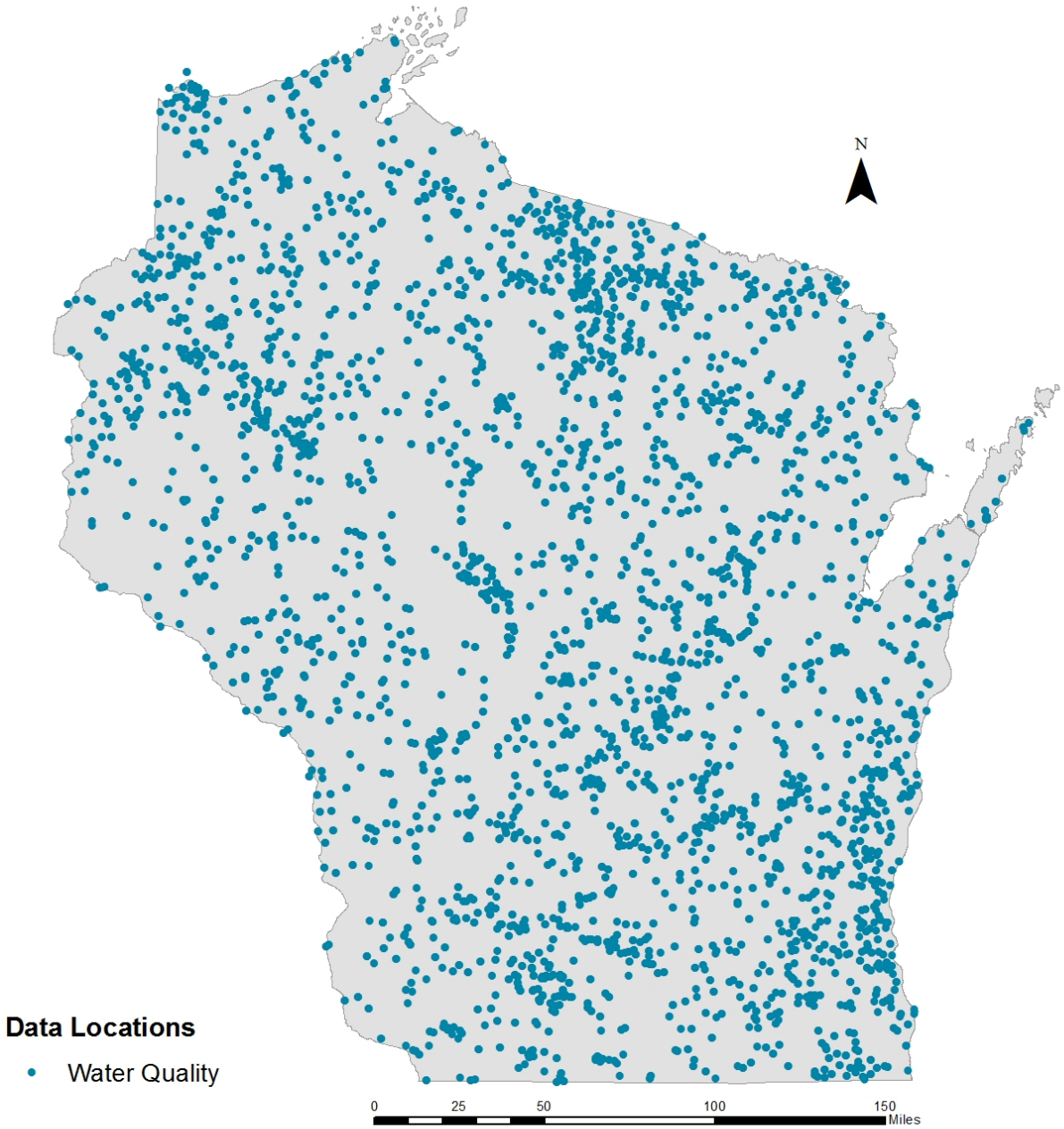

Figure 4 Map of monitoring locations with water quality data.

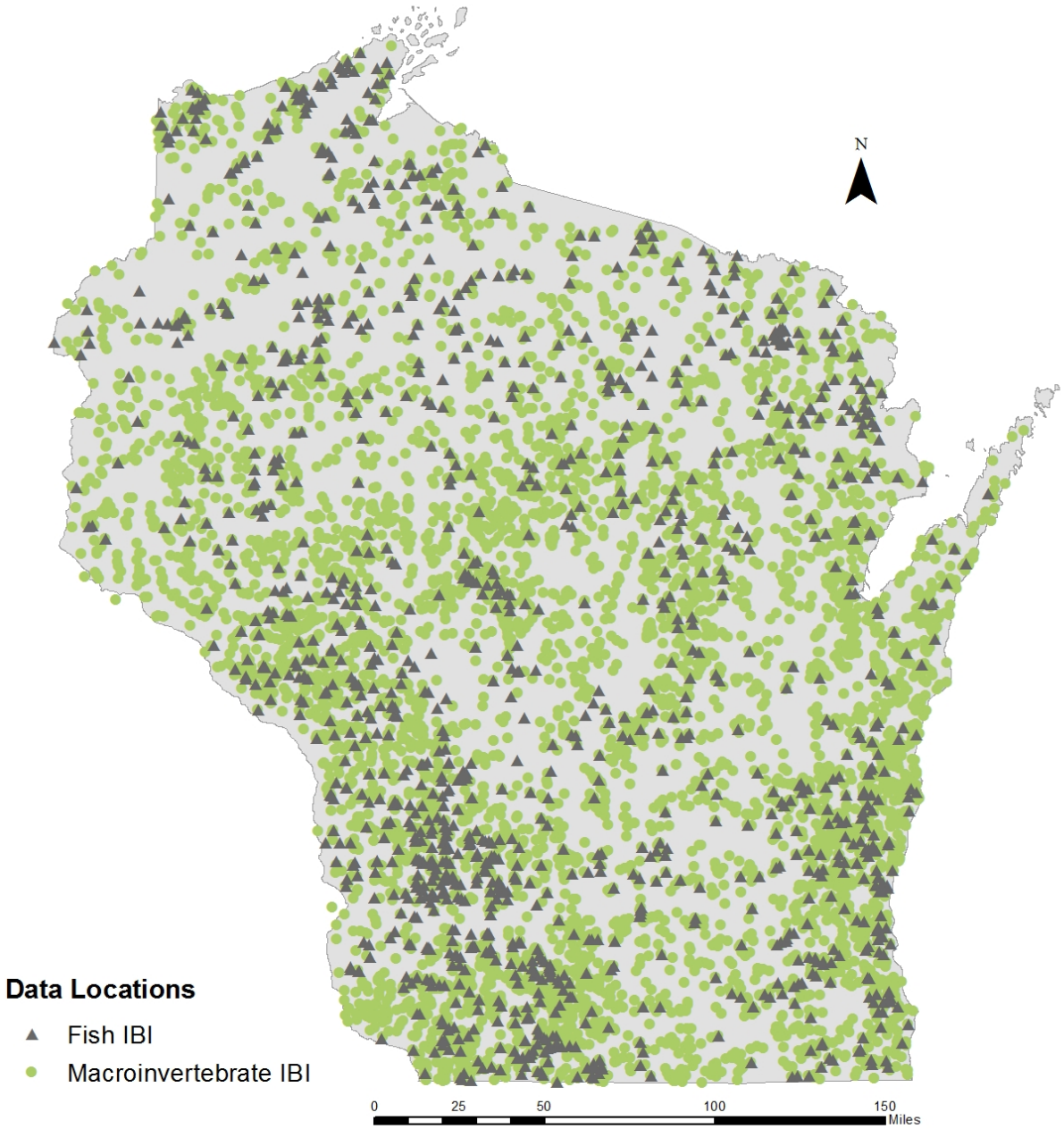

Figure 5 Map of monitoring locations with Fish and Macroinvertebrate Index of Biotic Integrity data.

2.1.7 Watershed Vulnerability

As part of a healthy watersheds integrated assessment, an evaluation of watershed vulnerability can further inform the prioritization of protection and restoration strategies. Vulnerability can be defined as a combination of a system's exposure, sensitivity, and adaptive capacity to cope with stressors (IPCC, 2007). The stressors of most relevance to aquatic ecosystems and their watersheds are generally related to land use, water use, and climate change.

Climate Change Vulnerability

Since climate is the biggest driver of all watershed processes, its impacts on surface runoff are important to estimate and quantify in any kind of watershed vulnerability assessment. Further, changes in surface runoff undoubtedly affect changes in nutrient and sediment loading, which are important drivers of aquatic ecosystem health. Projected changes in surface runoff, total nitrogen, total phosphorus, and sediment loading between 2002 and 2050 were provided by Wisconsin DNR (Theresa Nelson, Personal Communication; (Mednick, Nelson, & Watermodel, 2012) and used to represent climate change vulnerability at the catchment scale. These projections were developed with the Long-Term Hydrologic Impacts Assessment (L-THIA) model using downscaled general circulation models (GCMs) for the year 2050 and land use change projections for the year 2030 generated by Purdue University's Land Transformation Model (Pijanowski, 2006). The projected runoff volumes and loading rates were compared with current runoff volumes and loading rates (2002 climate and 1992 land use) to calculate a percent change metric for each of surface runoff, total nitrogen, total phosphorus, and sediment loading.

Land Use Vulnerability

Land use change has other impacts beyond changes in runoff and nutrient and sediment loading. It also impacts geomorphic processes, habitat availability, and biological condition. Projected changes in anthropogenic land cover (i.e., urban and agricultural land) between 2010 and 2030 were obtained from Purdue University's Land Transformation Model program (Pijanowski, 2006). In addition, the percent of lands protected (US Geological Survey Gap Analysis Program, 2011) within each catchment was quantified to complement the land use vulnerability assessment. Protected lands include both public lands, such as state forests and parks, as well as private lands, such as Nature Conservancy properties and other lands with conservation easements. Use of both land cover change projections and protected lands datasets provides complementary information about the relative risk that each catchment will experience significant land use change in the coming decades.

Water Use Vulnerability

Water use vulnerability was quantified by summing up all surface and ground water withdrawals permitted through Wisconsin DNR's Water Use Registration Program (Robert Smail, Personal Communication). Only withdrawals greater than 100,000 gallons per day are reported under this program. Therefore, information on smaller withdrawals was not included in the water use vulnerability assessment.

An index of groundwater dependency was calculated using methods developed by The Nature Conservancy (Howard & Merrifield, 2010) because catchments with more groundwater-dependent ecosystems are likely to be more vulnerable to degradation as a result of water withdrawals. Groundwater-dependent ecosystems often harbor high species richness for their overall size, contributing significantly to the ecological diversity of a region. GDEs often contain endangered, threatened, or rare plants and animals. In addition, GDEs can act as natural reservoirs, storing water during wet periods and releasing it during dry periods, and can function as refugia during periods of environmental stress.

2.2 Statistical Models for Predicting Indicators of Aquatic Ecosystem Health

Boosted regression tree (BRT) methods were used to model the relationships between watershed characteristics and instream indicators of water quality and biological and habitat condition, and to predict values of these indicators in unmonitored watersheds. BRTs differ from traditional statistical modeling techniques (e.g., linear regression) in that, instead of generating a single model to best describe a response, they fit many models to the data and group predictor variables based on similar response values. This method is carried out using two different algorithms: regression trees and boosting. Regression trees define binary splits in the predictor variables based on homogeneous response values for each split. More influential predictor variables are defined at the base of the tree, and less influential predictors branch from there to refine the model. Predictive performance of regression trees alone is generally poor, so a boosting method is applied. After generating the first regression tree and calculating the predictive deviance based on a cross validation with a subset of the training data, new trees are sequentially added and analyzed, with the goal of minimizing predictive deviance. If applied correctly, a gradual decrease in predictive deviance is observed, with the minimum occurring after hundreds of trees have been generated. The resulting trees describe the complex relationships and interactions between each predictor variable and the response.

The BRT method has many advantages, and is particularly suited to ecological data. These models are able to describe nonlinear relationships, they are insensitive to outliers and missing data, they can use both continuous and categorical predictor variables, and they do not require transformation of predictor variables to fit a normal distribution. Results of BRT models can be summarized by the relative influence of each predictor variable on the response, and the interpretation of their predictive performance is comparable to other modeling methods.

The BRT models were developed in R (R Core Team, 2012) using the “gbm” package (Ridgeway, 2013). BRT models were generated for each of the 7 instream indicators, using local and upstream watershed characteristics as predictor variables. Model parameters, including learning rate (the proportional influence of each single tree to the final model), tree complexity (number of possible interactions between predictor variables), and bag fraction (the proportion of training data withheld for cross validation), were systematically altered to obtain the minimum predictive deviance in the training dataset. When this minimum was achieved, the final model was applied to the validation data to obtain predicted values. The predictive accuracy of each model describing continuous data was assessed using pseudo-R^2 values (1-(mean residual deviance/mean total deviance)).

In addition to predicting catchment values, the most influential predictor variables were also identified by the BRT models. Each input predictor variable is assigned a relative influence on the final model once the minimum predictive deviance is achieved. The sum of these influences is equal to 100%. Variables that are modeled as having a large effect on the response or have a high degree of interaction with other predictive variables are considered more influential in the final model.

2.3 Multimetric Index Development

A multimetric index combines individual metric values into one overall index value. Each metric describes a different process or function and the multimetric index describes overall condition. The advantage to such an approach is that it summarizes a large amount of complex information into one overall score that is easily interpreted by a non-technical audience. However, this advantage is also the biggest limitation of multimetric indices. Summarizing large amounts of complex information into one overall score requires that the details of patterns and processes be 'hidden'. It is therefore important to examine not only the overall index scores, but the individual indicator scores before making any management decisions.

Generally, before being aggregated into a multimetric index, each individual metric must first be tested, calibrated to a consistent scale, and transformed into a unitless score. In this case, each of the instream indicators of water quality and biological and habitat condition also had to be predicted for every stream reach catchment in the state and summarized. The predictions were made with the BRT models described in Section 2.2. Each of the indicators was then normalized to a scale of 0-1 using the following formula:

$$\frac{X - Min}{Max - Min}$$

Each of the normalized indicators can be weighted if desired. For this preliminary presentation of results, equal weighting was applied to all indicators. Finally, each index was calculated using the following formula:

$$\frac{\sum X_{NormWeight}}{\sum Weights}$$

An index was calculated for each of Landscape Condition, Hydrologic Condition, Geomorphic Condition, Habitat Condition, Water Quality, and Biological Condition, Climate Change Vulnerability, Land Use Change Vulnerability, and Water Use Vulnerability, in addition to an overall Watershed Health Index and an overall Watershed Vulnerability Index. The Watershed Health Index and Watershed Vulnerability Index were calculated by treating each of their component indices as individual indicators. This approach was taken to ensure that component indices comprised of several indicators did not receive more weight than component indices with only one or two indicators.

3 Results & Discussion

This section describes the results of the individual BRT models that were used to predict instream indicators of water quality and biological and habitat condition. Results are presented in the form of relative influence plots, which are an intuitive method for communicating the results of an otherwise complex modeling process. The relative influence of each watershed characteristic included in the modeling is represented as a percentage score. Each bar chart in this section shows only the top 10 predictor variables in the models, but scores for all watershed characteristics included in the analyses are included in Appendix A. Model performance statistics associated with each of the models are provided in Table 4. Model performance is summarized in terms of cross-validation correlation statistics and pseudo-R^2 values for training and validation datasets. In addition, this section includes maps of the resulting multimetric indices for Landscape Condition, Hydrologic Condition, Geomorphic Condition, Habitat Condition, Water Quality, and Biological Condition, Climate Change Vulnerability, Land Use Change Vulnerability, and Water Use Vulnerability, in addition to an overall Watershed Health Index and Watershed Vulnerability Index.

Table 4 Model performance statistics.

Variable	Cross-Validation Correlation	Cross-Validation Standard Error	Training Pseudo-R^2	Validation Pseudo-R^2
Nitrate-Nitrite	0.75	0.02	0.78	0.61
Macroinvertebrate IBI Score	0.67	0.01	0.70	0.45
Suspended Sediment	0.65	0.08	0.89	0.05
Stream Habitat Score	0.46	0.02	0.43	0.23
Fish IBI Score	0.38	0.05	0.59	0.16
Ammonia	0.32	0.03	0.49	0.04
Phosphorous	0.30	0.02	0.38	0.03

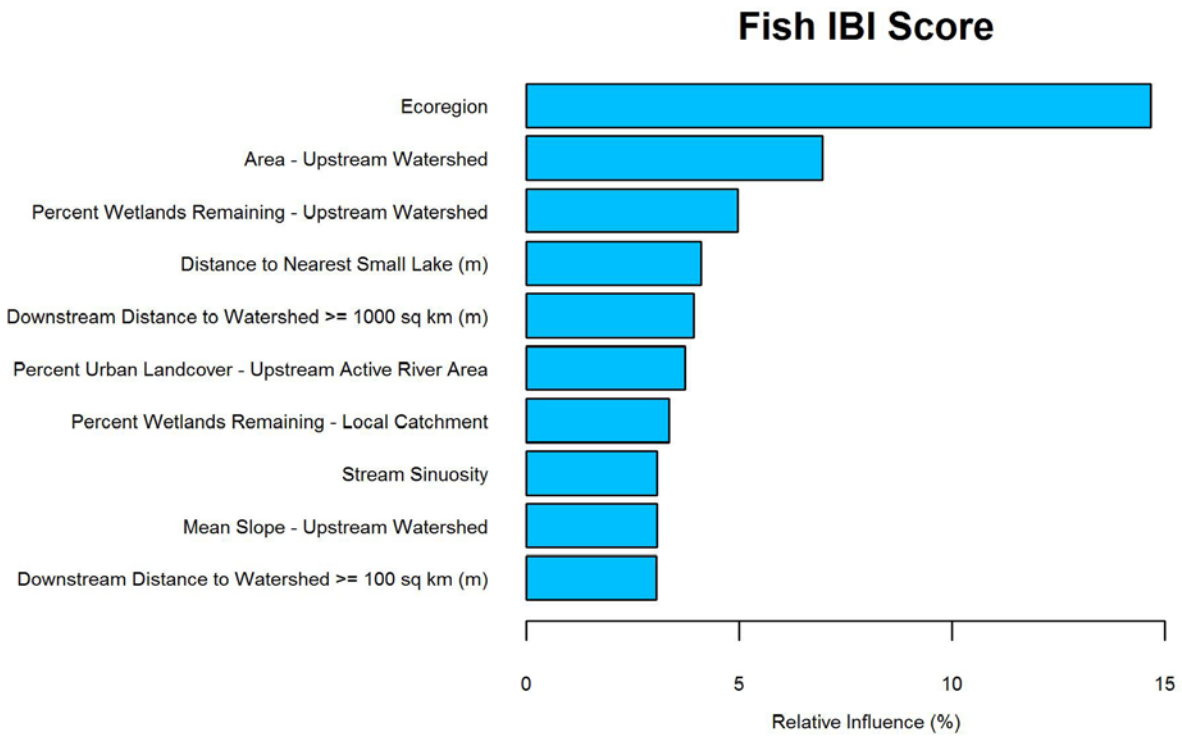

Figure 6 Relative influence plot for Fish Index of Biotic Integrity (IBI) boosted regression tree model.

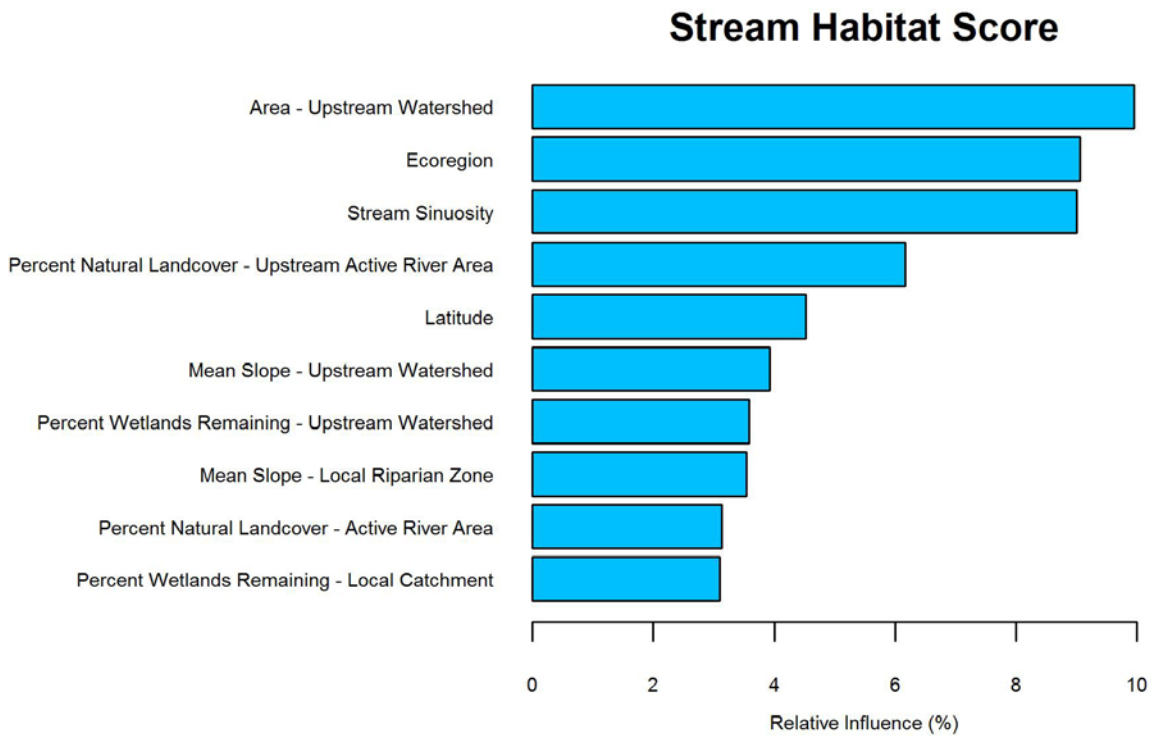

Figure 7 Relative influence plot for stream habitat boosted regression tree model.

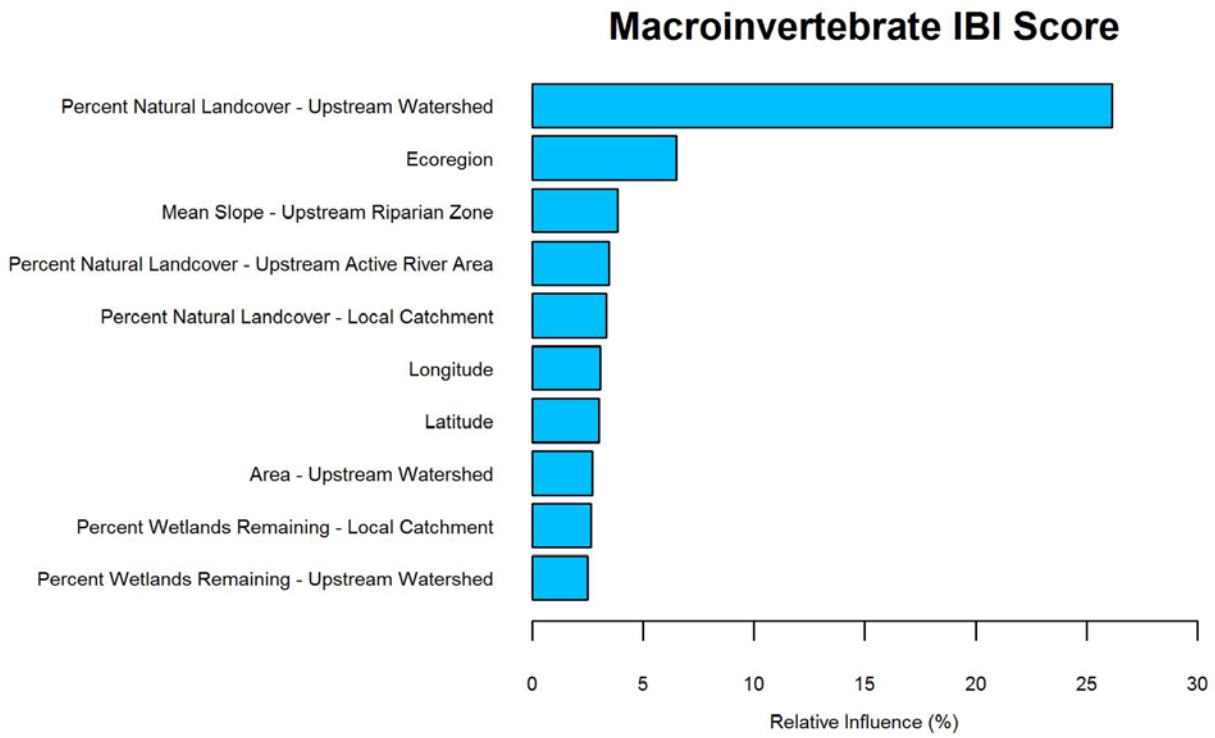

Figure 8 Relative influence plot for Macroinvertebrate Index of Biotic Integrity (IBI) boosted regression tree model.

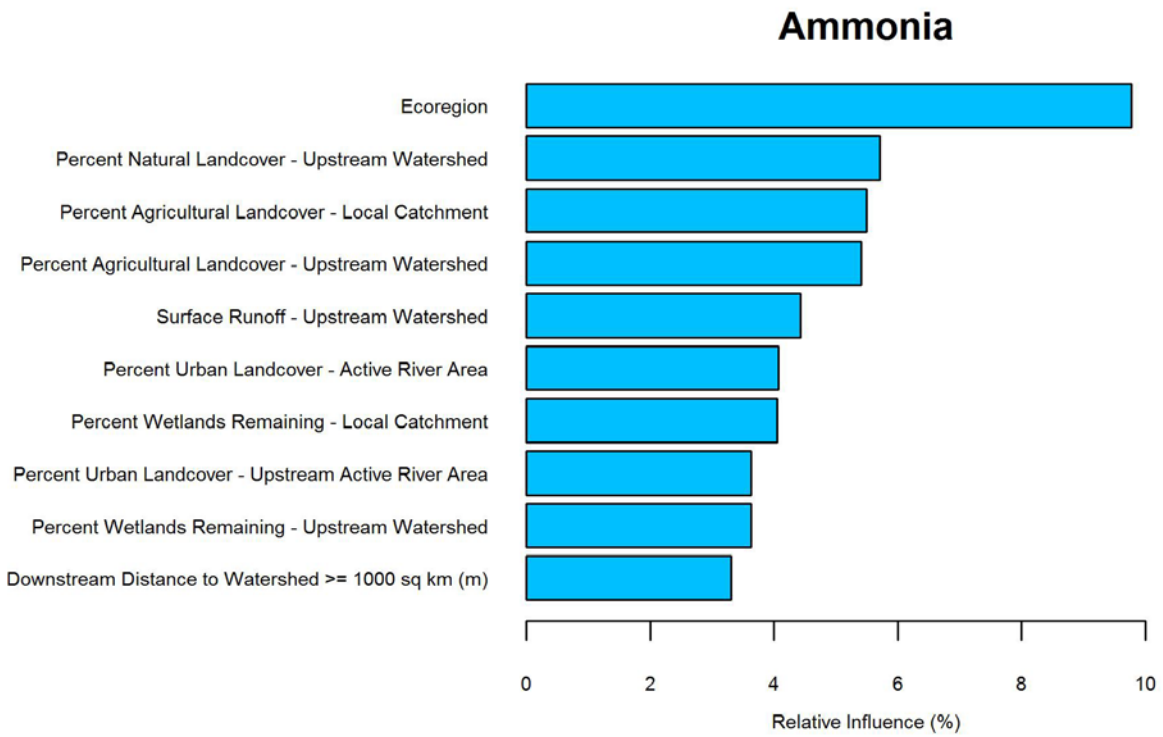

Figure 9 Relative influence plot for Ammonia boosted regression tree model.

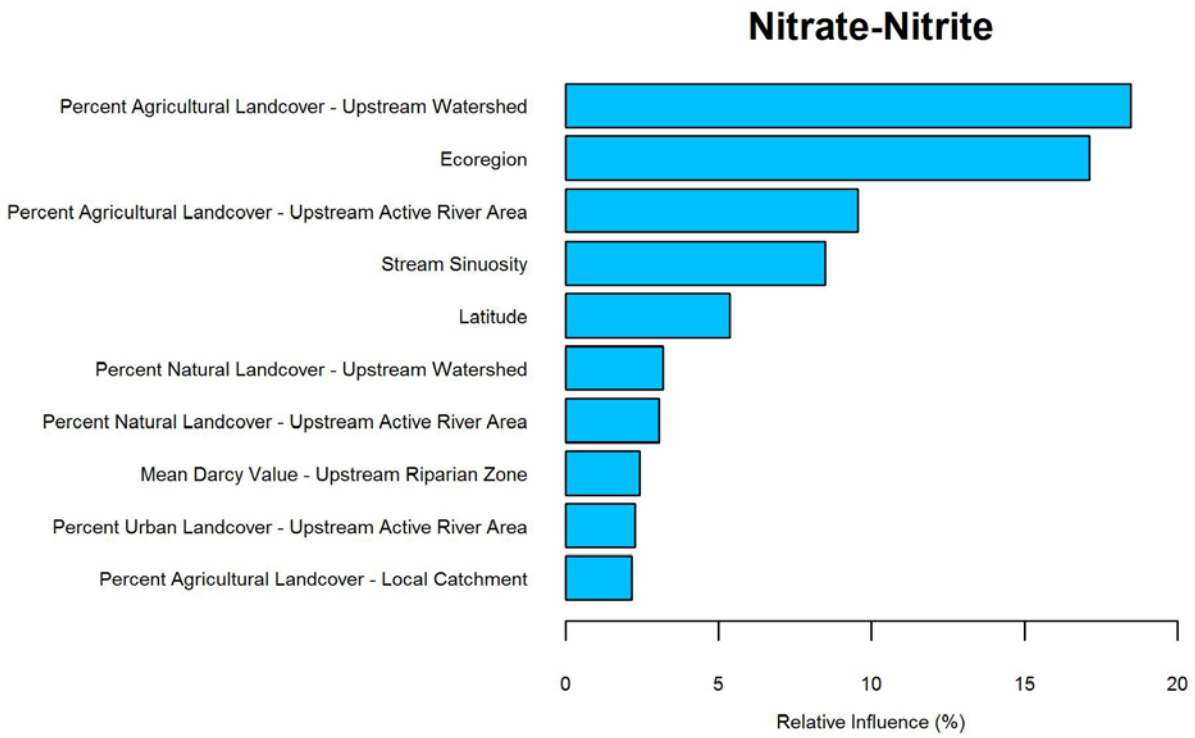

Figure 10 Relative influence plot for Nitrate-Nitrite boosted regression tree model.

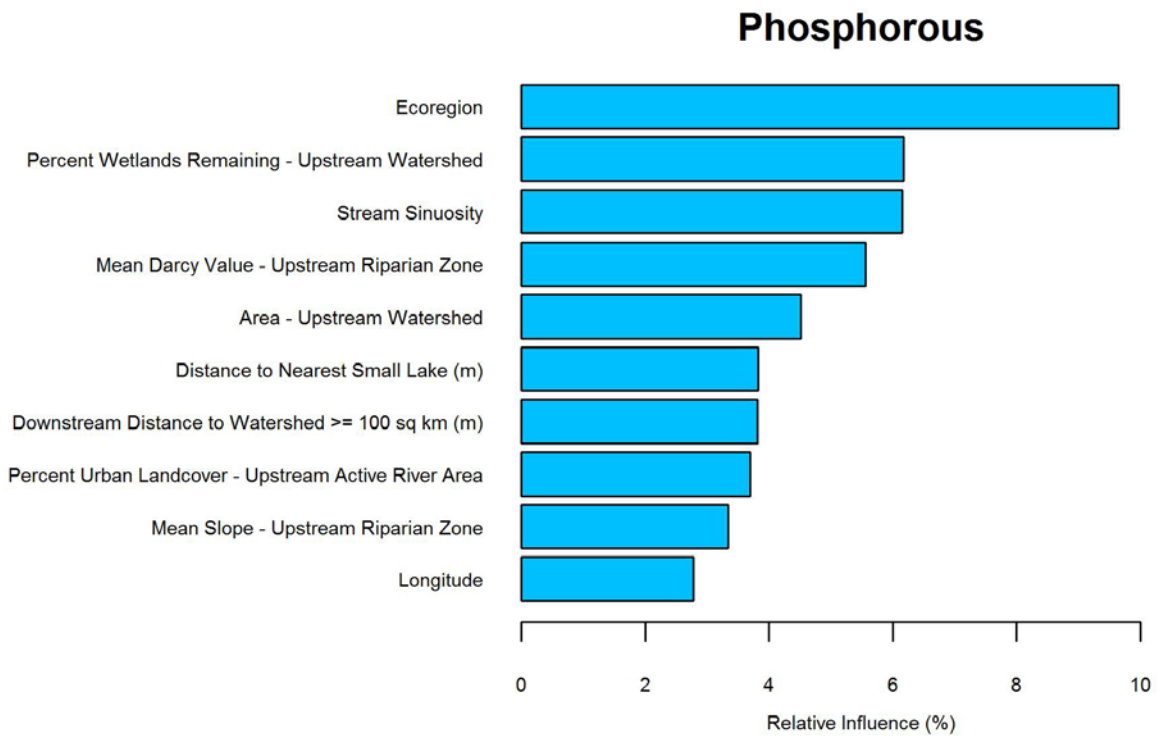

Figure 11 Relative influence plot for Total Phosphorus boosted regression tree model.

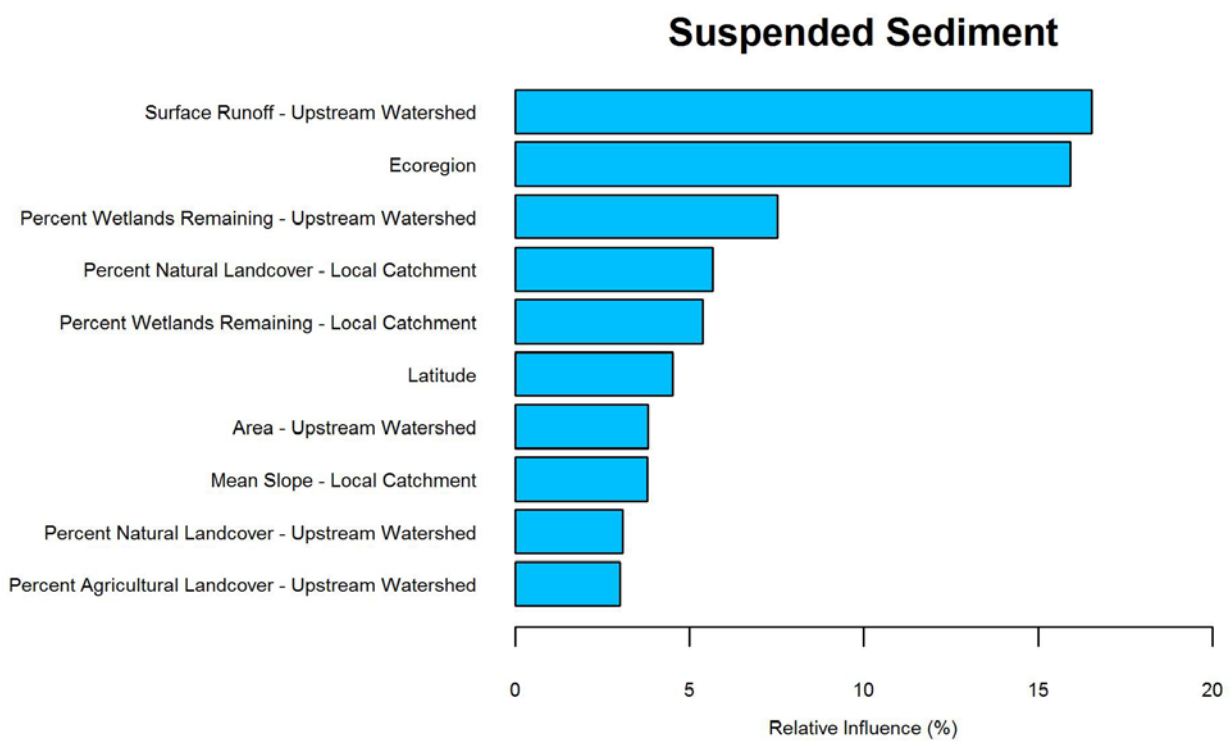

Figure 12 Relative influence plot for Suspended Sediment boosted regression tree model.

3.1 Watershed Health

TBD

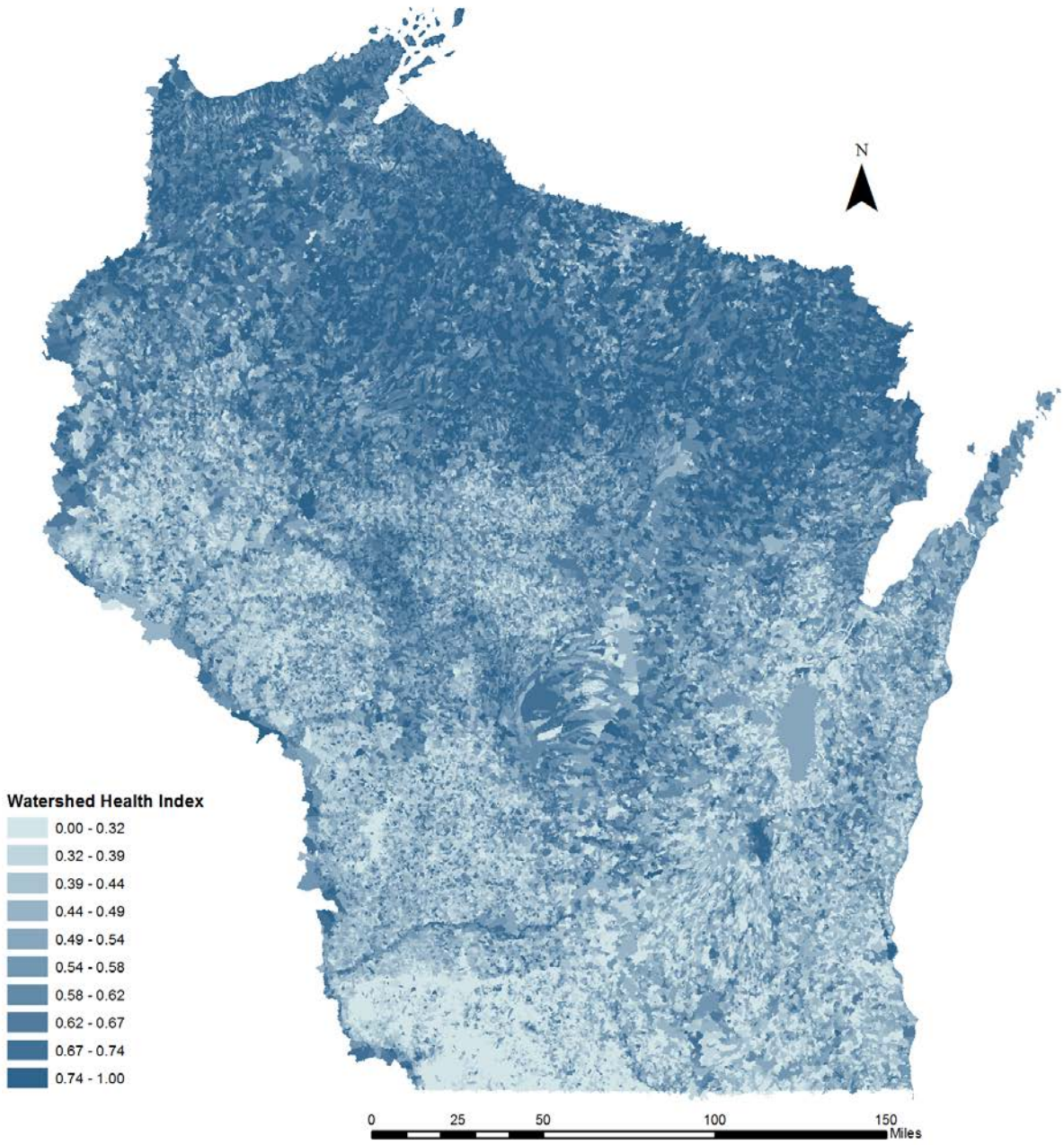

Figure 13 Map of Watershed Health Index Scores.

3.1.1 Landscape Condition

TBD

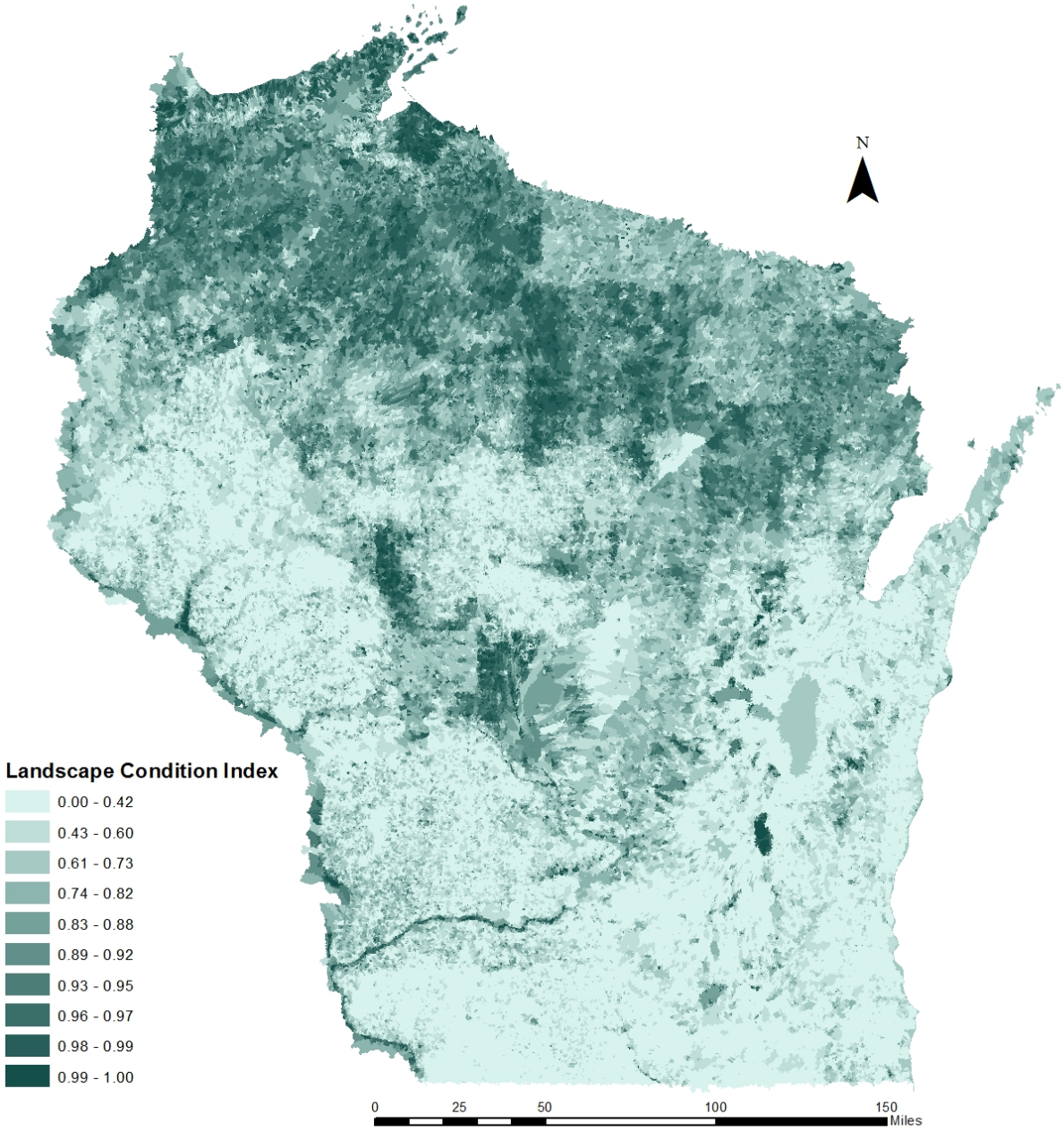

Figure 14 Map of Landscape Condition Index.

3.1.2 Hydrologic Condition

TBD

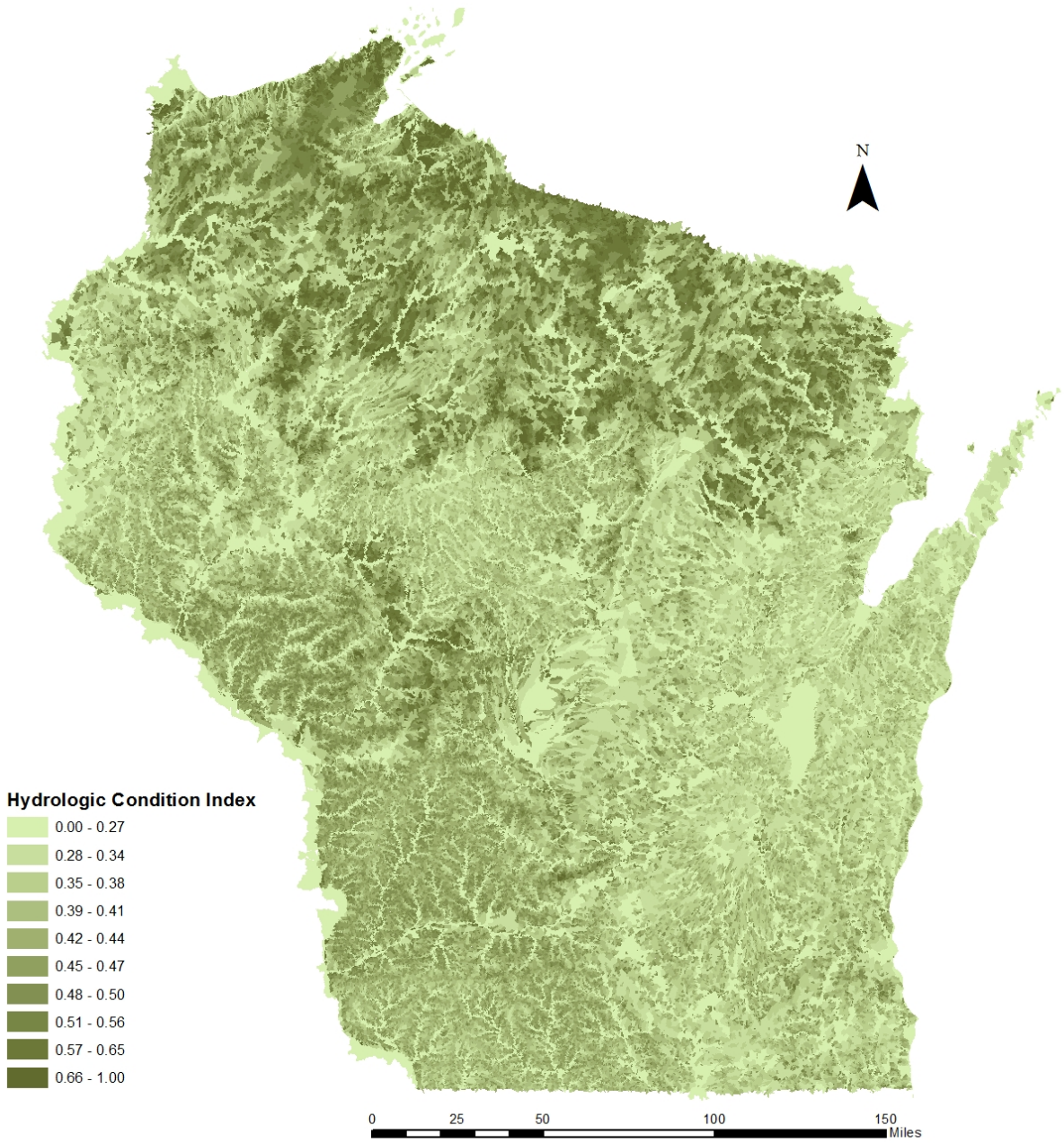

Figure 15 Map of hydrologic condition index.

3.1.3 Geomorphic Condition

TBD

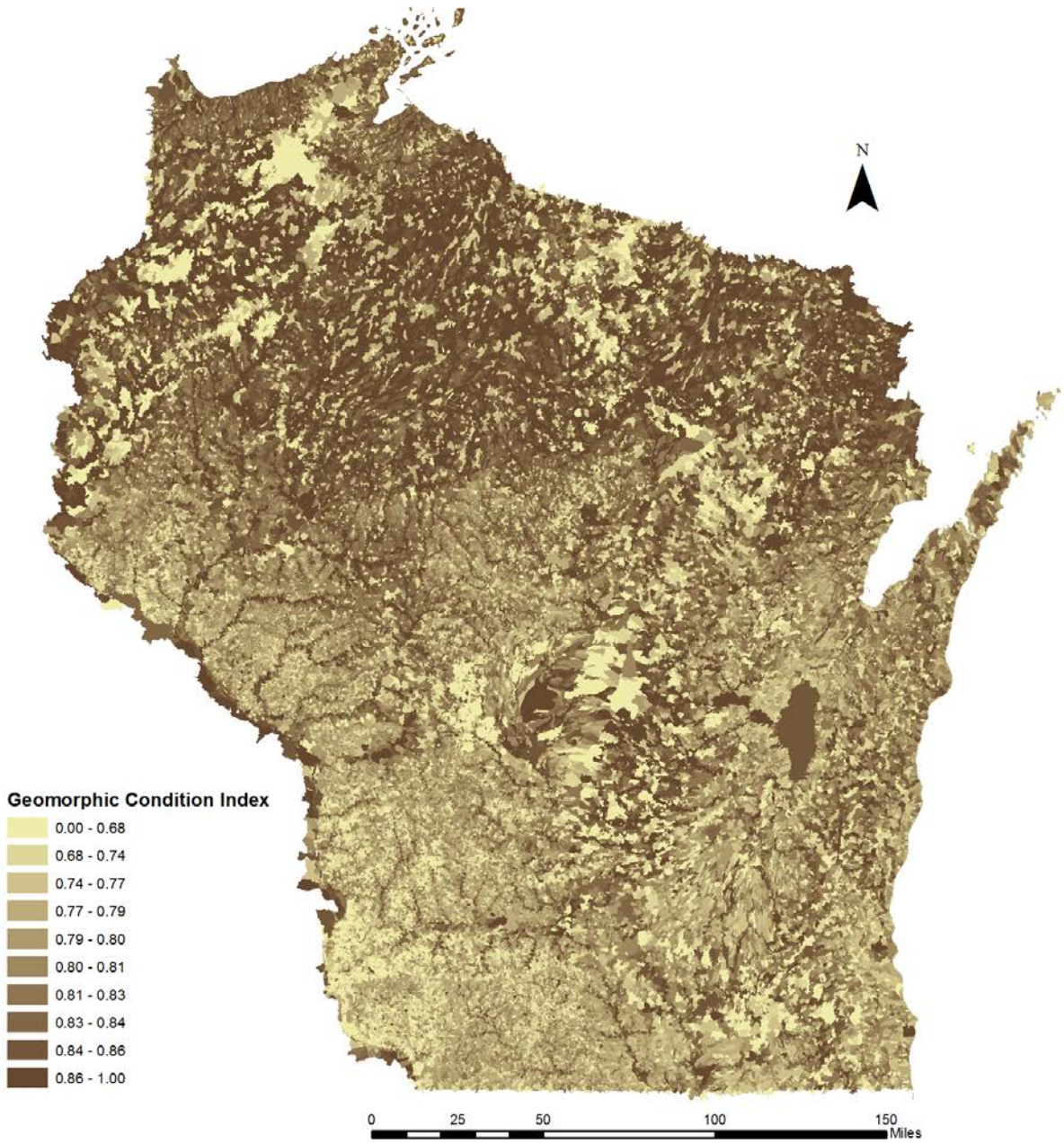

Figure 16 Map of geomorphic condition index.

3.1.4 Habitat Condition

TBD

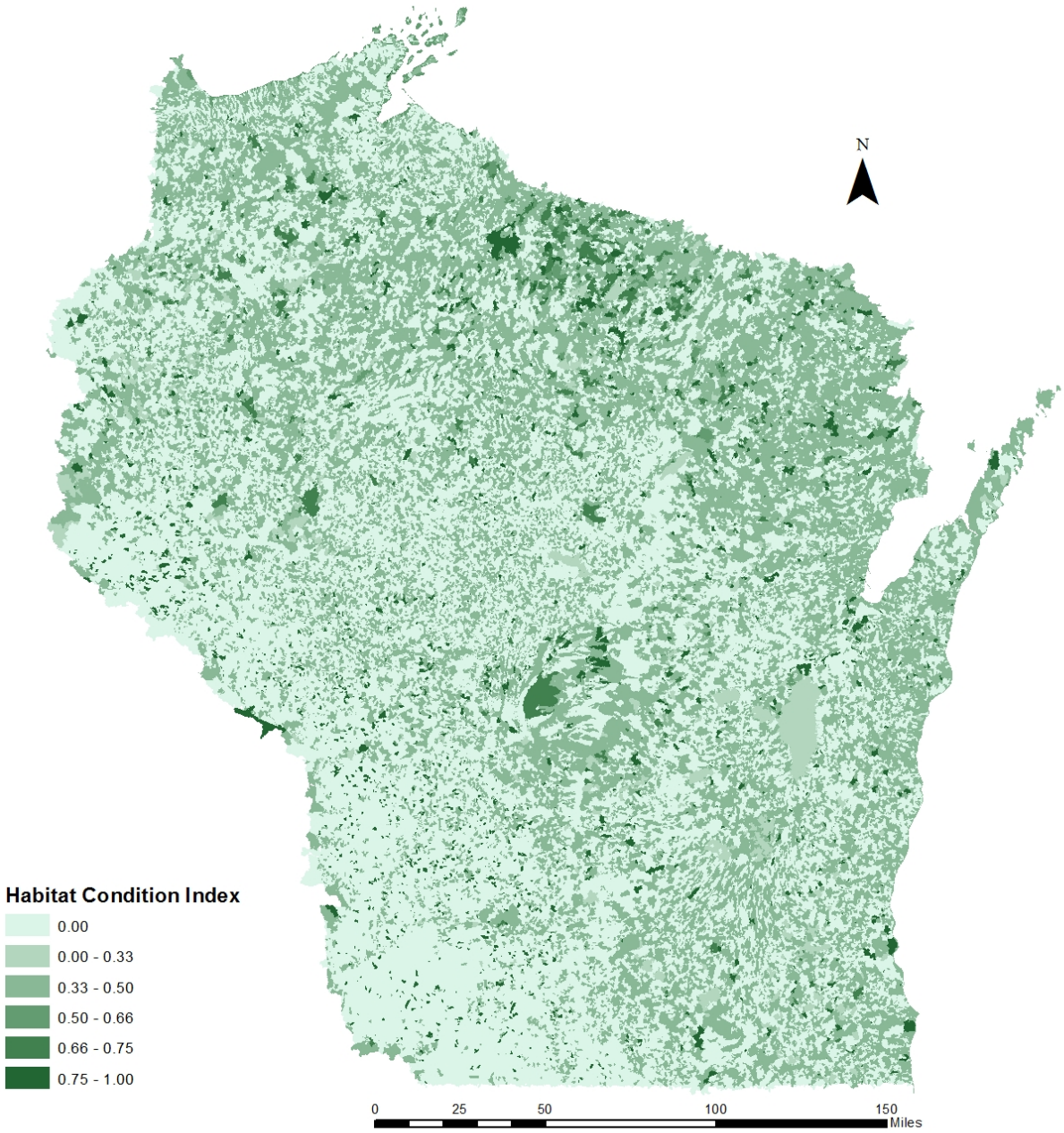

Figure 17 Map of habitat condition index.

3.1.5 Water Quality

TBD

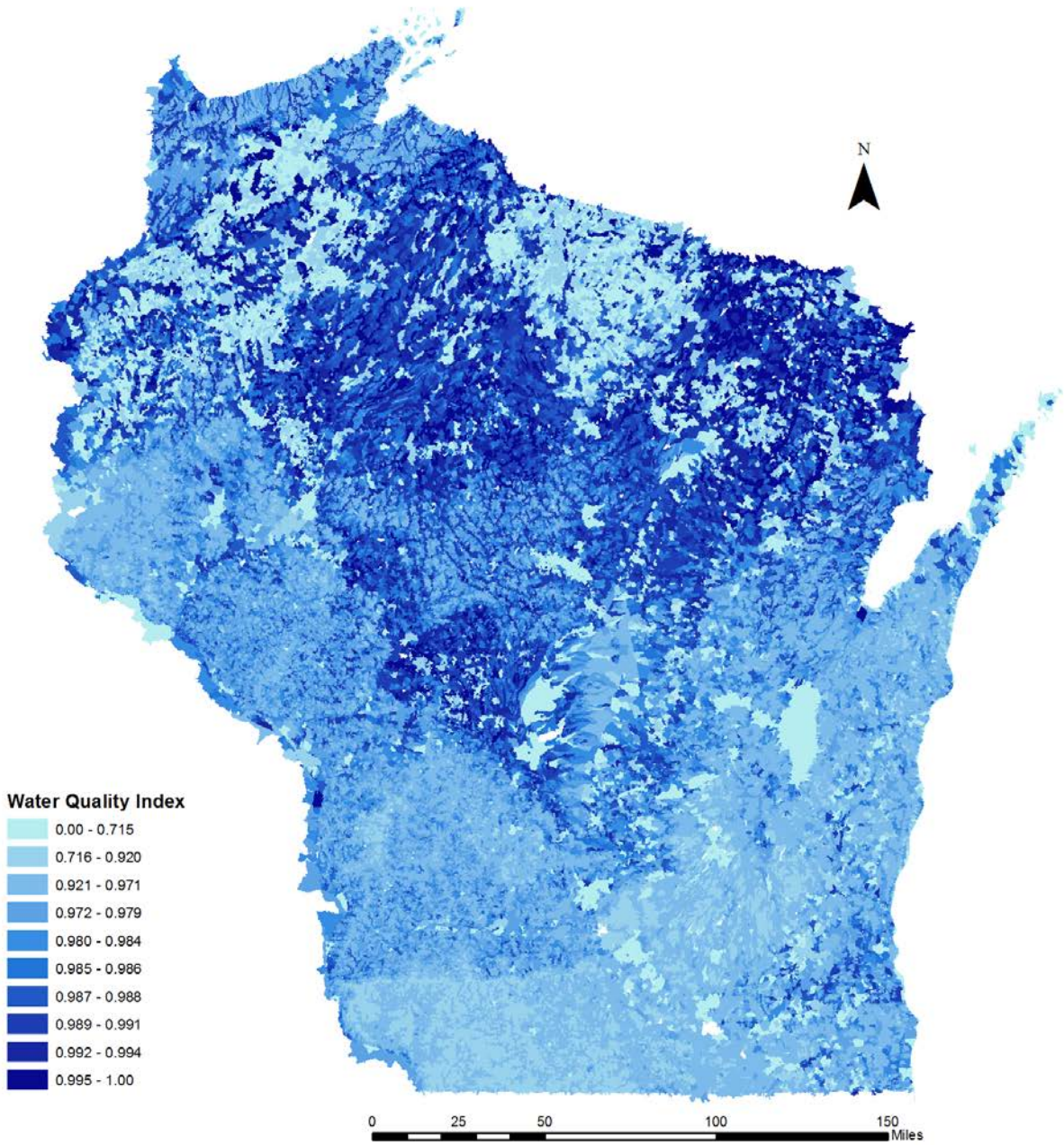

Figure 18 Map of water quality index.

3.1.6 Biological Condition

TBD

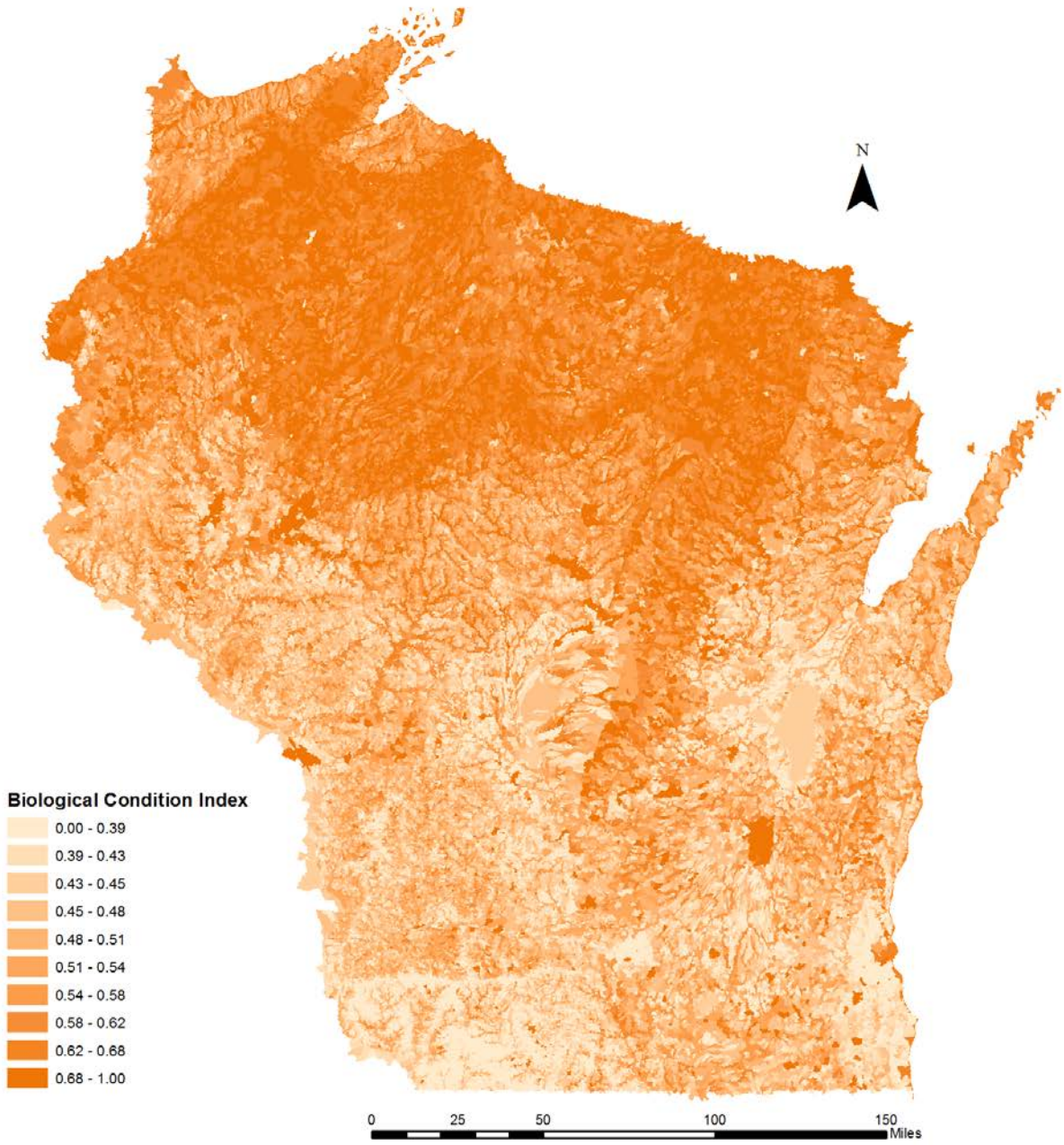

Figure 19 Map of biological condition index.

3.2 Watershed Vulnerability

TBD

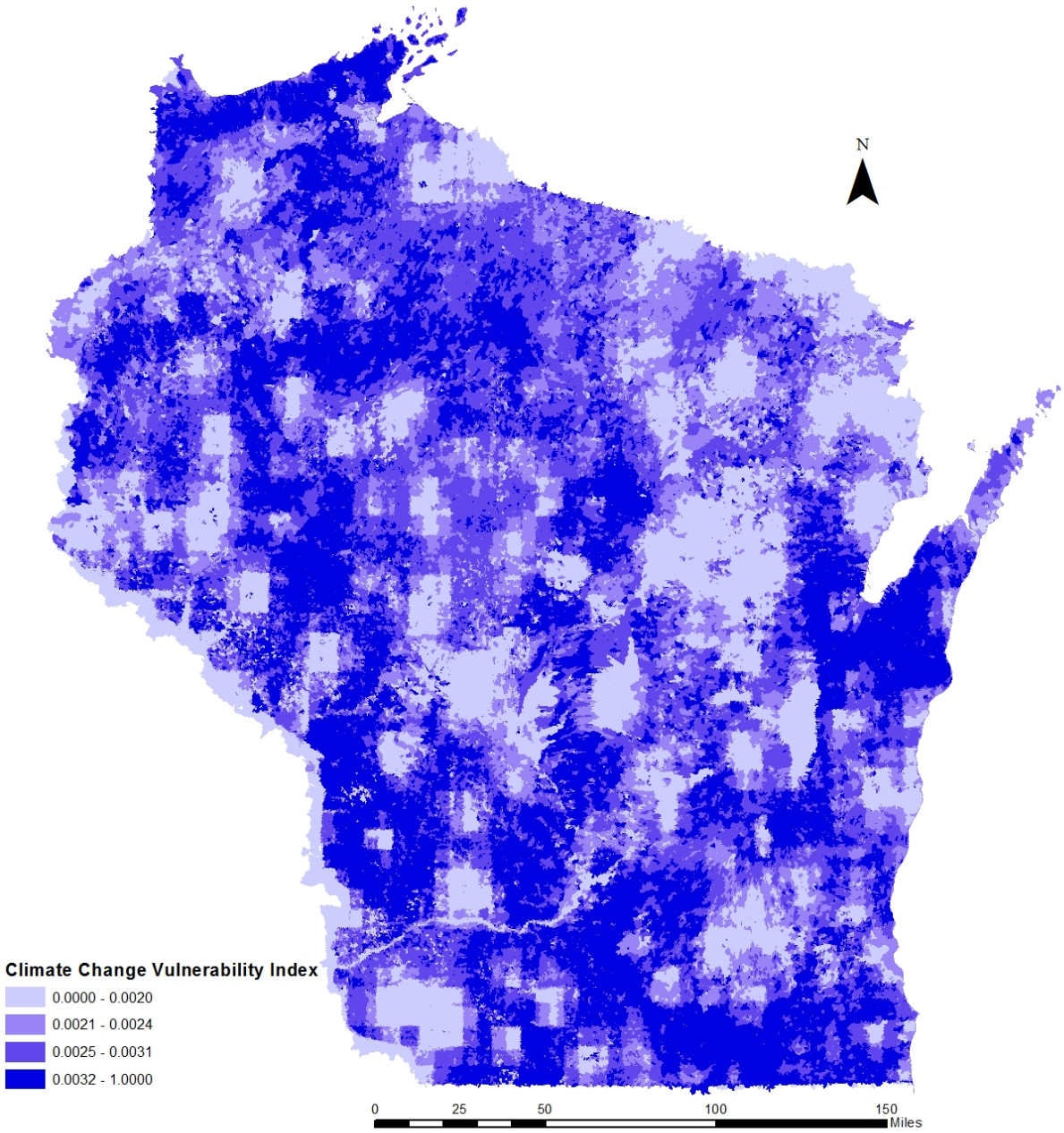

Figure 20 Map of Climate Change Vulnerability Index Scores.

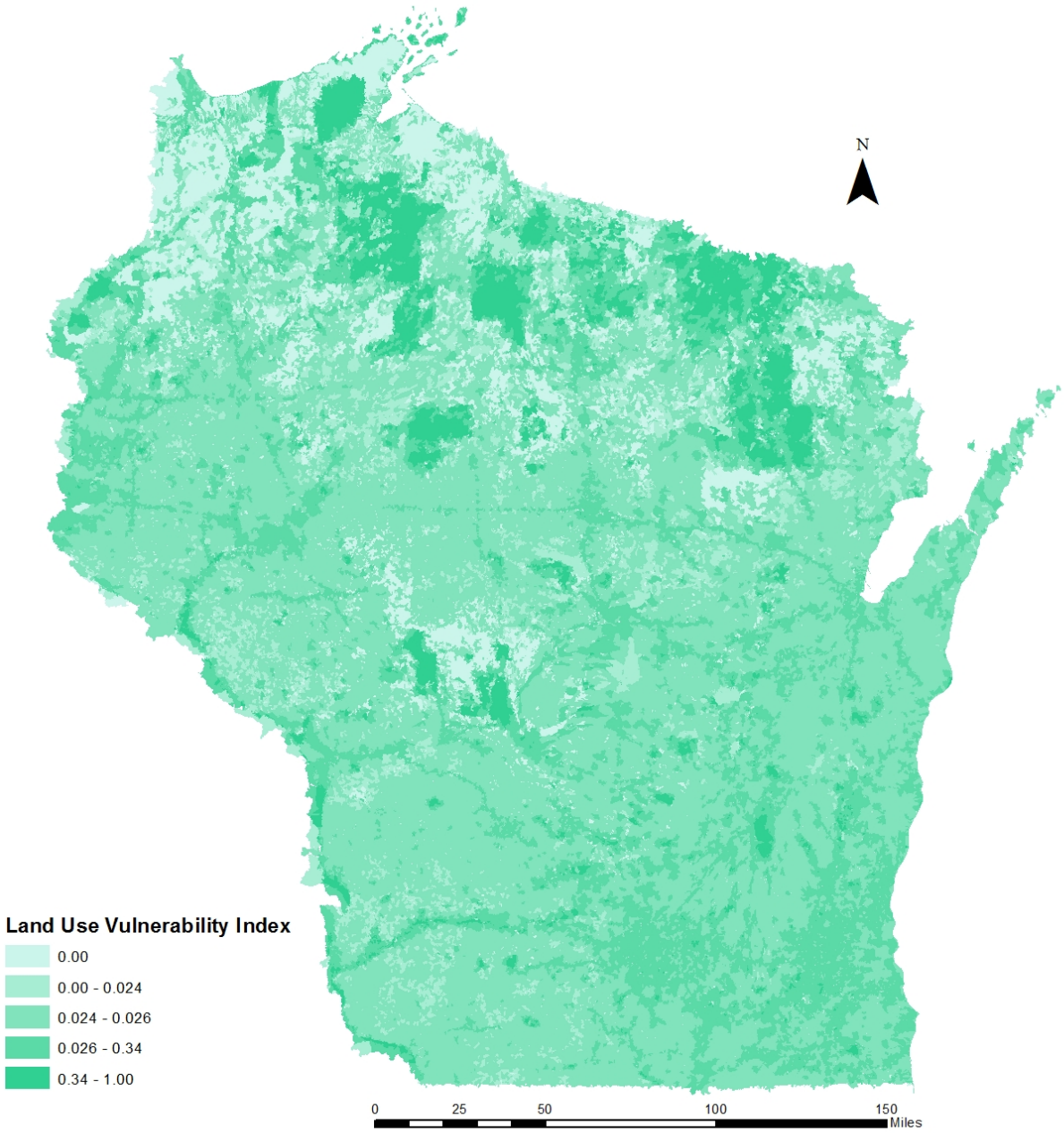

Figure 21 Map of Land Use Vulnerability Index.

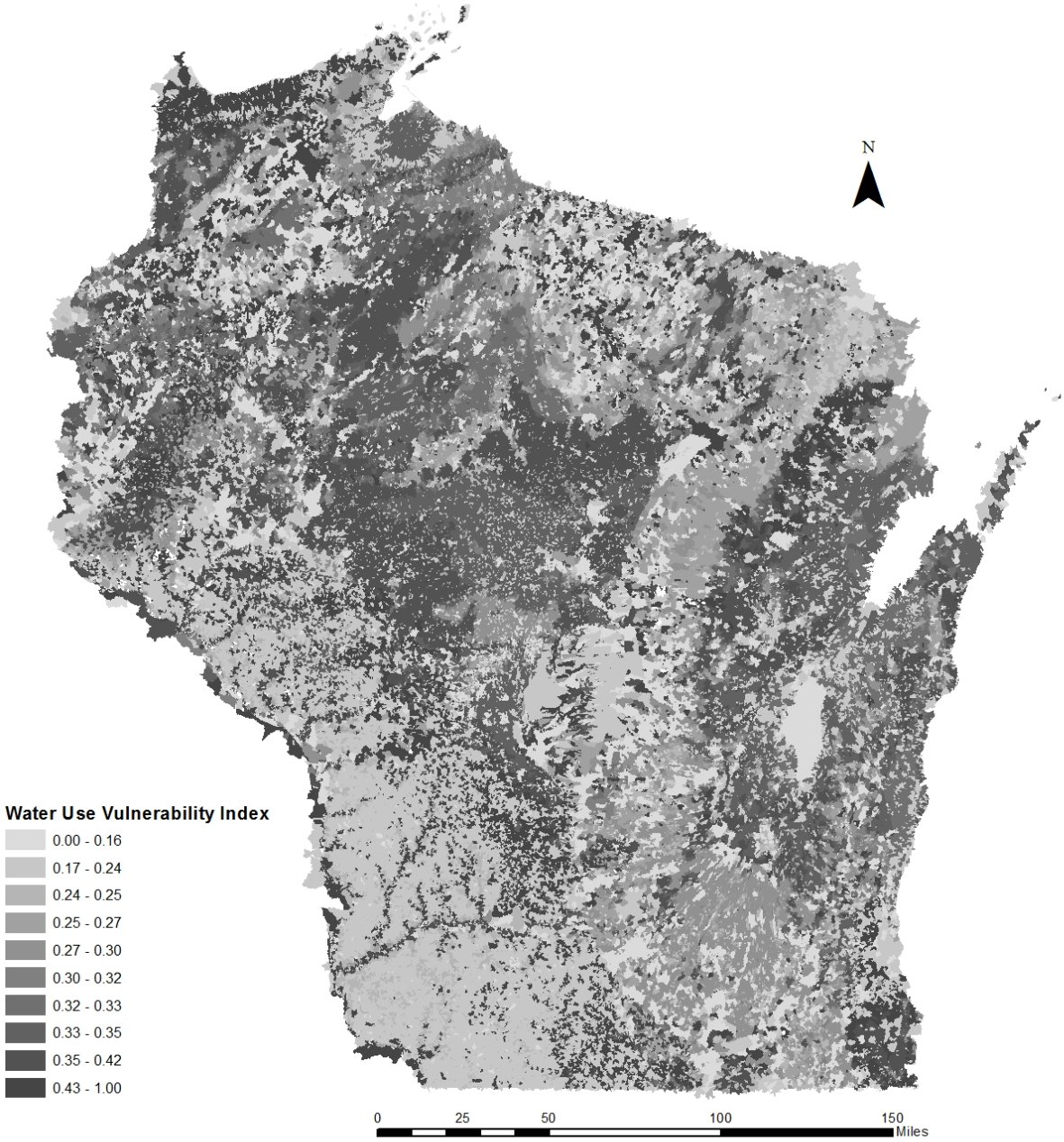

Figure 22 Water Use Vulnerability Index.

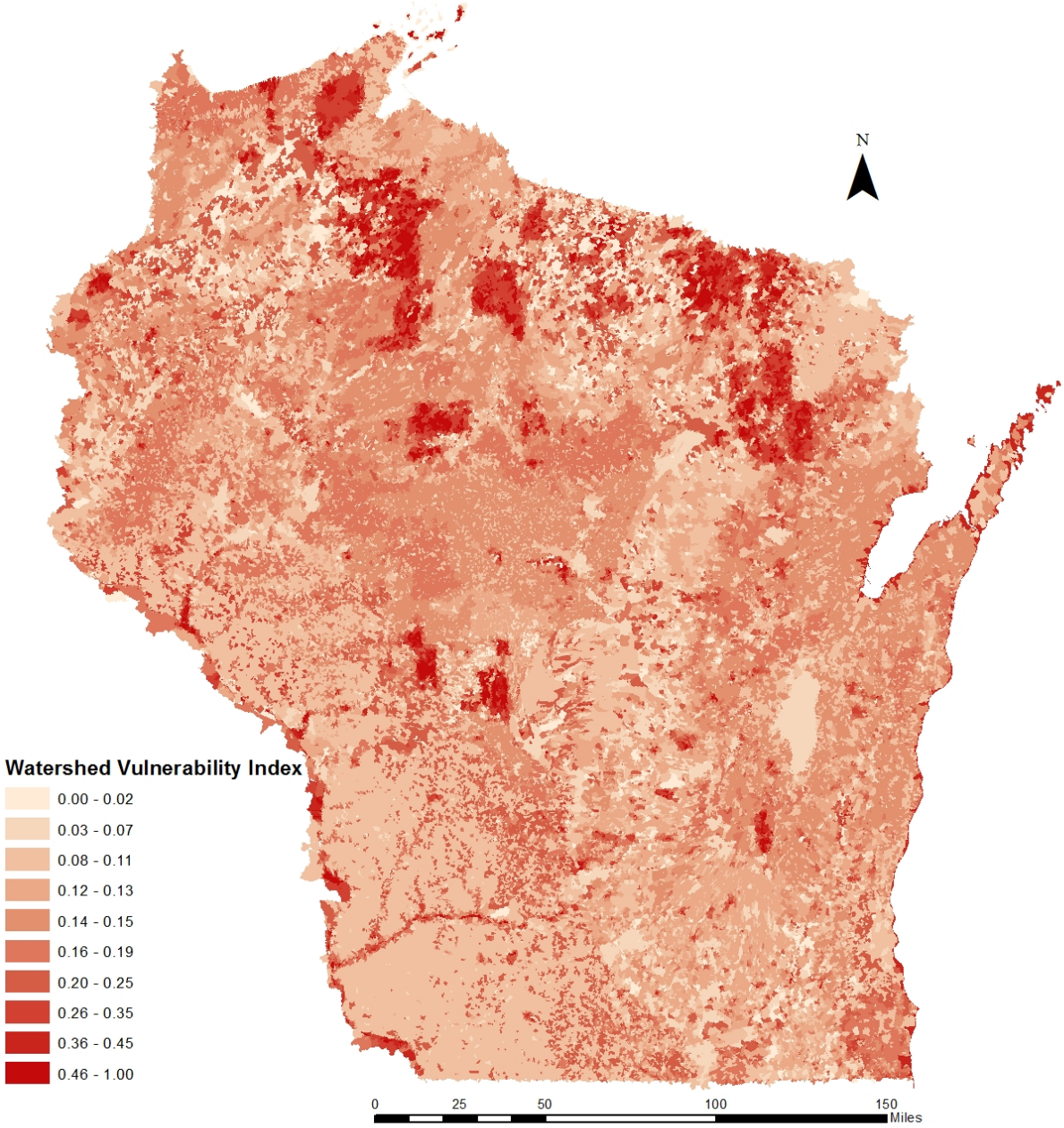

Figure 23 Map of Watershed Vulnerability Index scores.

4 Next Steps and Applications

TBD

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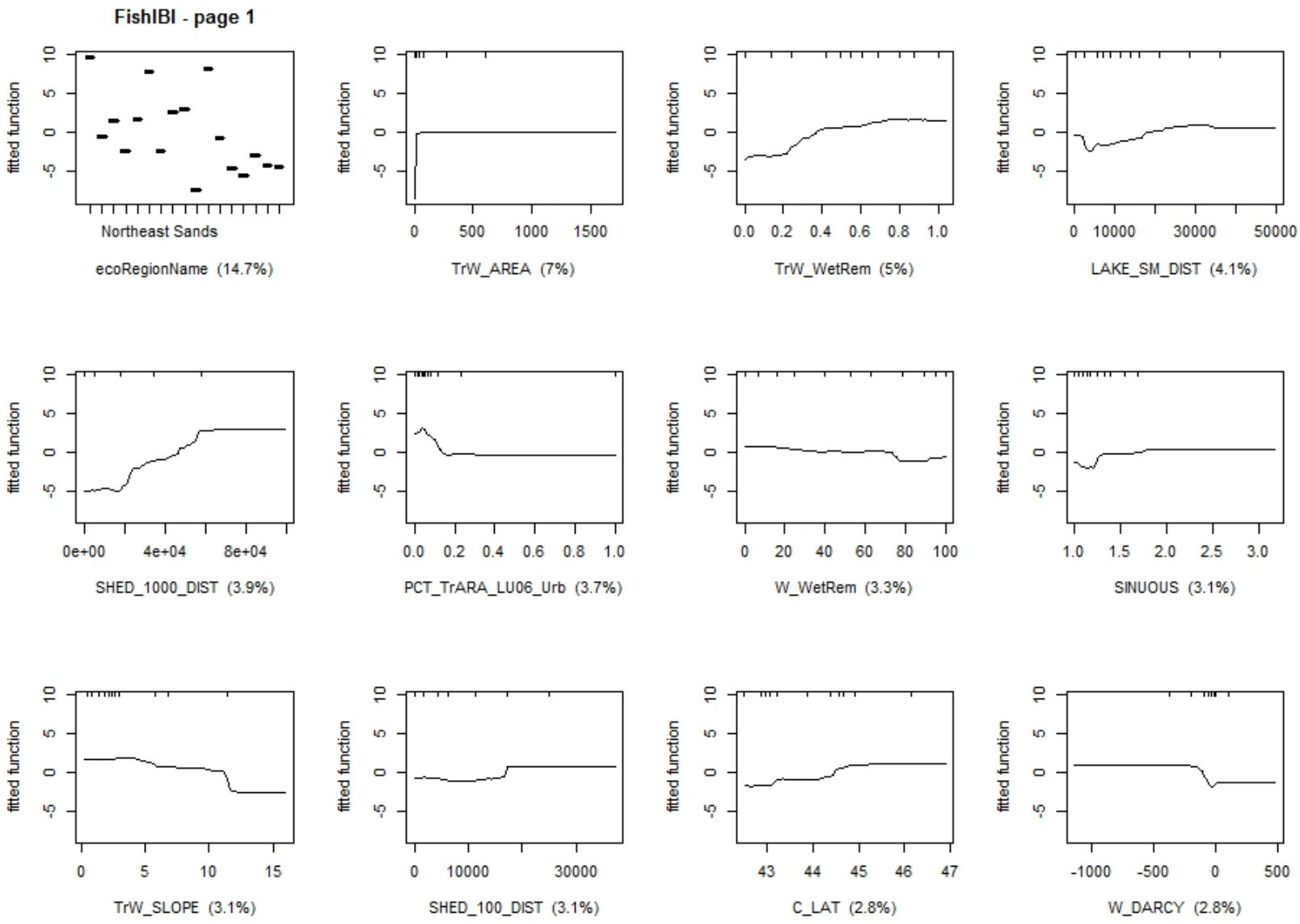
Appendix A. Detailed Results

The table below contains the relative influence values (in percent) for each explanatory variable in the seven boosted regression tree models. The figures that follow contain the partial dependency plots for each explanatory variable and the modeled response variable.

Explanatory Variable	Fish IBI Score	Stream Habitat Score	Macroinvert. IBI Score	Ammonia	Nitrate-Nitrite	Phosphorous	Suspended Sediment
Area - Upstream Watershed	6.96	9.96	2.72	2.13	0.91	4.51	3.81
Distance to Nearest Large Lake (m)	0.99	0.52	0.74	0.38	0.93	0.67	0.00
Distance to Nearest Medium Lake (m)	2.08	1.54	2.24	1.25	0.50	1.32	0.00
Distance to Nearest Small Lake (m)	4.10	2.58	1.49	1.66	1.14	3.82	0.35
Downstream Distance to Watershed >= 100 sq km (m)	3.05	3.05	2.07	1.86	0.72	3.81	0.98
Downstream Distance to Watershed >= 1000 sq km (m)	3.93	2.99	1.65	3.31	0.36	1.09	0.00
Ecoregion Name	14.67	9.06	6.50	9.78	17.13	9.64	15.93
Latitude	2.76	4.52	3.02	2.42	5.37	1.54	4.52
Longitude	1.32	0.85	3.07	1.79	1.78	2.78	0.94
Mean Darcy Value - Local Catchment	2.76	0.75	0.85	1.12	1.84	1.52	1.09
Mean Darcy Value - Upstream Riparian Zone	1.53	0.87	1.66	1.45	2.41	5.56	1.79
Mean Darcy Value - Upstream Watershed	1.90	0.81	1.75	0.96	0.62	1.67	0.94
Mean Slope - Local Catchment	1.34	1.70	1.56	1.61	0.83	1.54	3.79
Mean Slope - Local Riparian Zone	1.82	3.54	1.84	3.15	0.46	2.01	2.59
Mean Slope - Upstream Riparian Zone	1.34	2.42	3.86	1.22	1.40	3.34	1.75
Mean Slope - Upstream Watershed	3.07	3.92	1.42	1.75	0.97	1.96	0.87
Mean Soil Permeability - Local Catchment	0.88	0.97	0.83	0.83	0.26	2.37	0.23
Mean Soil Permeability - Local Riparian Zone	0.75	1.00	1.11	0.74	0.39	1.30	0.61
Mean Soil Permeability - Upstream Riparian Zone	1.17	1.40	0.77	1.31	1.48	1.58	0.43
Mean Soil Permeability - Upstream Watershed	1.14	1.55	1.16	1.23	0.77	1.19	0.15
Percent Agricultural Landcover - Active River Area	1.37	1.46	0.90	3.15	1.42	1.75	1.03
Percent Agricultural Landcover - Local Catchment	1.11	0.95	0.53	5.50	2.15	1.77	2.04

Explanatory Variable	Fish IBI Score	Stream Habitat Score	Macroinvert. IBI Score	Ammonia	Nitrate-Nitrite	Phosphorous	Suspended Sediment
Percent Agricultural Landcover - Upstream Active River Area	2.05	1.00	1.49	2.73	9.54	2.68	1.78
Percent Agricultural Landcover - Upstream Watershed	1.69	1.79	1.04	5.41	18.47	2.00	3.01
Percent Natural Landcover - Active River Area	1.30	3.13	1.57	1.71	1.09	2.33	0.69
Percent Natural Landcover - Local Catchment	1.61	1.65	3.35	2.27	0.40	1.16	5.66
Percent Natural Landcover - Upstream Active River Area	1.85	6.17	3.47	2.65	3.04	2.30	1.01
Percent Natural Landcover - Upstream Watershed	1.74	1.00	26.15	5.71	3.18	2.09	3.08
Percent of Streams Classified as Canals - Local Catchment	0.00	0.27	0.76	0.00	0.91	0.23	0.00
Percent Protected Land - Local Catchment	0.14	0.16	0.33	0.86	0.26	0.28	0.04
Percent Protected Land - Upstream Watershed	0.83	0.46	1.13	0.54	0.42	0.77	0.78
Percent Urban Landcover - Active River Area	2.13	1.89	1.57	4.08	1.22	2.42	1.62
Percent Urban Landcover - Local Catchment	1.95	1.98	1.05	1.42	0.62	1.10	1.26
Percent Urban Landcover - Upstream Active River Area	3.72	1.66	2.16	3.63	2.27	3.70	2.72
Percent Urban Landcover - Upstream Watershed	2.45	1.06	1.82	2.81	0.40	1.09	1.06
Percent Wetlands Remaining - Local Catchment	3.35	3.10	2.64	4.05	1.21	2.38	5.38
Percent Wetlands Remaining - Upstream Watershed	4.97	3.58	2.49	3.63	1.83	6.18	7.52
Presence of Dam	0.00	0.07	0.22	0.08	0.04	0.00	0.00
Stream Sinuosity	3.07	9.01	2.11	1.74	8.48	6.15	2.15
Surface Runoff - Upstream Watershed	2.59	2.44	1.37	4.43	0.96	2.30	16.54
Total Nitrogen Loading - Upstream Watershed	1.42	1.29	0.91	1.65	1.07	1.13	1.11
Total Phosphorus Loading - Upstream Watershed	0.89	0.55	0.87	0.33	0.11	0.65	0.21
Total Suspended Solids Loading - Upstream Watershed	2.17	1.34	1.77	1.70	0.63	2.32	0.52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SHED_1000_DIST (3.9%)
PCT_TrARA_LU06_Urb (3.7%)
W_WetRem (3.3%)
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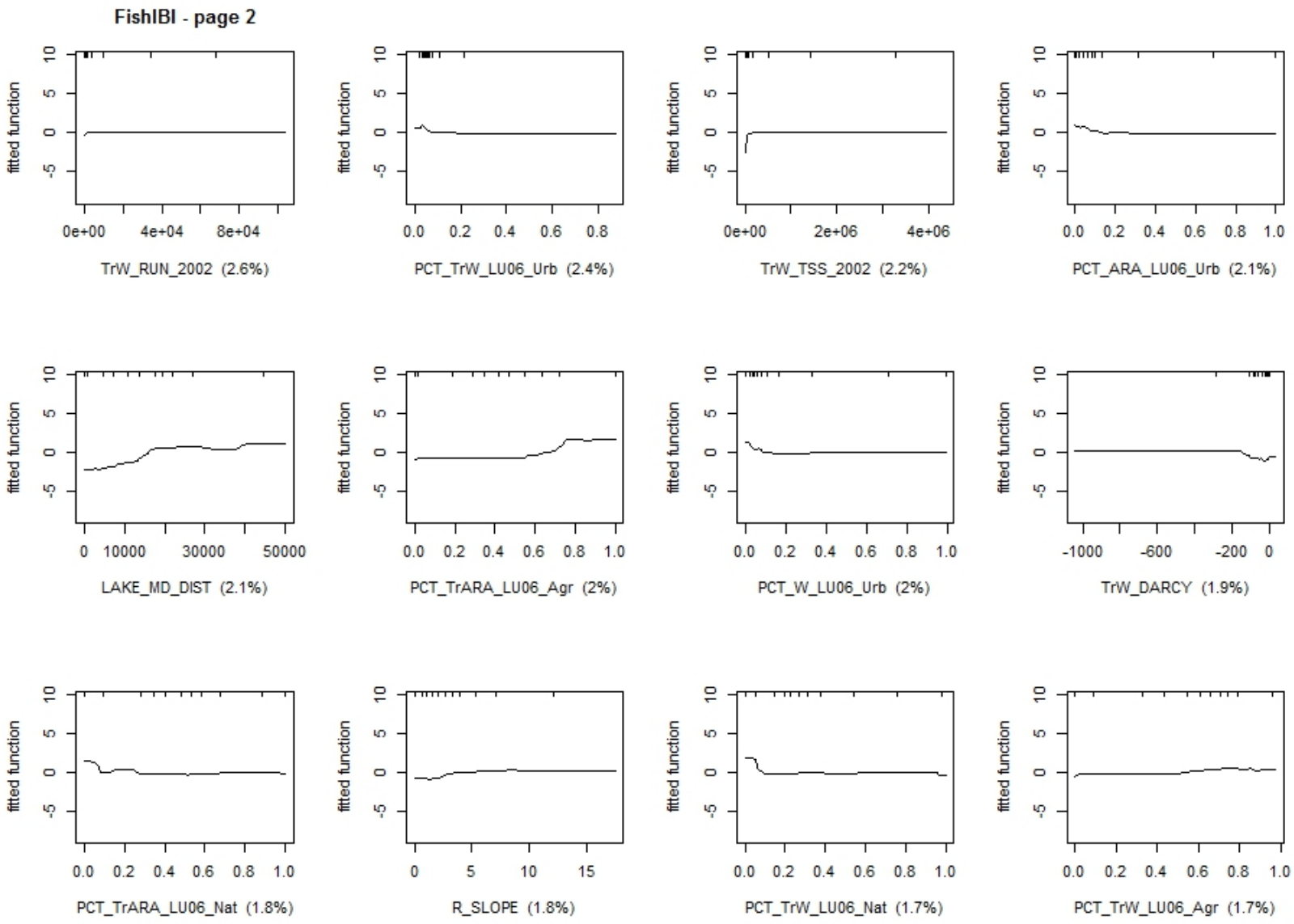
W_DARCY (2.8%)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PCT_TrARA_LU06_Agr (2%)
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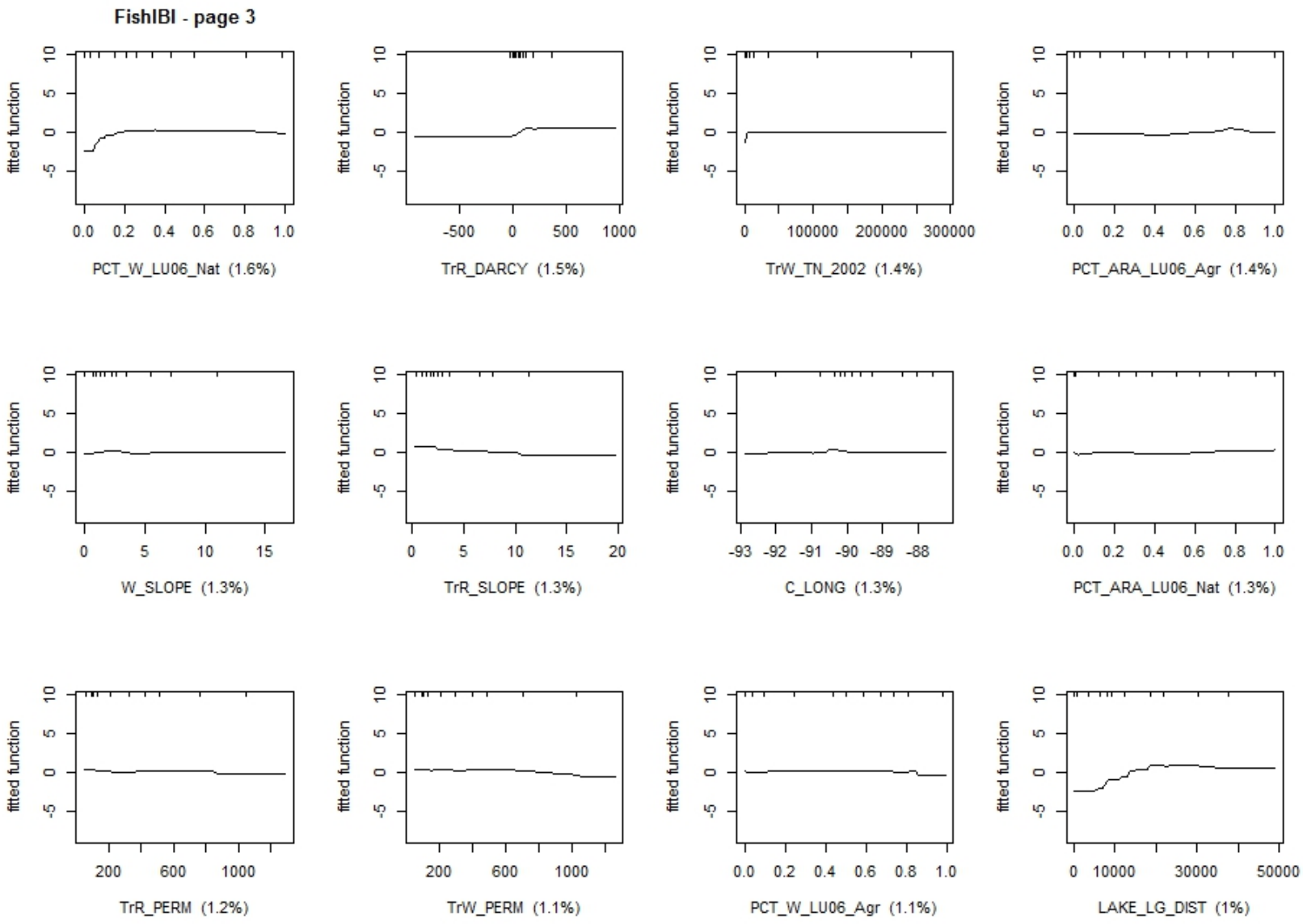
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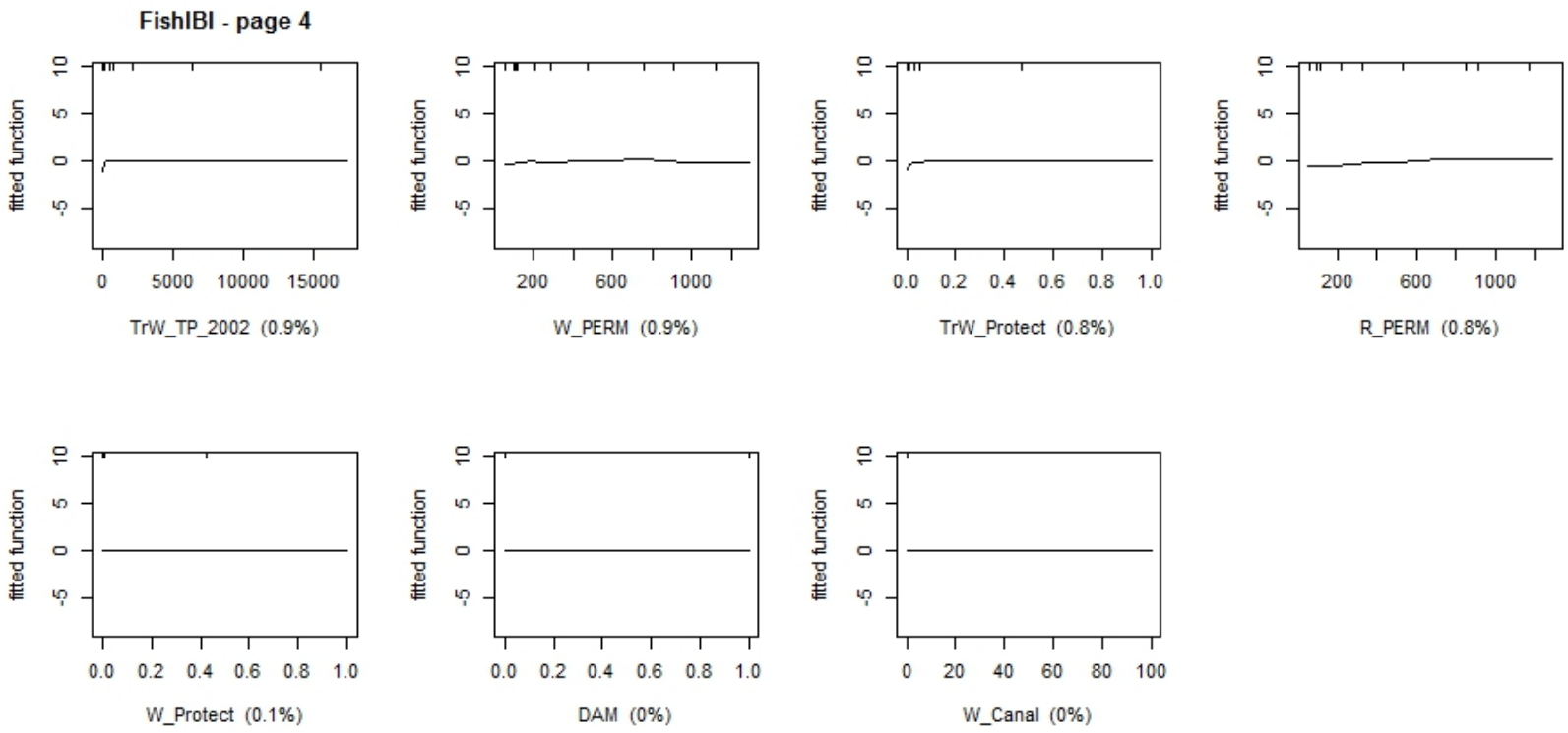
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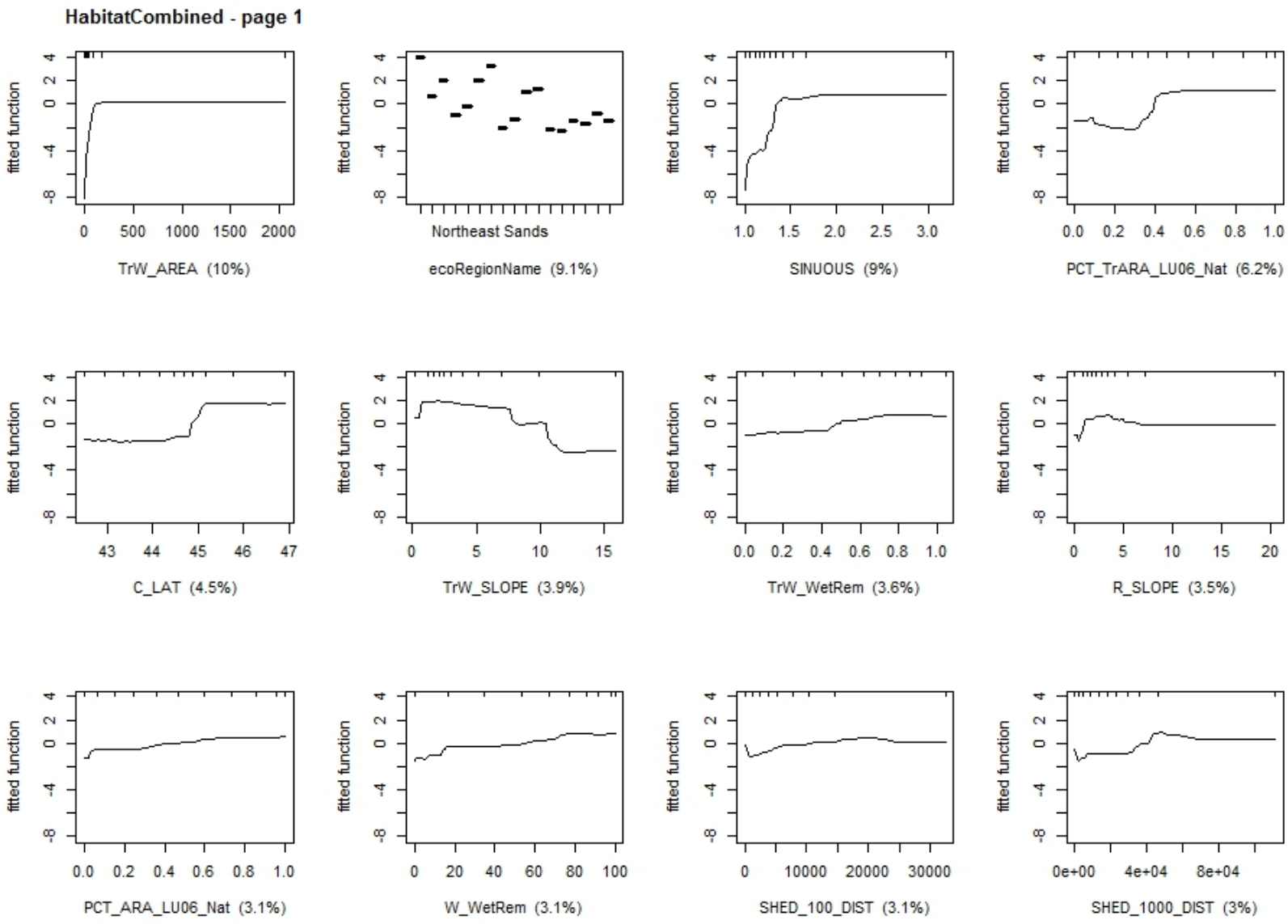
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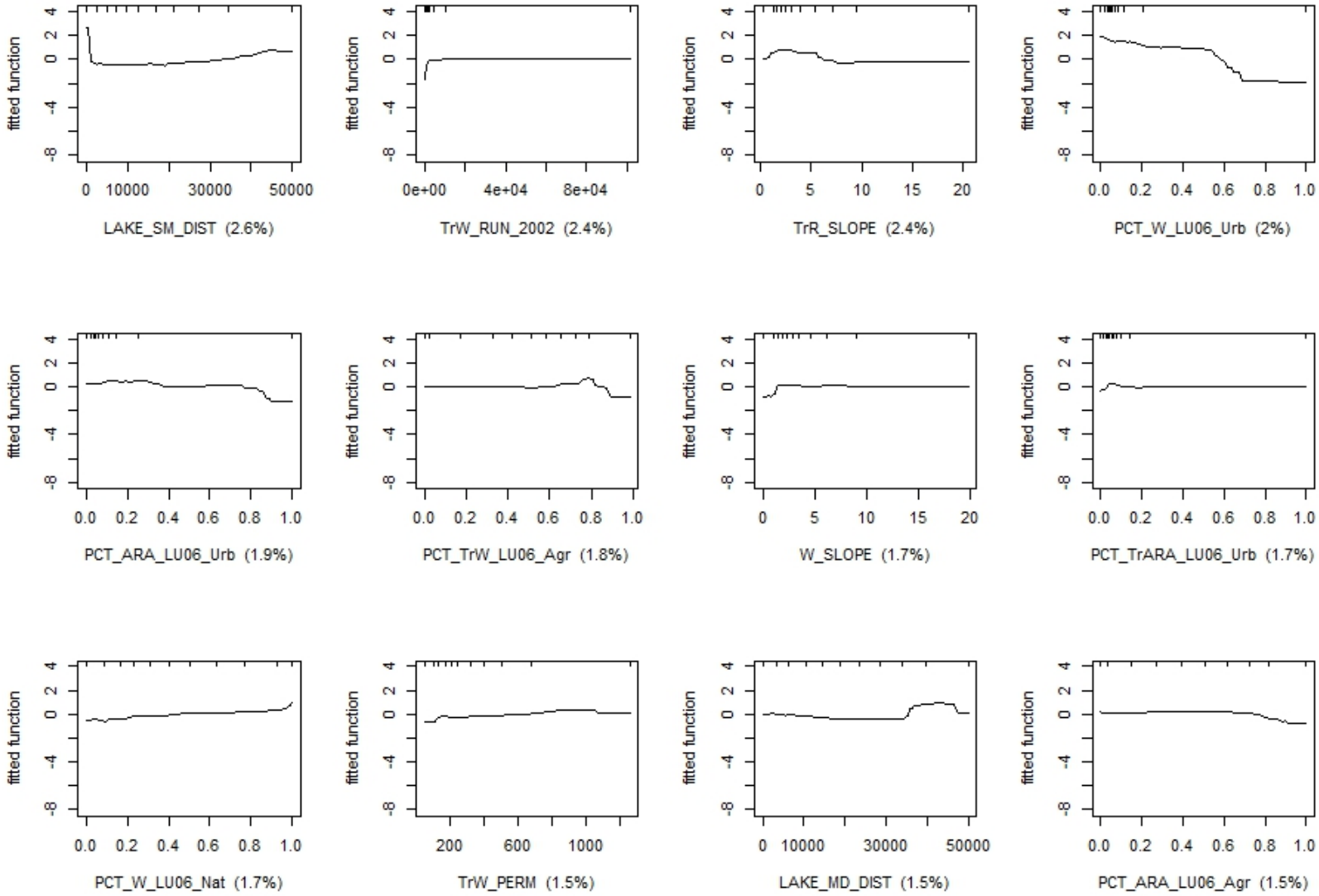
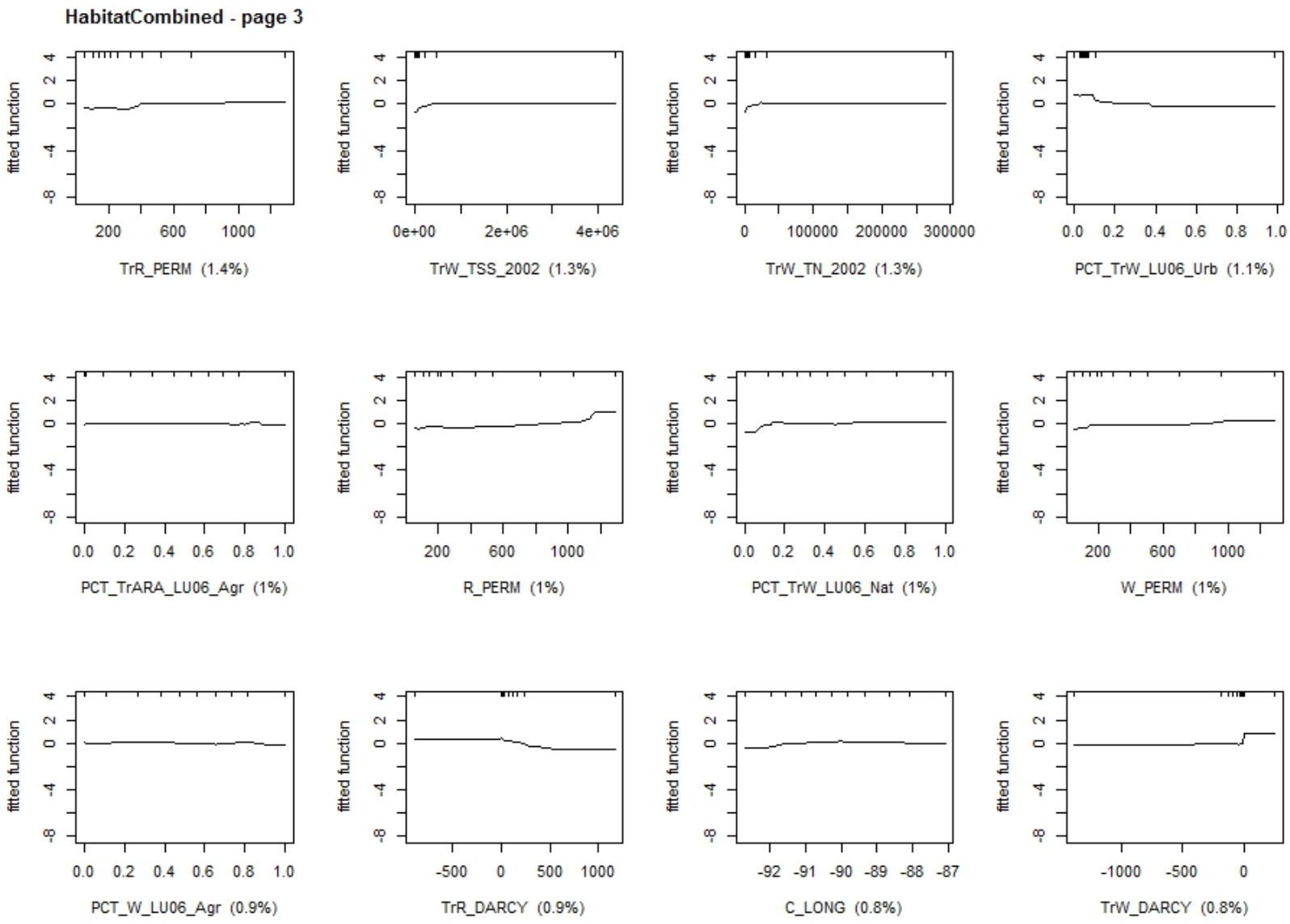
HabitatCombined - page 2

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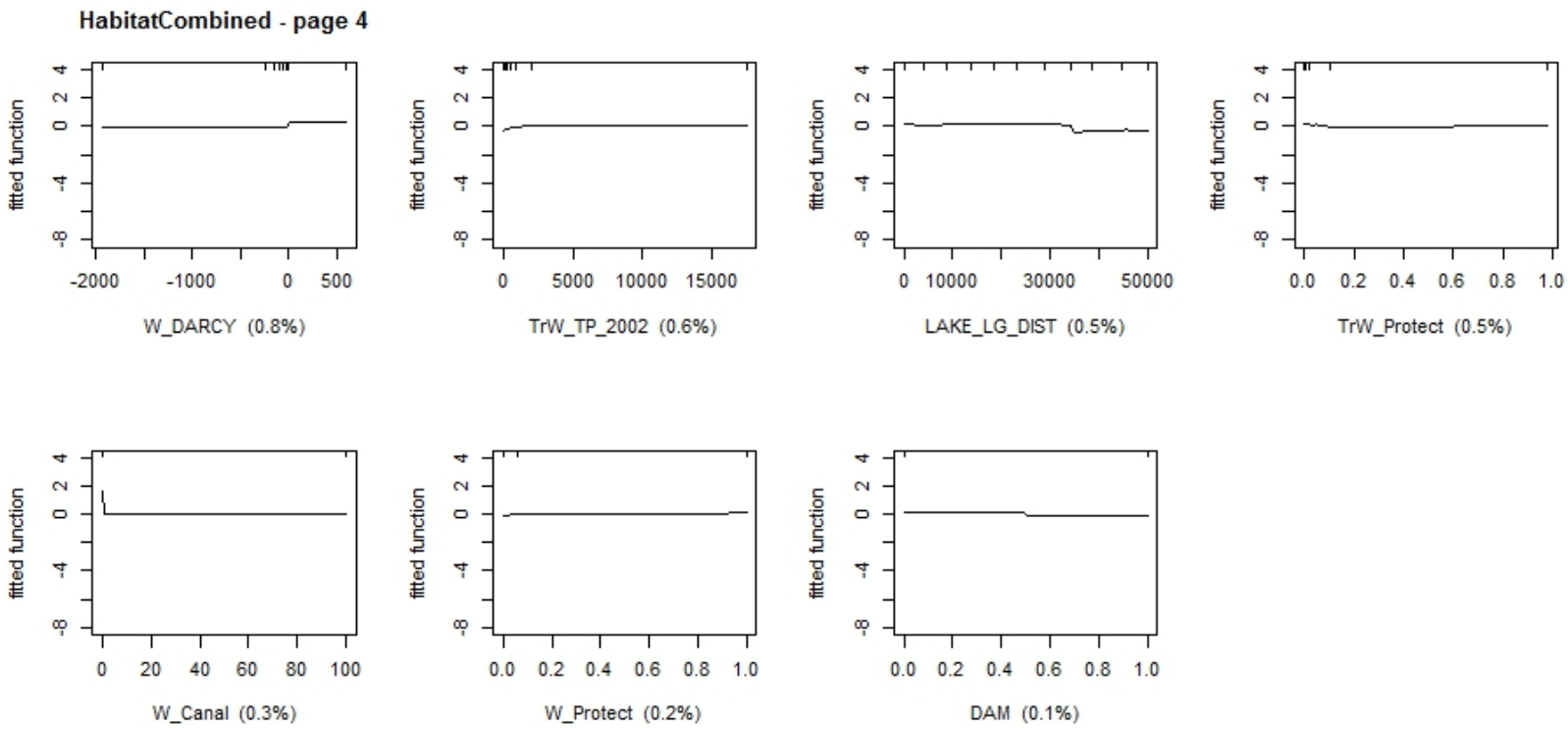
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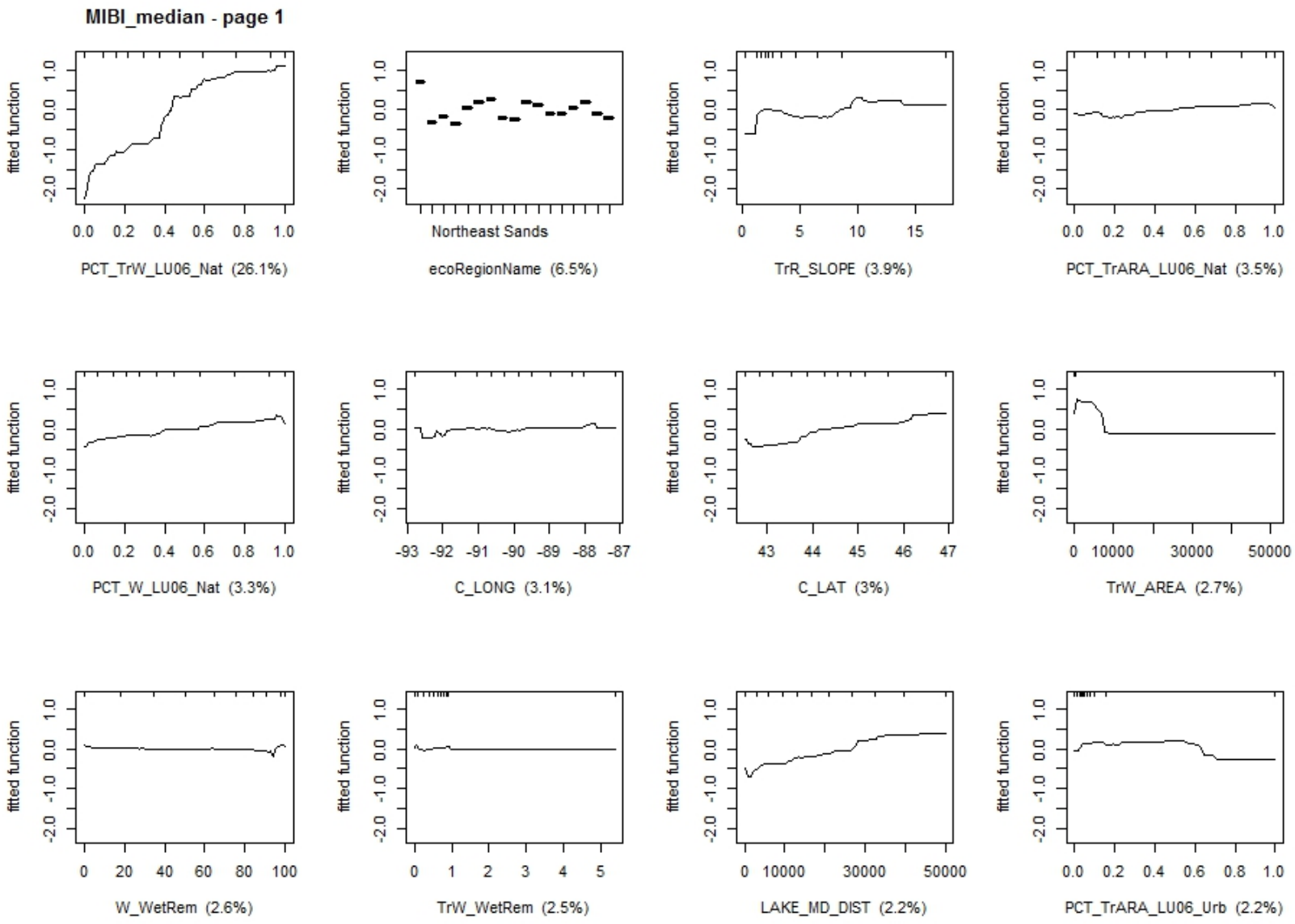
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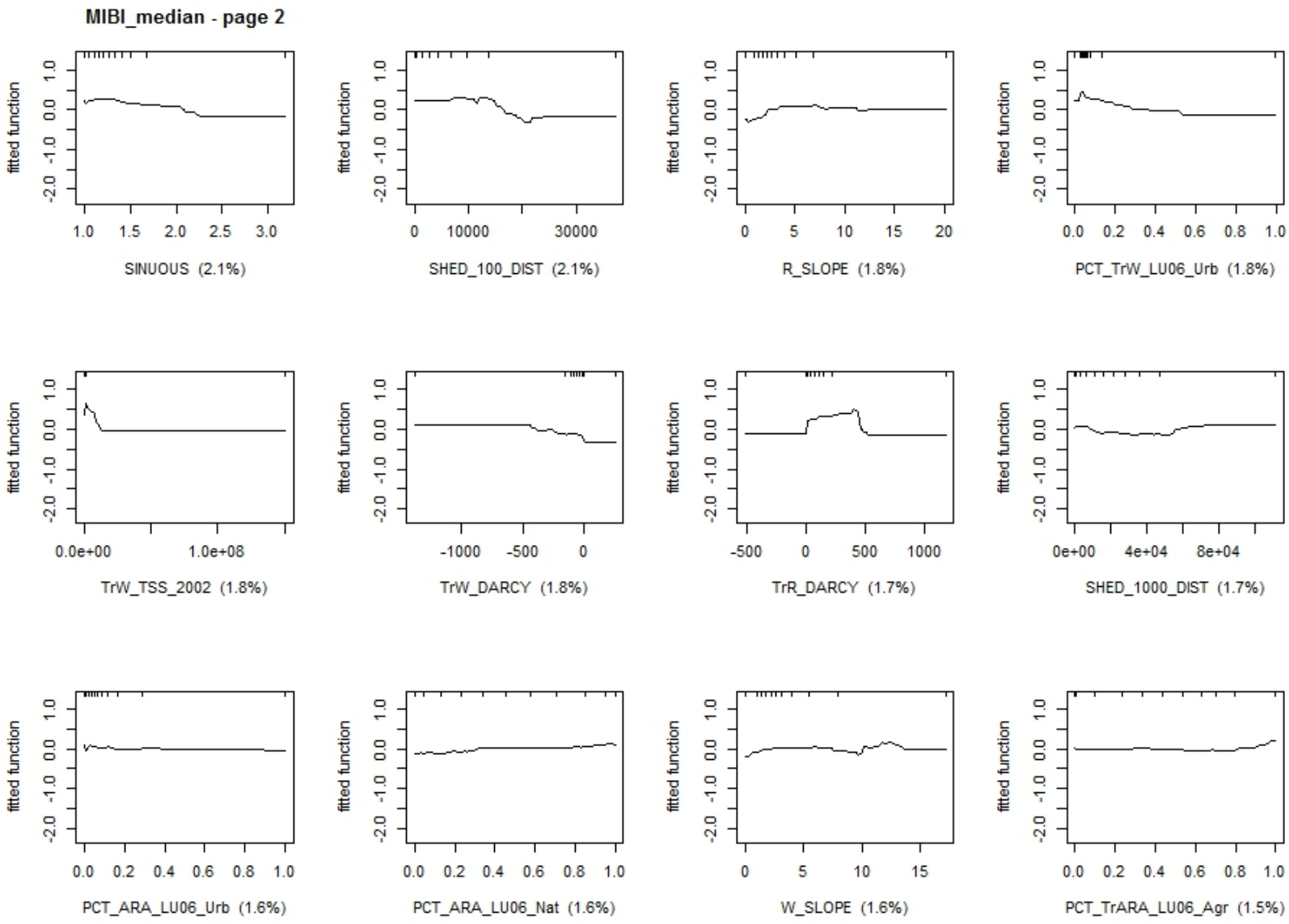
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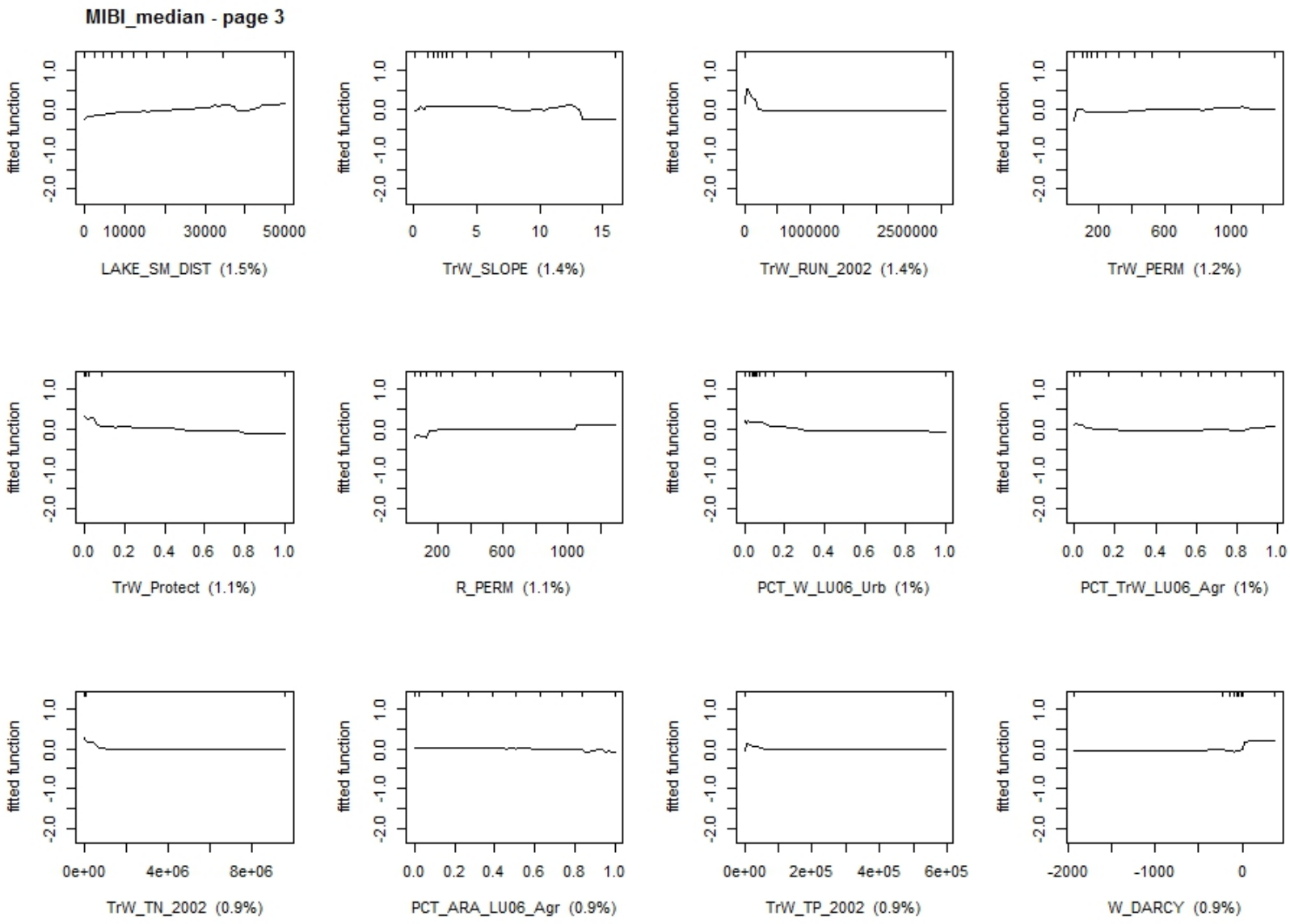
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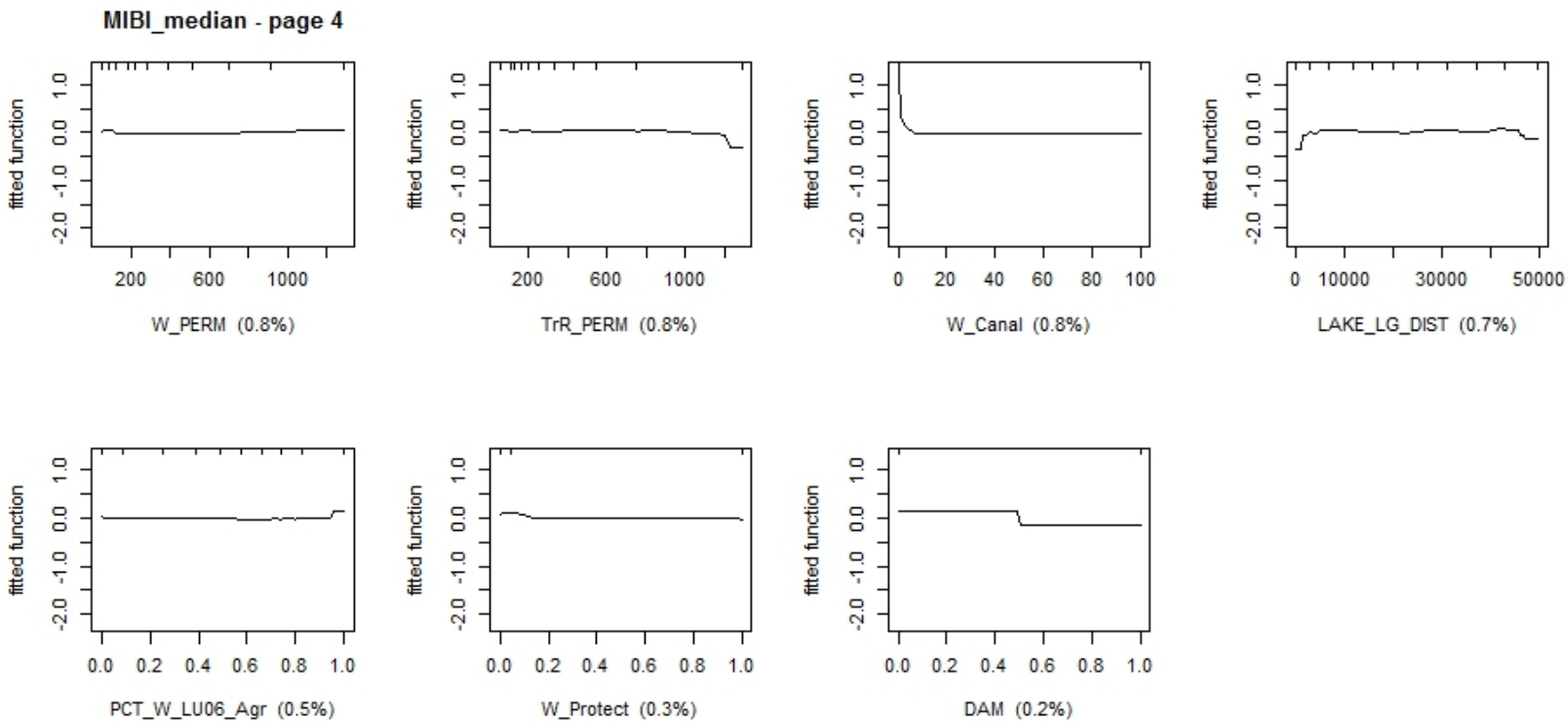
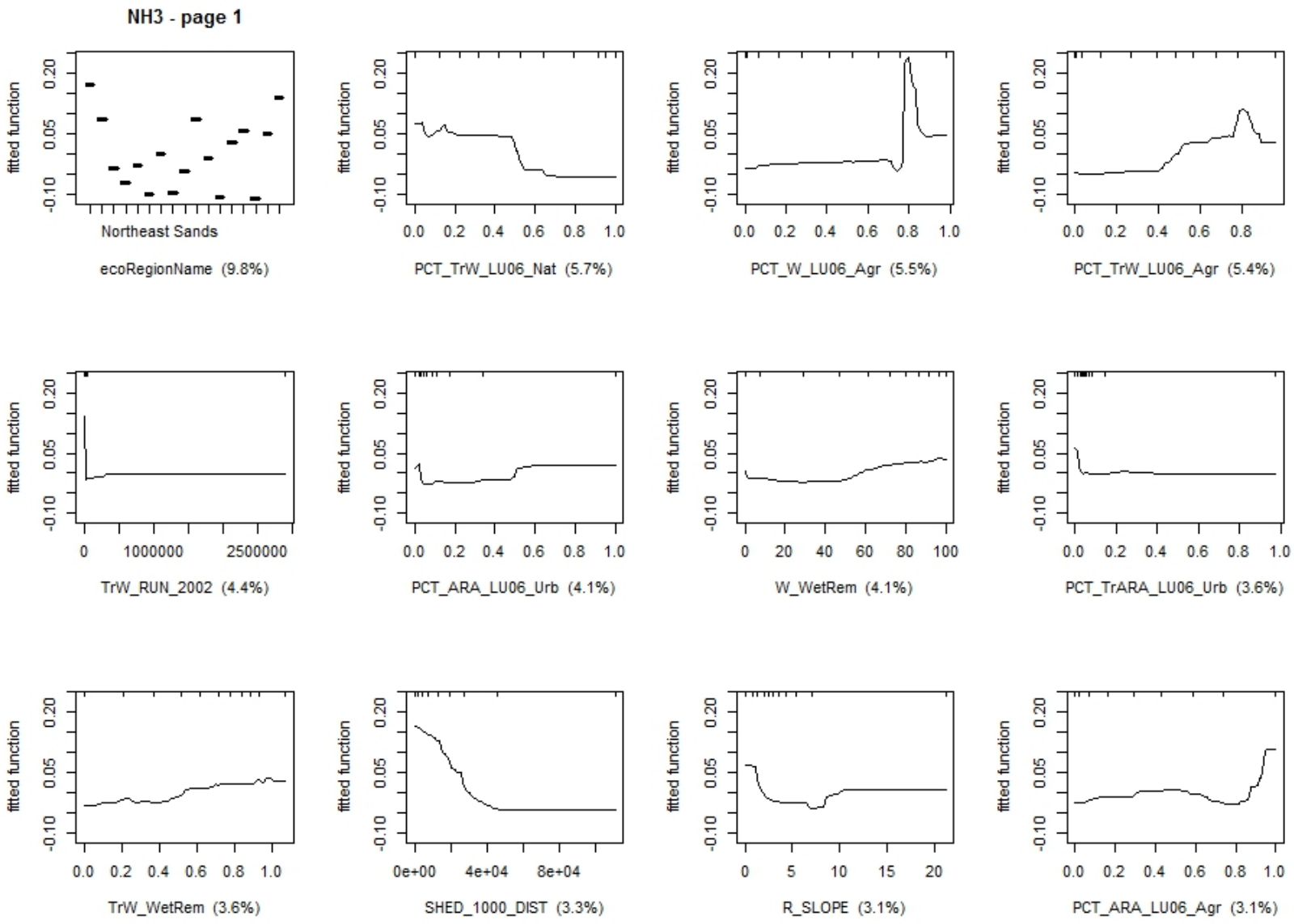
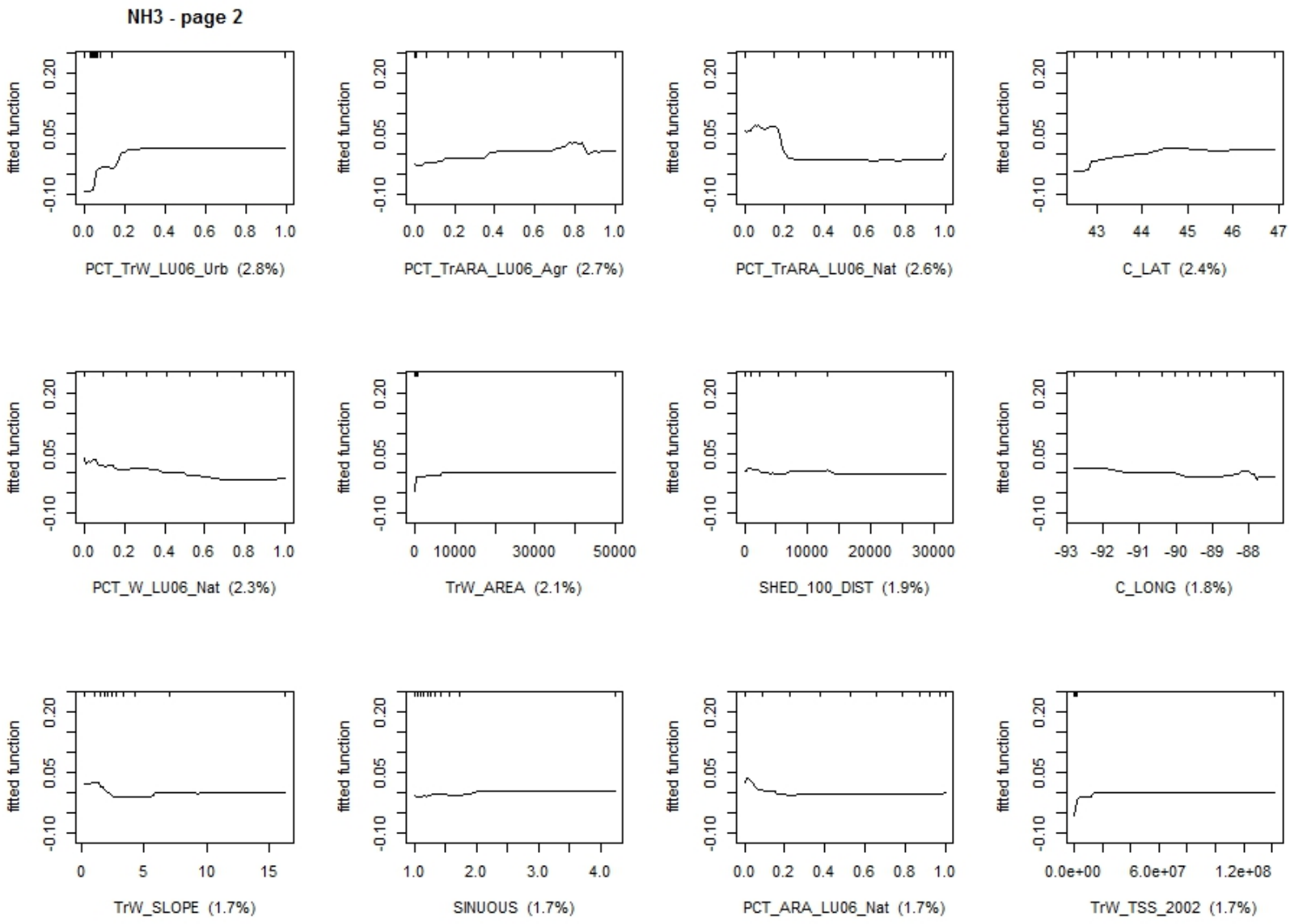
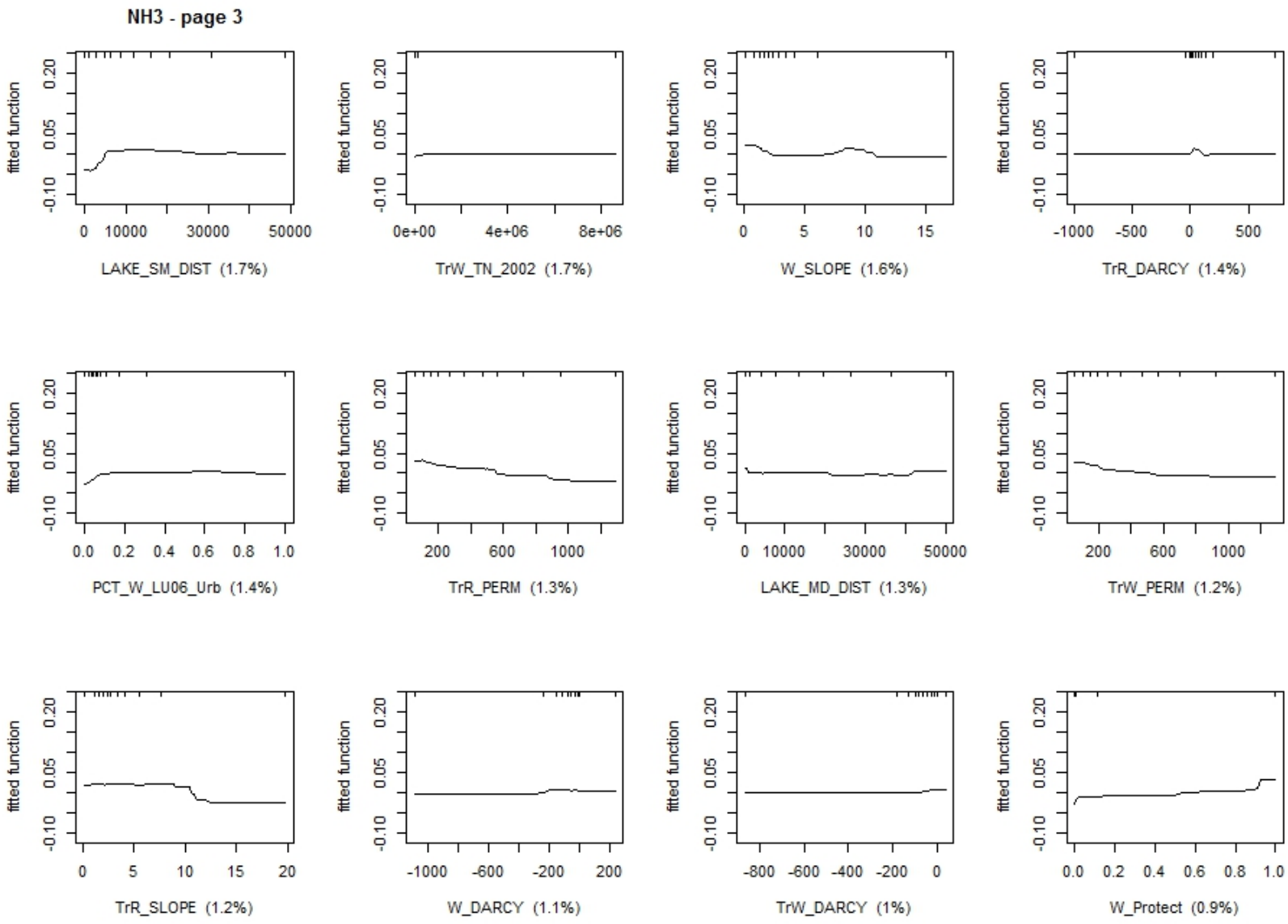
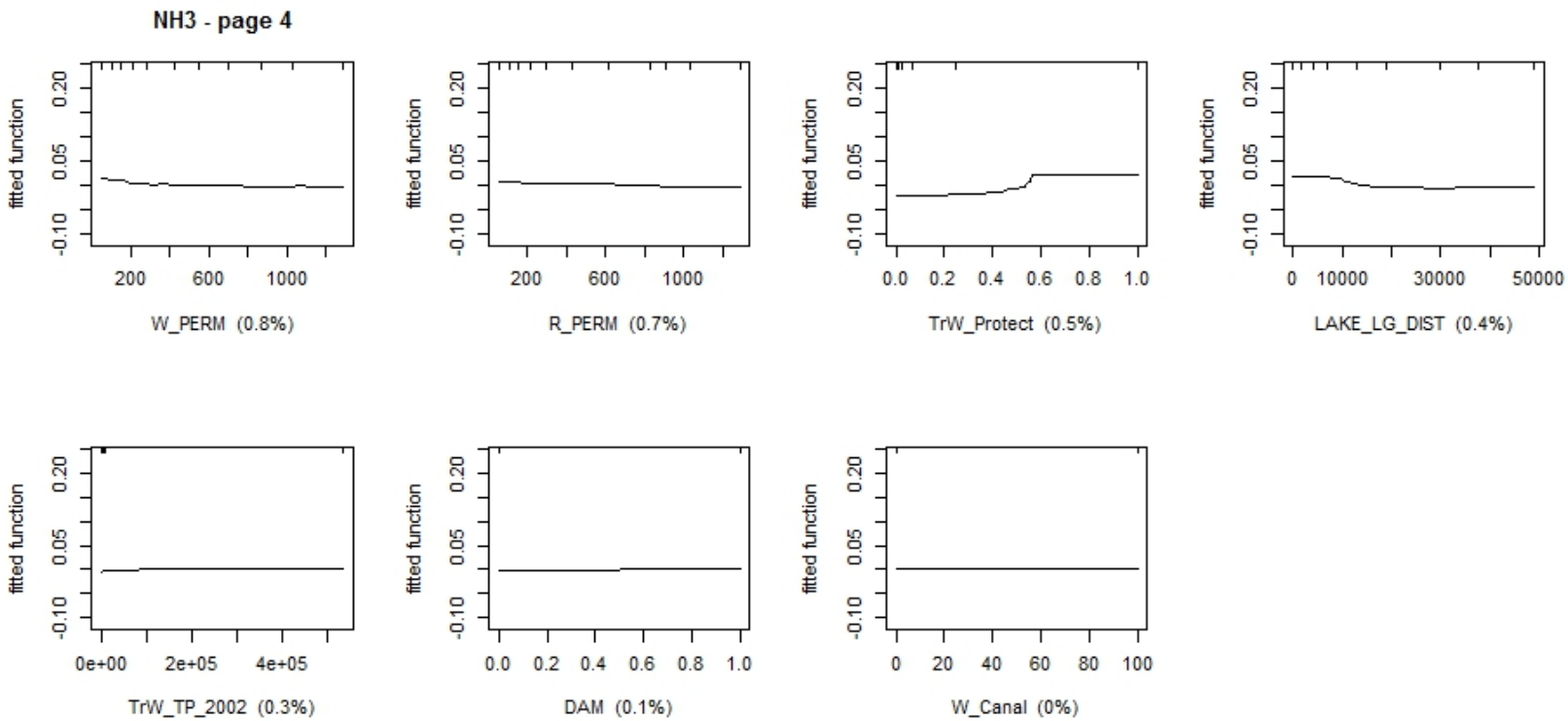
TrW_PERM (1.2%)
TrW_Protect (1.1%)
R_PERM (1.1%)
PCT_W_LU06_Urb (1%)
PCT_TrW_LU06_Agr (1%)
TrW_TN_2002 (0.9%)
PCT_ARA_LU06_Agr (0.9%)
TrW_TP_2002 (0.9%)
W_DARCY (0.9%)

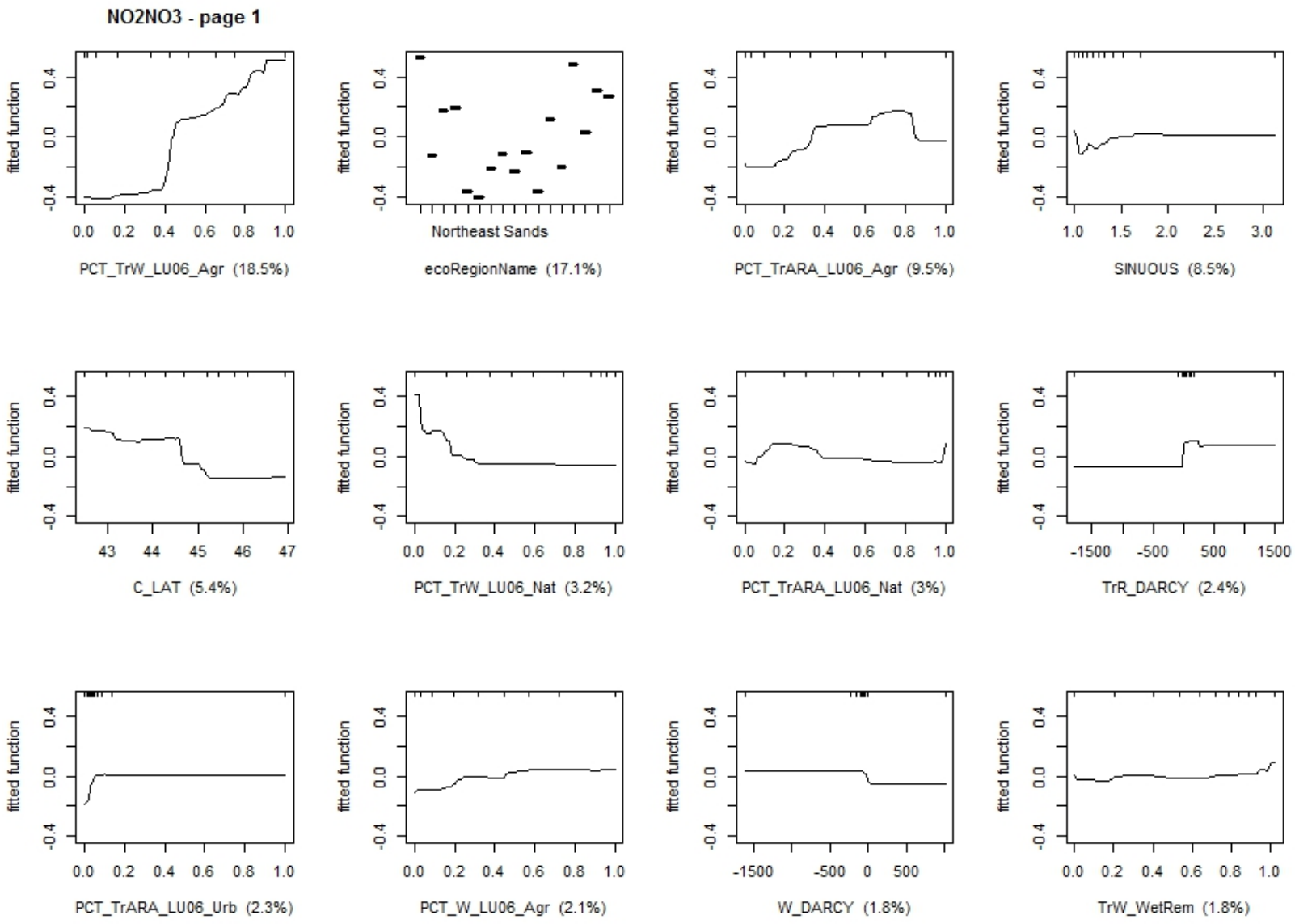

MIBI_median - page 4
fitted function
W_PERM (0.8%)
TrR_PERM (0.8%)
W_Canal (0.8%)
LAKE_LG_DIST (0.7%)
PCT_W_LU06_Agr (0.5%)
W_Protect (0.3%)
DAM (0.2%)

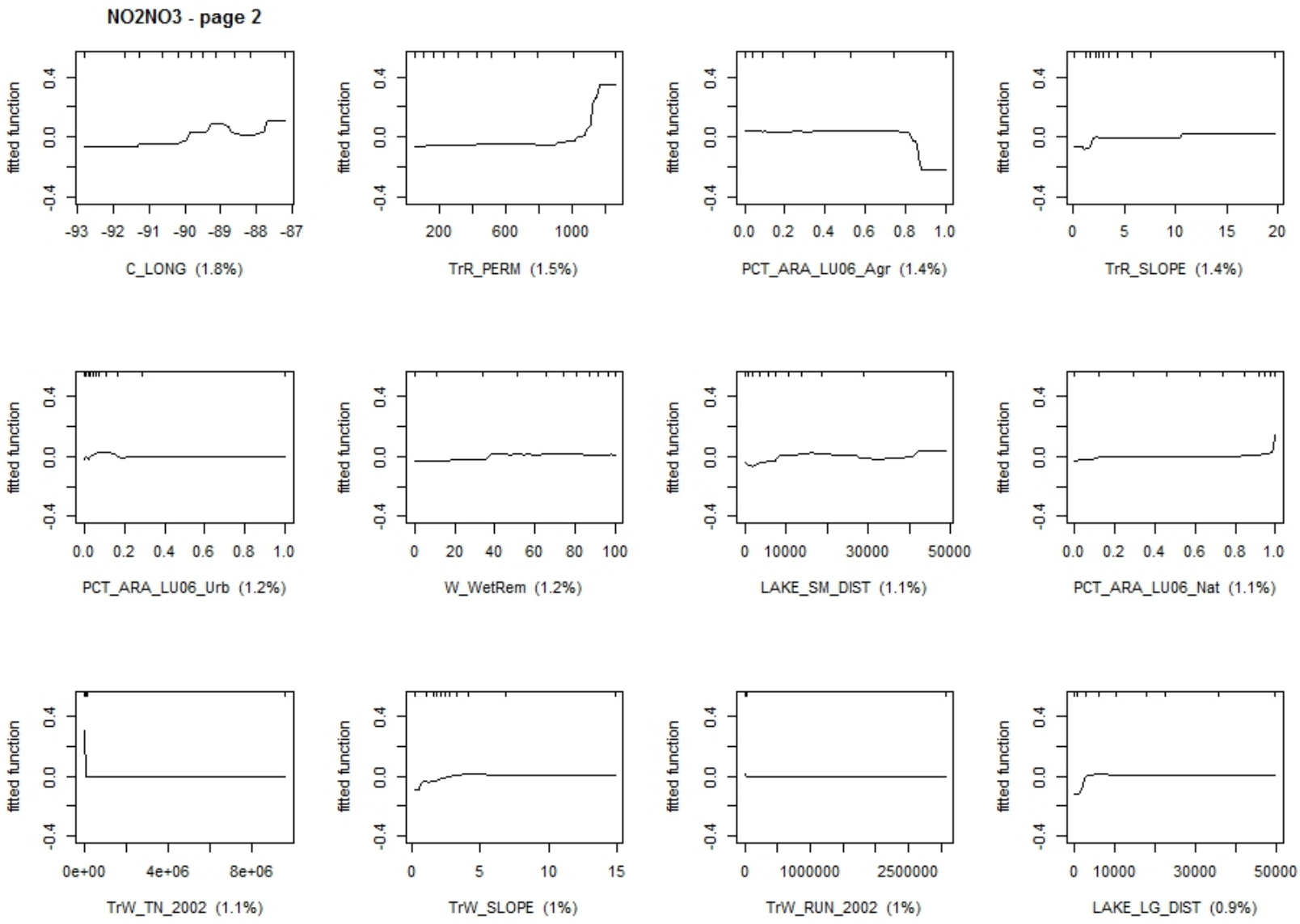

NH3 - page 1
fitted function
Northeast Sands
ecoRegionName (9.8%)
PCT_TrW_LU06_Nat (5.7%)
PCT_W_LU06_Agr (5.5%)
PCT_TrW_LU06_Agr (5.4%)
TrW_RUN_2002 (4.4%)
PCT_ARA_LU06_Urb (4.1%)
W_WetRem (4.1%)
PCT_TrARA_LU06_Urb (3.6%)
TrW_WetRem (3.6%)
SHED_1000_DIST (3.3%)
R_SLOPE (3.1%)
PCT_ARA_LU06_Agr (3.1%)

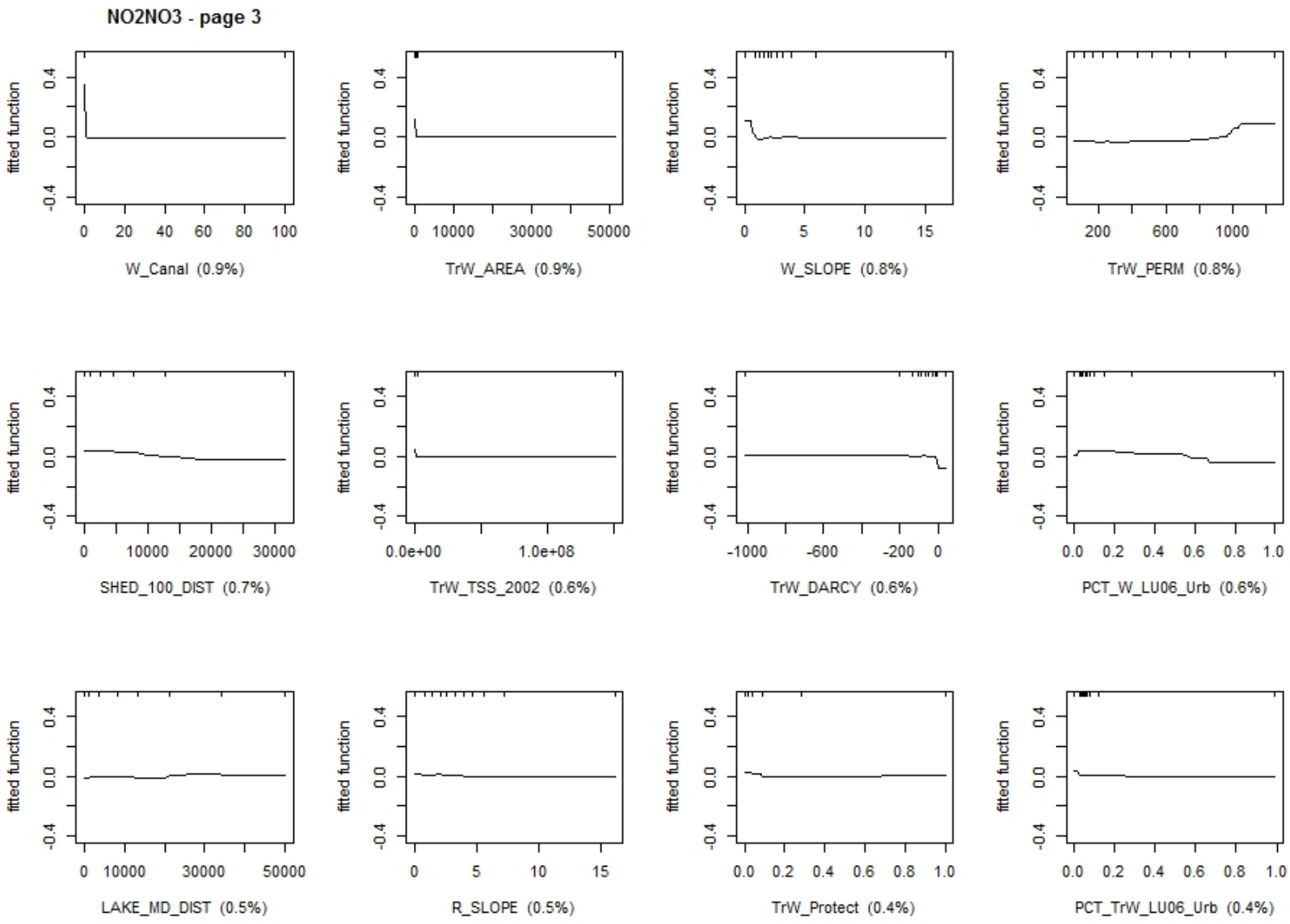

NH3 - page 2
fitted function
PCT_TrW_LU06_Urb (2.8%)
PCT_TrARA_LU06_Agr (2.7%)
PCT_TrARA_LU06_Nat (2.6%)
C_LAT (2.4%)
PCT_W_LU06_Nat (2.3%)
TrW_AREA (2.1%)
SHED_100_DIST (1.9%)
C_LONG (1.8%)
TrW_SLOPE (1.7%)
SINUOUS (1.7%)
PCT_ARA_LU06_Nat (1.7%)
TrW_TSS_2002 (1.7%)

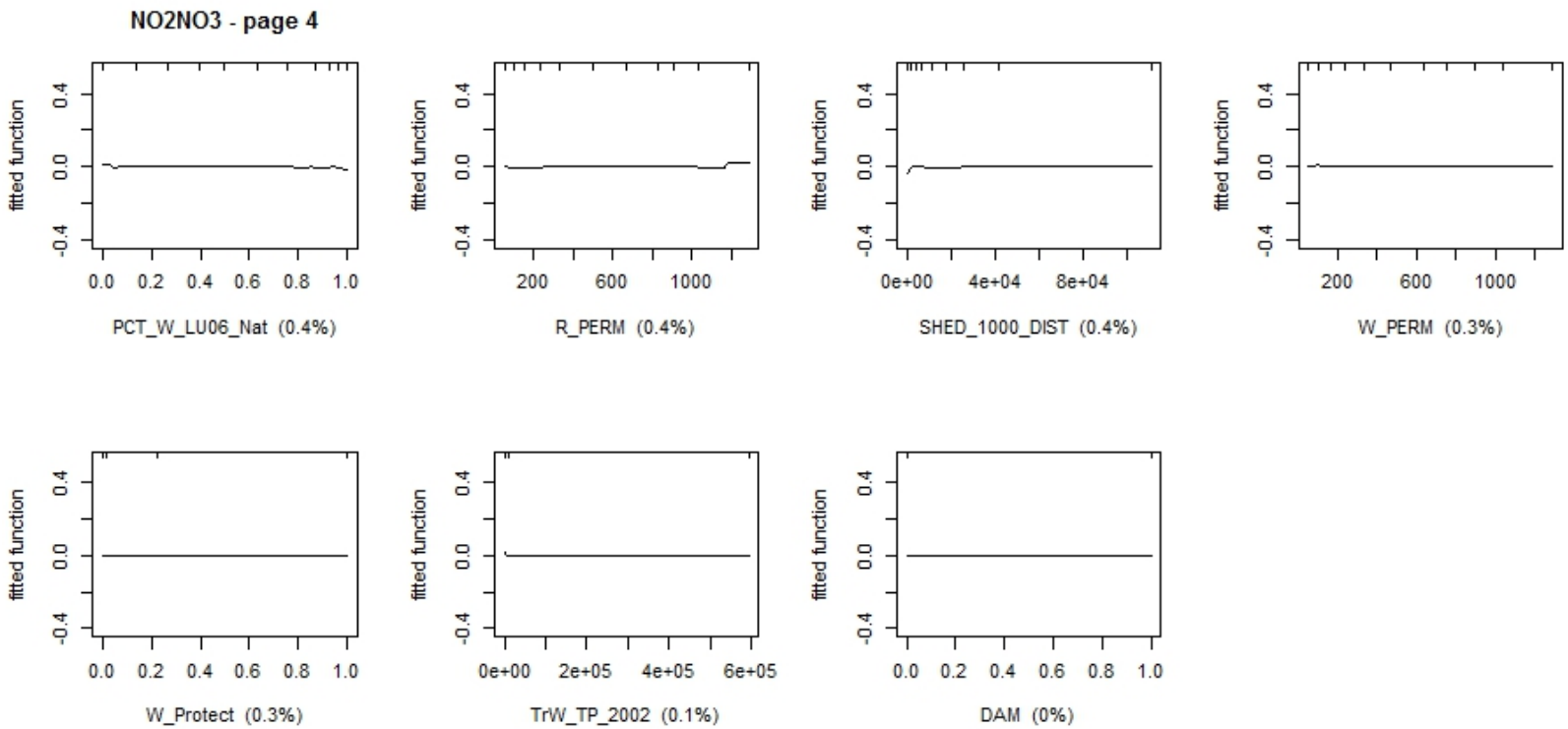

NH3 - page 3
fitted function
LAKE_SM_DIST (1.7%)
TrW_TN_2002 (1.7%)
W_SLOPE (1.6%)
TrR_DARCY (1.4%)
PCT_W_LU06_Urb (1.4%)
TrR_PERM (1.3%)
LAKE_MD_DIST (1.3%)
TrW_PERM (1.2%)
TrR_SLOPE (1.2%)
W_DARCY (1.1%)
TrW_DARCY (1%)
W_Protect (0.9%)

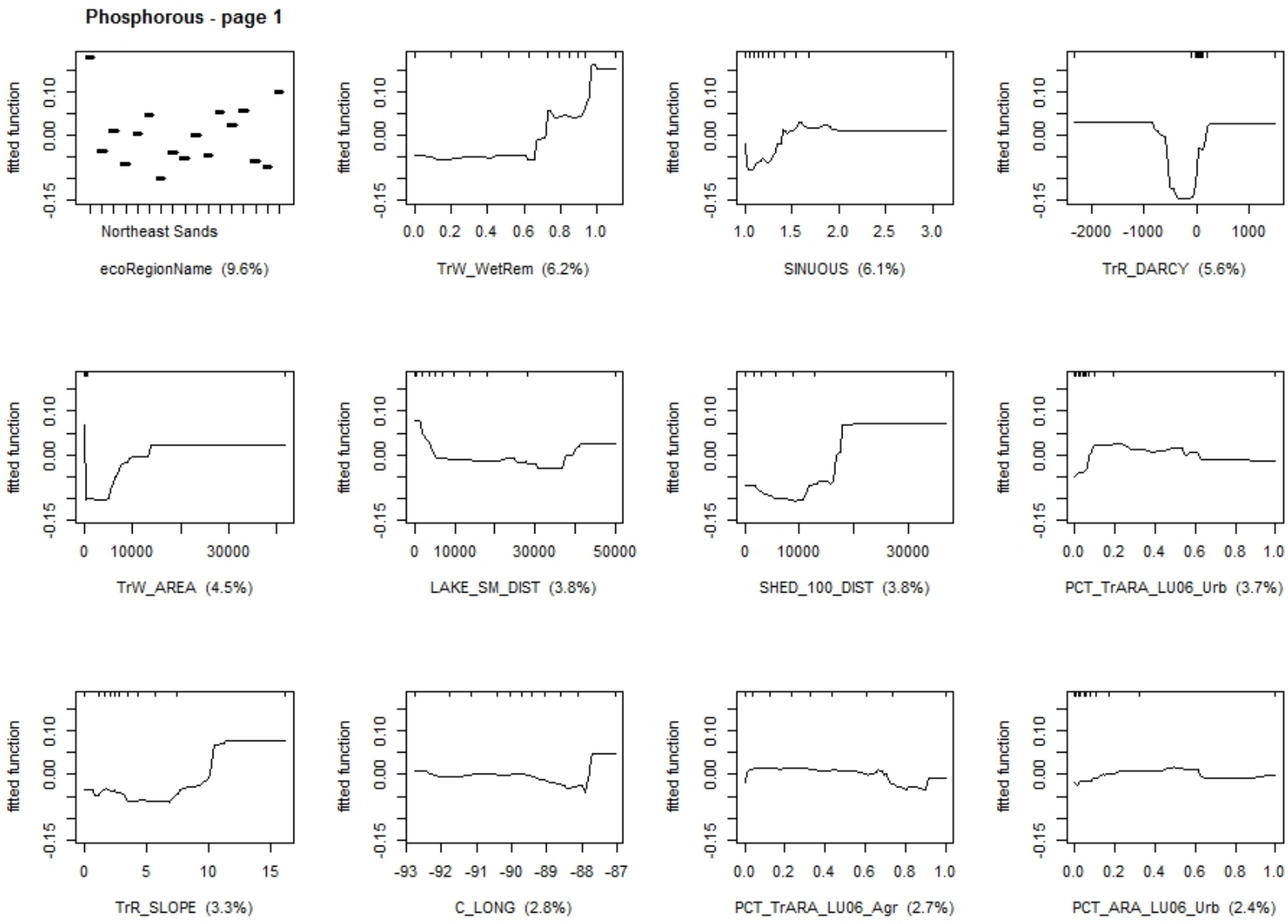

NH3 - page 4
fitted function
-0.10
0.05
0.20
200
600
1000
W_PERM (0.8%)
R_PERM (0.7%)
0.0
0.2
0.4
0.6
0.8
1.0
TrW_Protect (0.5%)
0
10000
30000
50000
LAKE_LG_DIST (0.4%)
0e+00
2e+05
4e+05
TrW_TP_2002 (0.3%)
DAM (0.1%)
0
20
40
60
80
100
W_Canal (0%)

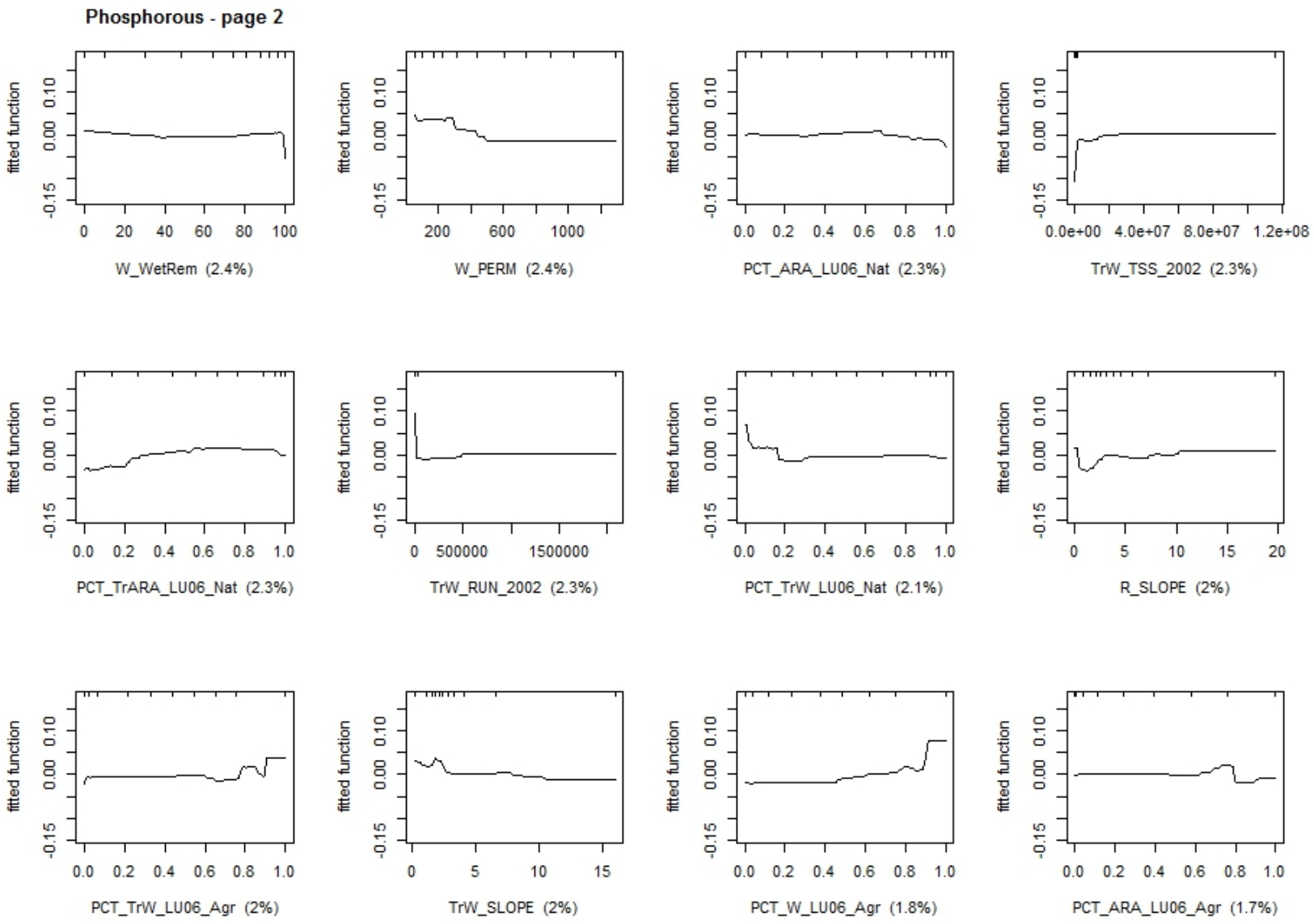

NO2NO3 - page 1
fitted function
PCT_TrW_LU06_Agr (18.5%)
ecoRegionName (17.1%)
Northeast Sands
PCT_TrARA_LU06_Agr (9.5%)
SINUOUS (8.5%)
C_LAT (5.4%)
PCT_TrW_LU06_Nat (3.2%)
PCT_TrARA_LU06_Nat (3%)
TrR_DARCY (2.4%)
PCT_TrARA_LU06_Urb (2.3%)
PCT_W_LU06_Agr (2.1%)
W_DARCY (1.8%)
TrW_WetRem (1.8%)

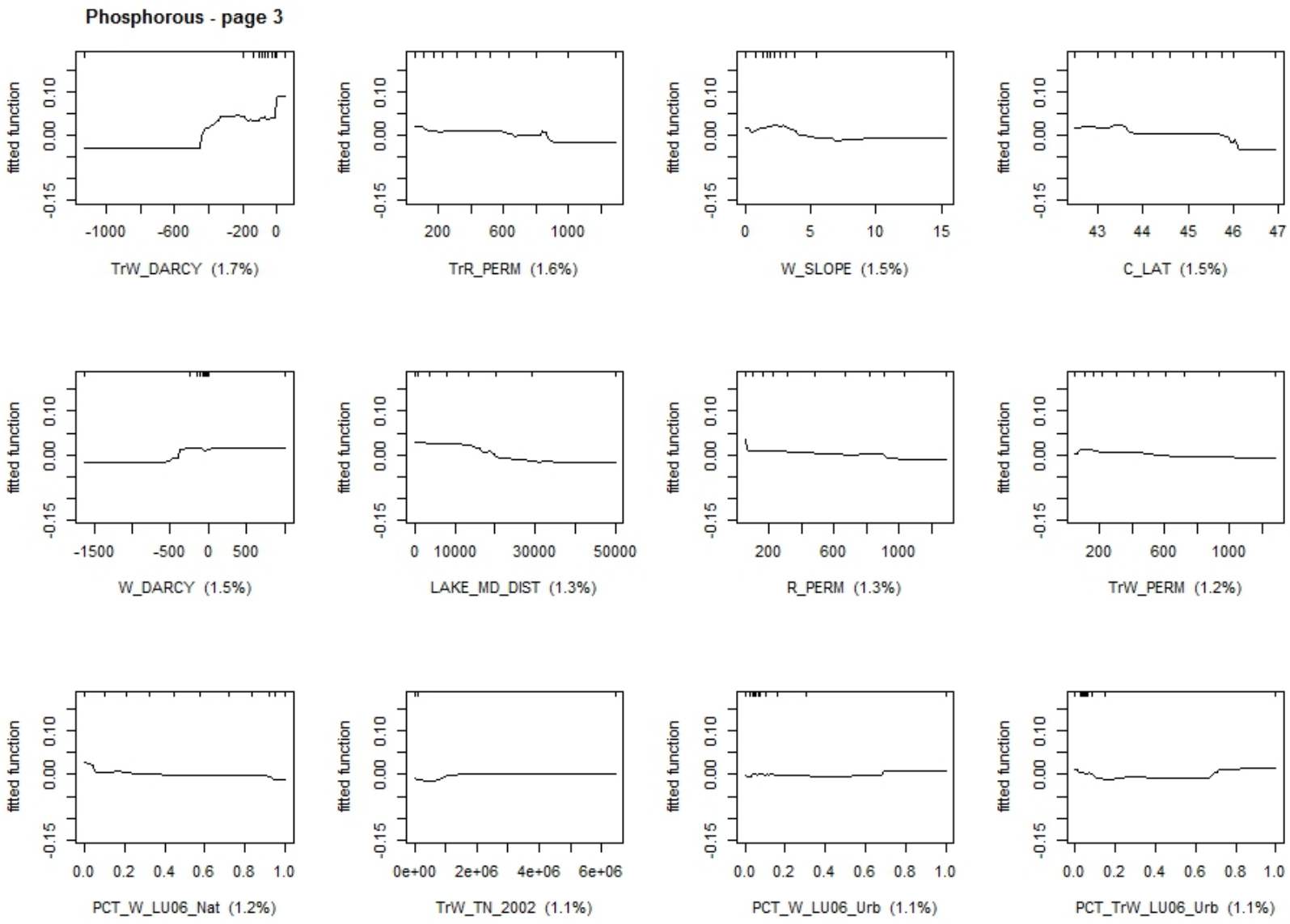

NO2NO3 - page 2
fitted function
C_LONG (1.8%)
TrR_PERM (1.5%)
PCT_ARA_LU06_Agr (1.4%)
TrR_SLOPE (1.4%)
PCT_ARA_LU06_Urb (1.2%)
W_WetRem (1.2%)
LAKE_SM_DIST (1.1%)
PCT_ARA_LU06_Nat (1.1%)
TrW_TN_2002 (1.1%)
TrW_SLOPE (1%)
TrW_RUN_2002 (1%)
LAKE_LG_DIST (0.9%)

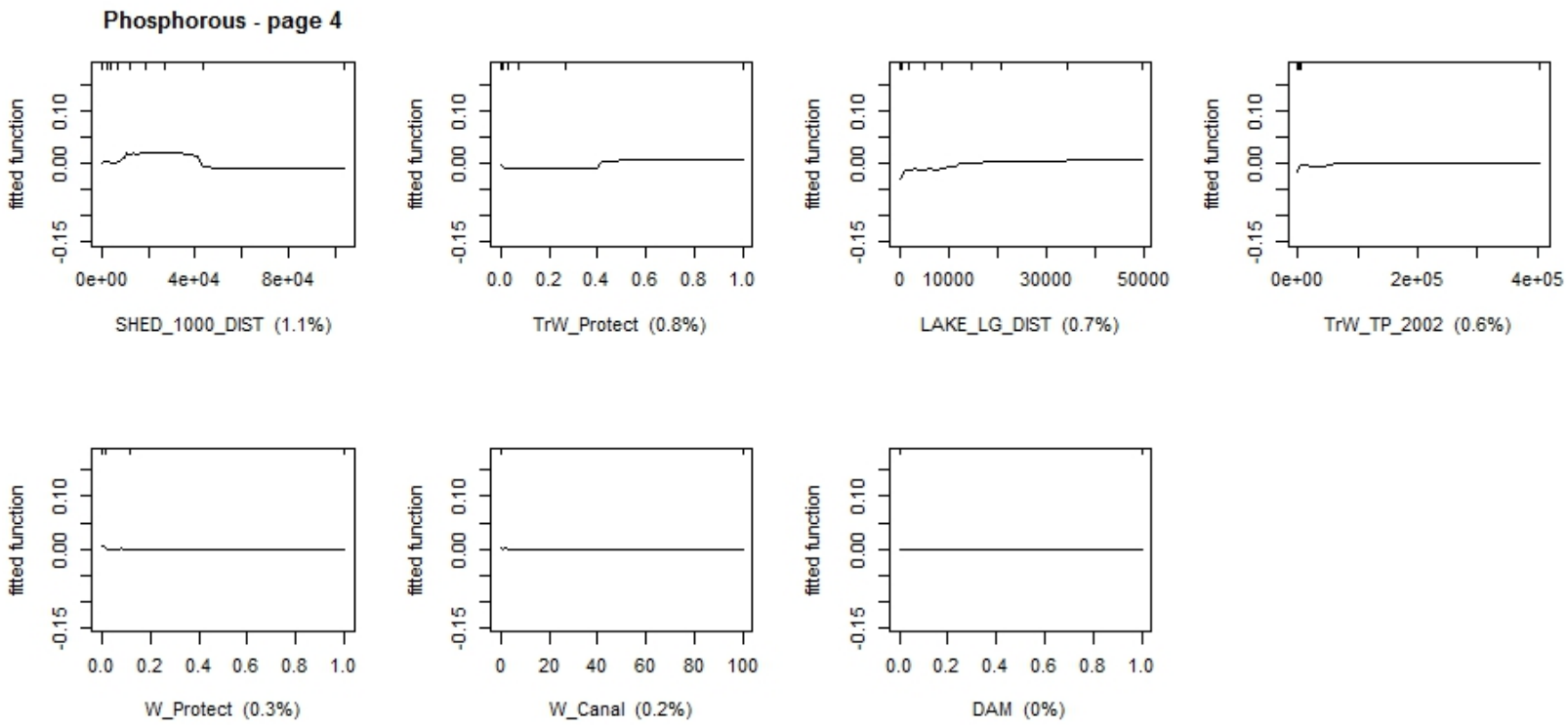

NO2NO3 - page 3
fitted function
W_Canal (0.9%)
TrW_AREA (0.9%)
W_SLOPE (0.8%)
TrW_PERM (0.8%)
SHED_100_DIST (0.7%)
TrW_TSS_2002 (0.6%)
TrW_DARCY (0.6%)
PCT_W_LU06_Urb (0.6%)
LAKE_MD_DIST (0.5%)
R_SLOPE (0.5%)
TrW_Protect (0.4%)
PCT_TrW_LU06_Urb (0.4%)

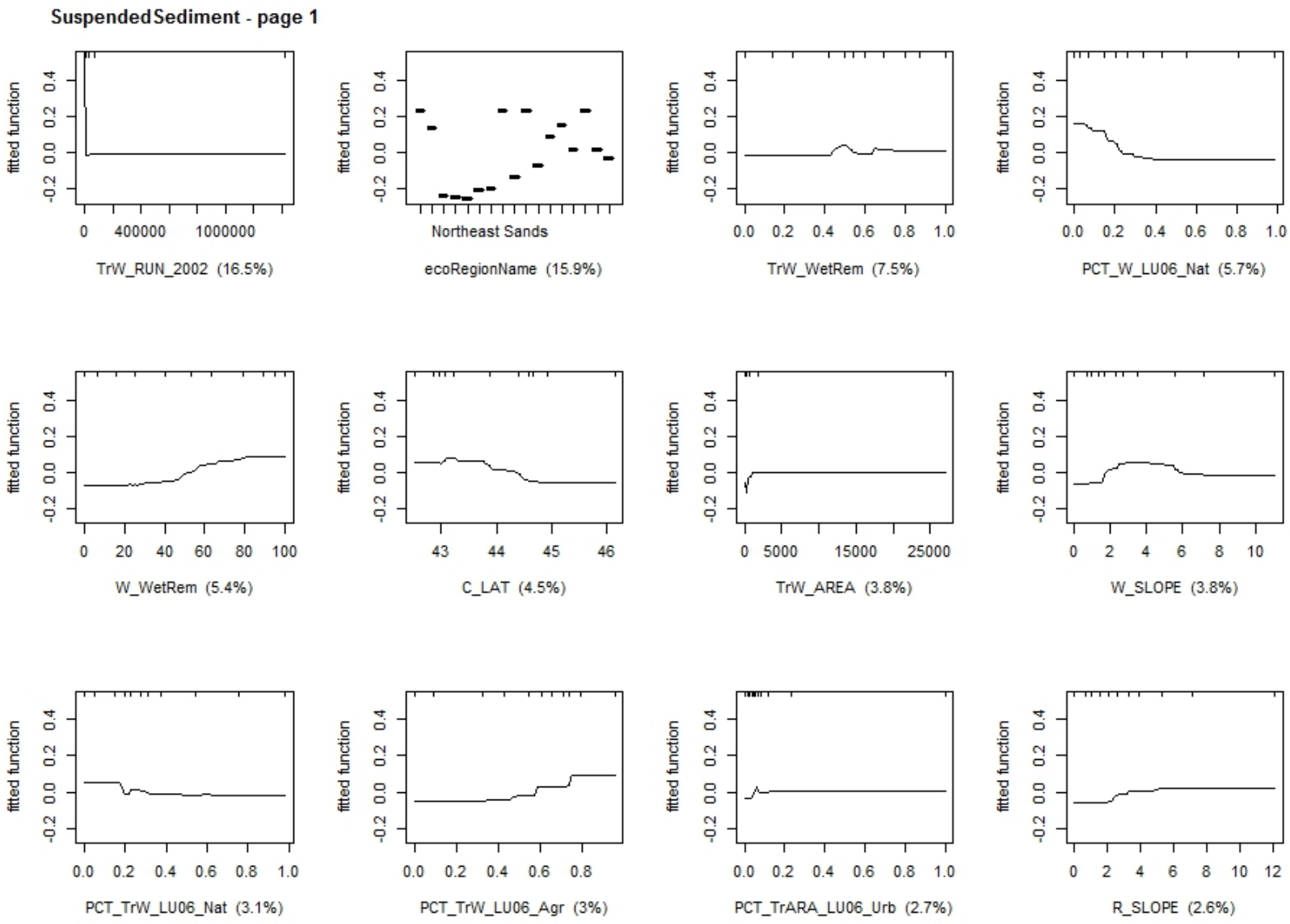

NO2NO3 - page 4
fitted function
PCT_W_LU06_Nat (0.4%)
R_PERM (0.4%)
SHED_1000_DIST (0.4%)
W_PERM (0.3%)
W_Protect (0.3%)
TrW_TP_2002 (0.1%)
DAM (0%)


Phosphorous - page 1
fitted function
-0.15 0.00 0.10
Northeast Sands
ecoRegionName (9.6%)
0.0 0.2 0.4 0.6 0.8 1.0
TrW_WetRem (6.2%)
1.0 1.5 2.0 2.5 3.0
SINUOUS (6.1%)
-2000 -1000 0 1000
TrR_DARCY (5.6%)
0 10000 30000
TrW_AREA (4.5%)
0 10000 30000 50000
LAKE_SM_DIST (3.8%)
0 10000 30000
SHED_100_DIST (3.8%)
0.0 0.2 0.4 0.6 0.8 1.0
PCT_TrARA_LU06_Urb (3.7%)
0 5 10 15
TrR_SLOPE (3.3%)
-93 -92 -91 -90 -89 -88 -87
C_LONG (2.8%)
0.0 0.2 0.4 0.6 0.8 1.0
PCT_TrARA_LU06_Agr (2.7%)
0.0 0.2 0.4 0.6 0.8 1.0
PCT_ARA_LU06_Urb (2.4%)

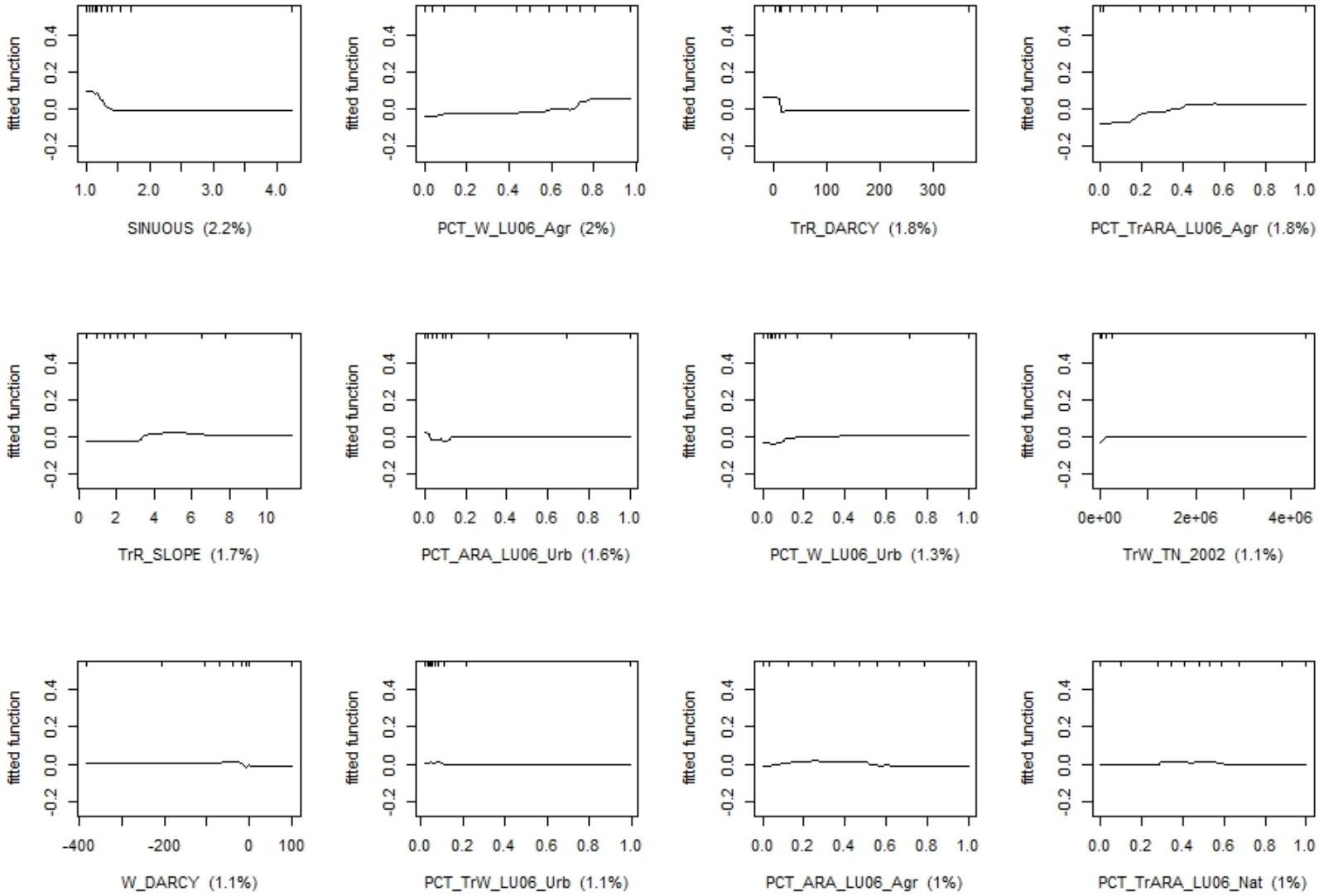

Phosphorous - page 2
fitted function
W_WetRem (2.4%)
W_PERM (2.4%)
PCT_ARA_LU06_Nat (2.3%)
TrW_TSS_2002 (2.3%)
PCT_TrARA_LU06_Nat (2.3%)
TrW_RUN_2002 (2.3%)
PCT_TrW_LU06_Nat (2.1%)
R_SLOPE (2%)
PCT_TrW_LU06_Agr (2%)
TrW_SLOPE (2%)
PCT_W_LU06_Agr (1.8%)
PCT_ARA_LU06_Agr (1.7%)


Phosphorous - page 3
fitted function
-0.15
0.00
0.10
-1000
-600
-200
0
TrW_DARCY (1.7%)
200
600
1000
TrR_PERM (1.6%)
0
5
10
15
W_SLOPE (1.5%)
43
44
45
46
47
C_LAT (1.5%)
-1500
-500
0
500
W_DARCY (1.5%)
0
10000
30000
50000
LAKE_MD_DIST (1.3%)
R_PERM (1.3%)
TrW_PERM (1.2%)
0.0
0.2
0.4
0.6
0.8
1.0
PCT_W_LU06_Nat (1.2%)
0e+00
2e+06
4e+06
6e+06
TrW_TN_2002 (1.1%)
PCT_W_LU06_Urb (1.1%)
PCT_TrW_LU06_Urb (1.1%)

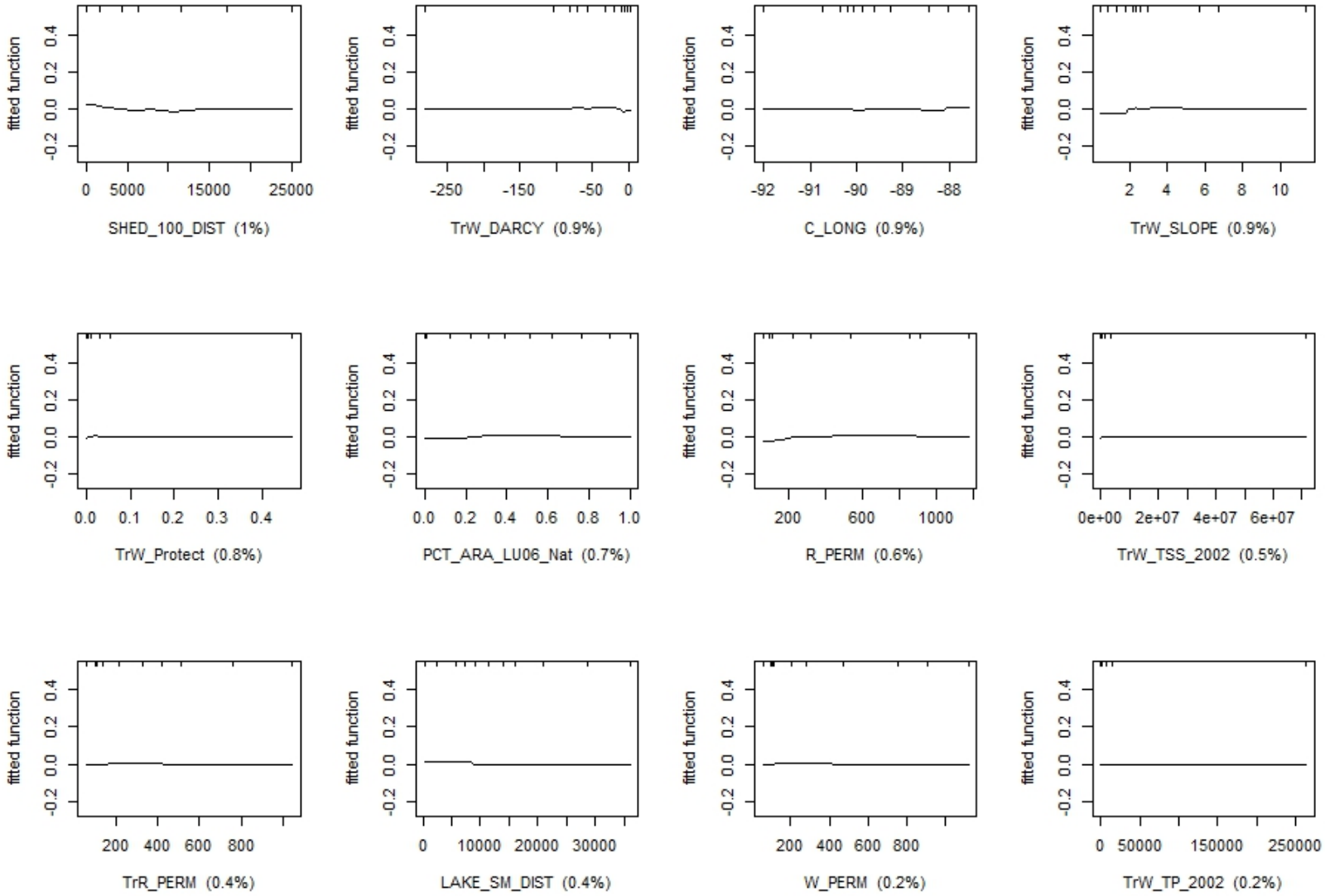

Phosphorous - page 4
fitted function
-0.15
0.00
0.10
0e+00
4e+04
8e+04
SHED_1000_DIST (1.1%)
0.0
0.2
0.4
0.6
0.8
1.0
TrW_Protect (0.8%)
0
10000
30000
50000
LAKE_LG_DIST (0.7%)
0e+00
2e+05
4e+05
TrW_TP_2002 (0.6%)
W_Protect (0.3%)
0
20
40
60
80
100
W_Canal (0.2%)
DAM (0%)


Suspended Sediment - page 1
fitted function
TrW_RUN_2002 (16.5%)
ecoRegionName (15.9%)
Northeast Sands
TrW_WetRem (7.5%)
PCT_W_LU06_Nat (5.7%)
W_WetRem (5.4%)
C_LAT (4.5%)
TrW_AREA (3.8%)
W_SLOPE (3.8%)
PCT_TrW_LU06_Nat (3.1%)
PCT_TrW_LU06_Agr (3%)
PCT_TrARA_LU06_Urb (2.7%)
R_SLOPE (2.6%)

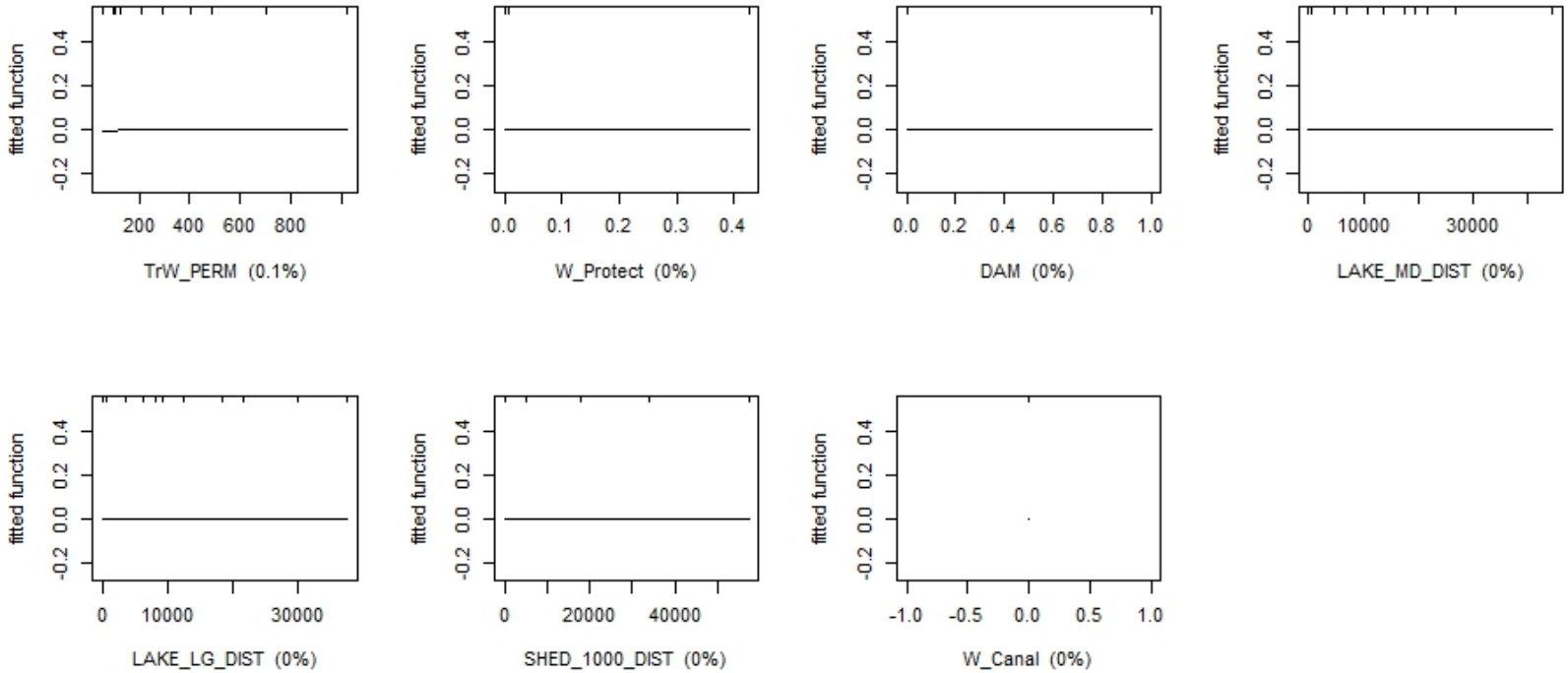
Suspended Sediment - page 2



Suspended Sediment - page 3



Suspended Sediment - page 4



Appendix B. Detailed Methods

TBD