Application of an index of nutrient status based on macroinvertebrate assemblages to New Jersey streams

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Abstract

The New York State Department of Environmental Conservation (NYSDEC) has developed a nutrient biotic index (NBI), which uses macroinvertebrate assemblages to estimate phosphorus and nitrogen conditions in streams. Tolerance values are calculated for widespread taxa based on frequency of occurrence in samples of various nutrient concentrations. For any sample, the NBI is calculated as a weighted sum of the tolerance values of taxa in the sample, weighted by the relative abundances of taxa. This approach was tested for New Jersey sites, using macroinvertebrate data collected by AMNET biomonitoring program and linked data on nutrient concentrations. Tolerance values were developed from New Jersey data, since relatively few taxa present in the New Jersey samples were rated in the NewYork study. NBIs for the New Jersey data calculated using the New Jersey-based tolerance values were significantly related to nutrient concentrations, with correlations similar to those observed in the New York study. For taxa in common, the New Jersey-based tolerance values were only weakly correlated with the analogous New York values. To verify the NBI Approach, NBI scores were calculated for different data sets than those used to estimate tolerance values. These comparisons found statistically significant, but weak, correlations between the NBIs and nutrient concentrations. Factors which weaken these relationships include availability of tolerance values for relatively few taxa in independent datasets, weak temporal matching of macroinvertebrate and nutrient samples, variability in estimates of tolerance values and NBIs, and the effort of other factors on macroinvertebrate relationships. While the NBI cannot be used with existing data to infer nutrient conditions, the NBI could be improved by use of additional data to improve estimates of nutrient concentrations, tolerance values and NBIs, and modifications of the definition of the NBI to weight taxa, by sensitivity to nutrients, variance in estimates of tolerance values, or other other factors. For all datasets examined, nitrogen and phosphorus concentrations were positively correlated, as were nitrogen and phosphorus tolerance values for taxa, and nitrogen and phosphorus NBI scores for sites. These correlations need to be considered in selection of sampling sites for development of tolerance values, weighting of taxa in calculation of NBIs, and interpretation of NBI values for the two nutrients.

Introduction

Diagnosis of specific causes of environmental impairment is a potentially important application of biomonitoring data. The Stream Biomonitoring Unit of the New York State Department of Environmental Conservation (NYSDEC) has developed a novel Nutrient Biotic Index (NBI) for evaluating nutrient conditions from data on benthic macroinvertebrate assemblages (Smith et al., 2007). The two nutrient biotic indices (NBIs) developed by NYSDEC correlate with increasing mean TP and NO_3 values, and a

three-tiered scale of nutrient status (oligotrophic, mesotrophic and eutrophic) was defined using cluster analysis of invertebrate assemblage data. Therefore, the NBIs appear to accurately reflect differences in stream trophic state. Smith, et al. calculated nutrient tolerance values from modal values of nutrients for common macroinvertebrate taxa. The NBIs were calculated as the average of the nutrient tolerance values for taxa in each sample, weighted by the proportion of each taxon in the sample.

Concurrently, NJDEP, through the Patrick Center for Environmental Research (PCER) at The Academy of Natural Sciences of Philadelphia, has developed its own state-wide monitoring protocols and an assessment methodology for nutrient impairments using diatoms (Ponader et al., 2007), developed in the New Jersey Algal Indicators (NJAI) project. The NJAI diatom indices were based on benthic diatom and water chemistry samples collected from over a hundred sites in five NJ ecoregions: Northern Piedmont, Northeastern Highlands, Ridge and Valley, and Inner and Outer Coastal Plains. Multivariate analysis in this assessment also showed that nutrient concentrations explain significant proportions of the variation in diatom species composition.

New Jersey shares five ecoregions with NY State, three of which are contiguous. Therefore, the NBIs developed by NYSDEC may be applicable to New Jersey streams. Aquatic macroinvertebrates have been used for freshwater monitoring and assessment for several decades in NJ, but biomonitoring techniques for macorinvertebrates have not yet incorporated nutrient measures into assessment strategies. Macroinvertebrates are sampled by the AMNET program, and metrics of impairment are calculated from the assemblage data. NJDEP has taken water samples at a number of sites where macroinvertebrate sampling has also been done. In this paper, the NYSDEC NBI approach is applied to these macroinvertebrate and chemistry data. In addition to evaluating potential use of the NBI in NY, these analyses represent an independent validation of the NBI approach.

The primary elements of this study were to:

1) Compile existing water chemistry data for NJ sites and link them to AMNET macroinvertebrate data
2) Identify the subset of sites that have both relevant macroinvertebrate and water chemistry data.
3) Obtain NY macroinvertebrate nutrient tolerance values for different taxa and calculate N and P NBIs for New Jersey sites based on NY tolerance values.
4) Relate the N and P NBIs to water chemistry data.
5) Develop new tolerance values based on NJDEP water chemistry data and use these to calculate new NBIs.
6) Relate the new NBIs to water chemistry data. Two comparisons were made, one using the same data used to estimate the tolerance values, and the using a validation data set which was independent of the data used to estimate the tolerance values.
7) Compare the macroinvertebrate NBIs with the diatom-based nutrient indices developed for NJ by ANS.

Methods

Data Compilation

Nutrient bin data and tolerance values were provided by A.J. Smith of NYSDEC.

The New Jersey Ambient Biological Monitoring Network (AMNET) macroinvertebrate data were obtained from NJDEP. AMNET data are collected by multiple traveling D-frame kick samples within riffle and run habitats within each site. These data consist of relative abundances of macroinvertebrate taxa. Two datasets were available. One data set (subsequently called the main dataset), containing data from 98 sites, contained raw macroinvertebrate data. These data were also used to relate macroinvertebrate assemblages to land use and fish data (Flinders, et al. 2008). These invertebrate data were not subsampled. The other dataset (subsequently called the validation dataset) contained subsamples of raw macroinvertebrate counts for 50 sites. Subsamples were of a nominal 100 individuals using a subsampling program which mimics a physical subsampler.

NJDEP provided water chemistry data from 98 sites that were sampled between 1996 and 2007 and had macroinvertebrate data. The NJAI project sites were also AMNET sites, and water chemistry data from 29 NJAI sites were provided by D. Charles (ANSP). Water chemistry samples were analyzed using several different methods for different groups of analytes. For consistency, only total phosphorus (TP), nitrate+nitrite (NO_3), and total nitrogen (TN) data were used in our analyses, as measured by methods in Table 1. For many sites, only nitrogen data were available. For a few sites, only phosphorus data were available. As a result, sample sizes for analyses involving each nutrient were smaller than the total number of sites in the database.

NJAI data also included measurements of total nitrogen. The NJAI project used diatom assemblages to infer total nitrogen and total phosphorus values (Ponader et al. 2007). While these are not measured values, they may be more relevant to macroinvertebrate assemblages, since they are a time-integrated measure of nutrients.

Three datasets were used for developing and testing the NBIs in NJ:

Main Dataset. This set contained AMNET macroinvertebrate data on 98 sites, water chemistry data that were collected by NJDEP between 1996 and 2007 at the same sites. D. Charles (PCER) provided additional water chemistry data from 29 sites taken as part of the NJAI project.

Validation Dataset. This set contained subsampled AMNET macroinvertebrate counts from 50 sites, and NJDEP water chemistry data were from these sites.

Diatom Subset. A subset of the main dataset was formed, containing data from 29 sites which were also sampled as part of the NJAI project. This subset contains AMNET macroinvertebrate data from these sites and three types of water chemistry measures:

1) NJDEP data (i.e., those used for the main dataset analysis);

2) Water chemistry data collected as part of the NJAI project. These data were from the same sites as the macroinvertebrate data, but did not usually meet temporal criteria used for linking NJDEP chemistry data (see below);

3) Inferred total nitrogen and total phosphorus values.

Data Matching and Filtering

Due to the lack of synchrony between NJDEP's invertebrate and nutrient sampling schedules, very few sites had nutrient and invertebrate samples taken within the same 90 days, the criterion used by Smith et al. to match nutrient and biotic data. In order to obtain a reasonable sample size for our study, yet still relate our nutrient and invertebrate data in a meaningful way, for the main and validation databases, nutrient and macroinvertebrate samples that were collected within five years of each other and in the same season were matched. Seasons were defined according to the following scheme:

Spring: 1 March to 31 May
Summer: 1 June to 1 August
Fall: 1 Septempber to 31 November
Winter: 1 December to 28/29February

At many sites, one macroinvertebrate sample corresponded to more than one nutrient measurement that met the temporal matching. In these cases, all the eligible measurements of a nutrient were averaged into one value for the site. For the main database, there were averages of 2.65 TP and 4.15 NO_3 measurements per site. All sites had appropriate water chemistry data from NJDEP studies. In addition, twelve sites included water chemistry data collected as part of the NJAI study. For the validation database, there were averages of 5.39 TP and 12.17 NO_3 measurements per site. In many cases, data on only nutrient (TP or NO_3) were available for a site, so that the sample size for each nutrient analysis is less than the total number of sites.

For the diatom subset, all water chemistry data collected as part of the NJAI study were used; for 17 of the 29 sites, these data did not meet the 5-year, same season criteria used for the other analyses.

Extremely high and low nutrient values were removed prior to analyses using a qualitative technique whereby a distribution of the data points were viewed using JMP 7, and points within the "long tails" at both ends were then excluded.

Because data from the Southern New Jersey Pine Barrens and Coastal Plains were sparse, and because preliminary analyses revealed stark differences between the nutrient profiles and invertebrate communities of the Southern and Northern New Jersey sites, those data were also excluded from the dataset prior to analysis.

After all the above criteria were applied, samples from 98 sites were available for analysis as part of the main database. After taxa found in less than 2% of sites were excluded as per Smith et al 2007, those sites yielded a total of 254 invertebrate taxa.

Calculation of nutrient optima for macroinvertebrate taxa and NBI for samples

The nutrient optima and NBI are calculated as follows (see Smith et al. 2007 for further details). Identical techniques were used for nitrogen and phosphorus data. The set of sample sites used to calculate optima were ordered by the appropriate nutrient concentration (i.e., NO_3 or TP) and divided into 15 bins with approximately equal numbers (n_i) of samples in each bin b_i. The mean nutrient concentration of each bin was calculated (m_i). For each taxon t, the frequency (f_i) of that taxon in each bin was calculated (i.e., the proportion of n_i samples in which the taxon was present). The nutrient optimum was calculated as:

$$O_t = \sum (f_i * m_i) / \sum (f_i).$$

Nutrient optima were ordered and divided into 11 bins with approximately equal numbers of taxa in each bin. The ranks of these bins were defined as the Tolerance values (TV_i) of each taxon in that bin, with the lowest value corresponding to occurrence at low nutrient concentrations. The rankings ranged from 0 to 10.

For each sample, a nutrient value (NBI_T) was calculated from the sum of the tolerance values of taxa in the sample, weighted by the proportion (p_i) of each taxon in the sample:

$$NBI_T = \sum p_t * TV_t.$$

For samples in which tolerance values were not available for all taxa in the samples, the proportion of individuals among all rated individuals was used, instead of the proportion of individuals in the entire sample.

Application of NY-based Tolerance Values to New Jersey Data

The first attempt at applying the NBI strategy to New Jersey streams consisted of using the taxon-specific tolerance values published in Smith et al. (2007) to calculate NBI scores for New Jersey sites. After resolving coding differences between New York and New Jersey identifications and eliminating differences between identifications based on splitting below the species level and “nr.” designations, the New York tolerance values could be applied to only 69 of 254 New Jersey taxa (about 27.5%). NBI scores of New Jersey sites were calculated using the process described in Smith et al. 2007. In effect, the abundances of un-rated New Jersey taxa were ignored by the calculations.

The total phosphorus and nitrate NBI scores were regressed against log-transformed total phosphorus and nitrate nutrient values.

Calculation of Tolerance Values Using New Jersey Data and calculation of new NBIs

Due to the small amount of taxonomic overlap between New York and New Jersey datasets and also because of the lack of a strong relationship between the NBI scores

calculated with NY tolerance values and corresponding nutrient levels (see Results), tolerance values were calculated for all New Jersey taxa, excepting rare taxa, using macroinvertebrate abundance and nutrient data collected in New Jersey. Tolerance values were calculated using the same methods in Smith et al. (2007) and described above, using their 15 original nutrient bins to calculate nutrient optima in the first phase of the calculations. The resulting NBI scores were then regressed against corresponding log-transformed nutrient values as described above.

Validation of New Jersey-based Tolerance Values Using a Second Dataset

Because of the circularity inherent in testing NBI scores against the nutrient values that produced them, NBIs were validated by using the tolerance values calculated from the main (98-sample) dataset to calculate NBI scores for 50 new sites. The resulting NBI scores were then tested against nutrient values from the 50 new sites as described above. The nutrient data from these 50 sites were not used in calculating the tolerance values that produced the NBI scores.

Validation using a split of the main dataset

A second validation was done by splitting a version of the main database (which included Southern New Jersey sites) and calculating tolerance values on one half, and calculating NBIs and comparing them with nutrient concentrations on the other half. The results of this validation were similar to the primary validation and are not reported in detail in this paper.

Analyses of diatom dataset

As a second test of the technique, the TP- and NO_3-based NBI scores from the diatom dataset were regressed with three types of chemistry measurements: inferred TP and TN indices, all chemistry data for the sites (i.e., the same chemistry data used for analyses of the main dataset), and the TP and TN measurements taken as part of the NJAI project. Multiple diatom samples were taken at the majority of sites, resulting in multiple inferred nutrient values. In these cases, the indices were averaged before comparisons to NBI scores were made. Because of the small overlap between NBI and diatom site sets, no temporal criteria were imposed on the matching of invertebrate to diatom samples, as very few of the matches would have withstood the five-year, same-season criteria described above for matching chemistry and invertebrate samples.

These analyses were done on a subset of the sites in the main database, using the same macroinvertebrate data as in the main database, but using two different sets of chemistry data in addition to the chemistry data used in the main database. Thus, the macroinvertebrate data in the diatom dataset were part of the data used to estimate nutrient optima. Therefore, these analyses do not represent an independent validation, but do allow comparison of NBIs with nutrient data from a single source taken with identical methods.

Statistical analyses

NBI scores were regressed against log-transformed nutrient values. In some cases, residuals from the regressions were regressed against factors which might affect the accuracy of the regressions. All data manipulations were performed using Microsoft Excel and Access, and all statistical analyses were performed using JMP 7. The minimum reported p-value is <0.0001. Canonical correspondence analysis was performed using Canoco software.

Results

Application of NY-based Tolerance Values to New Jersey Data

The regressions of the NBI scores calculated with NY-based tolerance values against log-transformed nutrient concentrations are shown in Figures 1 and 2. The relationships are positive and significant but very weak (Table 2, rows 1a and 1b). The poor relationships are at least partially due to the relatively low proportion of taxa (2-67%) rated in any given sample. Residuals from the NBI-nutrient regressions were negatively related (Figures 3 and 4) to the number of taxa rated (TP: $n = 68$, $r^2 = 0.11$, $p = 0.0051$; NO_3: $n = 97$, $r^2 = 0.08$, $p = 0.0039$). The lack of a strong temporal association between the chemistry and macroinvertebrate samples may have also played a role, but the residuals analysis (Figures 5 and 6) did not strongly implicate inter-sample interval (TP: $n = 68$, $r^2 = 0.03$, $p = 0.20$; NO_3: $n = 97$, $r^2 = 0.00013$, $p = 0.91$).

Calculation of Tolerance Values Using New Jersey Data

The regressions of the NBI scores calculated with NJ-based tolerance values against log-transformed nutrient concentrations are shown in Figures 7 and 8. The relationships are positive, significant, and moderately strong (Table 2, rows 2a and 2b); r^2 values are extremely similar to those reported by Smith et al. 2007.

The NJ-based tolerance values were only weakly correlated with the NY-based tolerance values for shared taxa (Figures 9 and 10; TP: $n = 69$, $r^2 = 0.13$, $p = 0.0026$; NO_3: $n = 69$, $r^2 = 0.06$, $p = 0.0478$). This suggests different responses between macroinvertebrates in the two states, interactions with other factors, or imprecision in estimation of optima and/or measurement of water chemistry.

Validation of New Jersey-based Tolerance Values Using Independent Datasets

NBI scores were calculated for the 50-site validation database using the NJ-based tolerance values. These NBI scores were only weakly correlated (Figures 11 and 12) with the nutrient values at those sites (Table 2, rows 3a and 3b).

A second validation calculated tolerance values from half of a version of the main dataset, calculated NBI scores on the other half, and compared with nutrient data from the other half (Table 2, rows 4a and 4b). The relationship was not-significant for total

phosphorus and was significant, but with relatively low correlation coefficient, for nitrogen. The tolerance values are estimated from relatively few samples, which may account for the weaker fit between resultant NBI scores and nutrient chemistry.

Analyses using New Jersey-derived NBI Scores on diatom subset

NBI scores calculated from NJ-based tolerance values were correlated with diatom-based inferred TN and TP indices calculated by Ponader et al. (2007) (Figures 13 and 14). The relationships were fairly strong despite relatively low sample numbers and poor temporal association between samples (Table 2, rows 5a and 5b). The NBI scores were nearly as highly correlated with the actual nutrient concentrations measured by the NJAI study (Figures 15 and 16 and Table 2, rows 6a and 6b). For total phosphorus, the relationship between NBI scores and the nutrient concentrations from the NJDEP data was somewhat weaker (Table 2, row 7a). For nitrogen, the relationship between NBI scores and NJDEP data (Table 2, row 7b) was slightly higher than those between NBI scores and the inferred total nitrogen and NJAI measured concentrations.

Relationship between water chemistry and macroinvertebrate assemblages

Relative abundances of taxa were ordinated with P and N concentrations (Figure 17). Relatively few taxa show strong relationships with either nutrient. Estimates of optima of taxa with weak relationships will be imprecise, and inclusion of these taxa in the NBI may mask signals from more diagnostic taxa.

Discussion

Smith et al. (2007) demonstrated a relationship between macroinvertebrate assemblages and nitrate and phosphorus concentrations. Using analogous methods, this study found similar levels of relationships. However, in both of these results, relationships were tested using the same data that were used to estimate nutrient optima for taxa. In this study, stronger relationships were found using a subset of sites which were used in the New Jersey Algal Indicators Study. The higher correlation between NBI and water chemistry in the subset relative to the main dataset could result from the smaller number of sites in the subset. The difference could also reflect differences in site selection. The NJAI study was designed to develop a diatom index. Sites were avoided which could complicate analysis of diatom-nutrient relationships; for example, sites in carbonate areas were not selected. Because of the nature of site selection, the subset is likely to be more homogeneous and show lower smaller amounts of residual variation from factors other than nutrients. Notably, for sites in the subset, relationships of the NBI to inferred nutrients were stronger than those with measured water chemistry. The inferred nutrient concentrations are derived from diatom assemblages, and these inferences are likely to be time-integrated, while the chemistry data are derived from one or a few point measurements. The stronger correlations for the diatom subset could also reflect greater uniformity and matching of nutrient data with macroinvertebrate data.

Two types of validation show a relationship between the NBIs of macroinvertebrate

assemblages and nutrients. These relationships are statistically significant, but they are weak. Estimates of nutrient optima of taxa from the NJ data are only weakly correlated with coresponding optima from the NYSDEC analyses, for taxa relatively common in samples from both states. When nutrient optima derived from one dataset were applied to a second, independent database, the relationship between the NBI and water chemistry was weak for TP and marginally-non-significant for NO_3.

While these analyses indicate that there is a relationship between macroinvertebrate assemblages and nutrient concentrations, estimates of NBIs based on existing information cannot be used to infer nutrient levels in other samples. In part, this is due to the difficulty of producing independent estimates of tolerance values for all taxa in a set of samples.

There are several aspects of the analyses which could contribute to the weakness of the observed NBI-nutrient relationships. These relate to the quality of the data available for analysis, the particular form of estimation of the NBI, and inherent variability between nutrients and macroinvertebrate assemblages.

Water chemistry data The consistency and relevance of the nutrient data affect estimation of tolerance values and the relationship between calculated NBIs and nutrient concentrations. Most of the water chemistry measurements were taken independently of the macroinvertebrate samples. In many cases, chemistry measurements and macroinvertebrate samples were taken several years apart, and chemistry data were originally collected using a variety of different methods (see Table 1). TP and NO3 were selected as relevant chemicals which were measured consistently across different programs. Other forms of phosphorus and nitrogen could contribute to the nutrient response by macroinvertebrates, but there were no consistent data for these.

The response of macroinvertebrates to nutrients will be temporally integrated; this is one of the main advantages for using biological indices. However, this will lower the correlation between macroinvertebrate indices and a few point samples of nutrients. For the diatom subset, the correlation between nitrogen NBIs and nitrogen values inferred from diatom assemblages was higher than any of the relationships between NBIs and measured chemistry values. The inferred values are derived from temporally integrated diatom responses.

The estimation of nutrient optima depends on the distribution of water chemistry among samples used to make the estimates. Gaps in the distribution of nutrient levels and low sample size of extreme nutrient levels will weaken the precision of the estimates of nutrient optima. The main dataset had a greater range in nutrient concentrations than the NYSDEC data used in Smith, et al. (2007).

Macroinvertebrate data

The approach used by Smith et al. (2007) and in this study is empirical and does not assume or incorporate causal bases for relationships between macroinvertebrate

assemblages and nutrient concentrations. Unlike algal responses (e.g., Ponader et al. 2007), macroinvertebrate responses are likely be indirect, reflecting either trophic effects or correlations between nutrients and other factors which directly affect macroinvertebrates. Trophic responses could include differences in macroinvertebrate feeding groups (e.g., grazers) in response to the quantity and type of algal food. Macroinvertebrates could be affected by changes in predator (e.g., fish) densities or diet in response to nutrient-driven changes in production. Increases in nutrient may commonly occur in agricultural or urban watersheds, where changes in sedimentation, geomorphology, hydrology, and temperature could have direct effects on macroinvertebrates. Analyses of the relationships of estimated nutrient optima and characteristics of macroinvertebrate taxa (e.g., feeding type, tolerance ratings) may provide evidence of some of these causal relationships. Such analyses could be used to improve estimates of nutrient optima or calculation of NBI scores.

There is an inherent question of the appropriate level of taxonomic resolution for these analyses. Estimated tolerance values frequently differed among species within genera. While differences in nutrient responses among taxa within families or genera would be more precisely fit using finer levels of resolution, finer levels of resolution will result in fewer points for the estimation of nutrient responses and fewer taxa with estimated tolerance values available for estimating NBI scores.

Calculation of nutrient optima and NBIs

For each taxon, nutrient optima were calculated based on occurrence of macroinvertebrates across different nutrient levels. Use of relative abundance within samples could improve sensitivity of the optima. For each sample, the NBI was calculated from nutrient optima and relative abundance of each taxon (excluding rare taxa). Various ways of weighting different taxa, e.g., giving more weight to sensitive taxa and to more sensitive estimates of optima, could improve sensitivity of the NBI. For example, taxa could be inversely related to some measure of the nutrient tolerance (e.g., range of occurrence), sample size, standard deviation of the frequency distribution, etc. For taxa that are relatively insensitive to nutrients, occurrence will be nearly independent of nutrients. As a result, the tolerance of uncommon taxa will depend on nutrient concentrations in the few samples in which they occur, and species will appear more sensitive than they really are. Weighting may reduce this effect. As noted above, use of information on feeding type, sensitivity to other factors or other characteristics of macroinvertrebrate taxa could also improve the NBI.

Availability of tolerance values for taxa

For the main dataset analyses, as with the analyses of Smith et al. (2007), the same data were used to calculate tolerance values and to compare NBIs with nutrient values. However, tolerance values could not be accurately estimated for rare taxa, so NBI scores were based on a subset of taxa in each sample. For validation analyses where different datasets were used to estimate tolerance values and calculate NBIs, the problem is greater, since tolerance values could not be estimated for many taxa in the validation

dataset which were rare or absent in the primary dataset. The residuals analyses indicate that accuracy of NBI scores at predicting nutrient concentrations was greater for samples with more rated taxa. However, these relationships were rather weak. The validation on the split main dataset had more taxa shared between the two halves than between the main dataset and the validation dataset. However, relationships between NBI scores and nutrient values were weak, similar to those calculated for the validation dataset. These results also suggest that the absence of tolerance values for some taxa in a sample is not the most important problem in comparing NBI scores and nutrient concentrations. As noted above, the taxonomic resolution of macroinvertebrate data will affect the availability of tolerance values.

A possible solution to the problems of estimation of tolerance values for a large number of taxa and independent verification is a jack-knife procedure: tolerance values (or nutrient optima) are calculated from all samples in a dataset except one, and these tolerance values (or nutrient optima) are then used to calculate the NBI for the omitted sample. Tolerance values would be available for all taxa in that sample, except for some rare taxa. The procedure could be repeated, omitting each sample in turn, to provide an estimate of NBI for each sample.

Inherent variability between macroinvertebrate assemblages and nutrient conditions

Even with perfect chemistry data and optimal NBI formulations, NBI-nutrient relationships will be weakened by a variety of factors, including effects of other factors on macroinvertebrate assemblages and tolerance of many taxa to a range of nutrient conditions.

Correlations between nitrogen and phosphorus indices will affect accuracy of estimates. These correlations may be caused by correlations at sample sites and by correlations in responses of taxa to the two nutrients. Both types make it impossible to completely separate responses to each nutrient individually. For example, if all sites with high nitrogen also had high phosphorus and vice versa, there would be no way to determine which nutrient taxa drive macroinvertebrate response, even if taxa are responding to single nutrients. Practically, a single nutrient index may be more appropriate in this case. Analogously, if some taxa require low concentrations of both indices, absence of those taxa (which would drive up the NBI) would not be useful to distinguish high phosphorus from high nitrogen conditions (although presence would be informative).

There were positive correlations between nutrient responses of taxa to TP and NO_3 for both the NYDEC- and NJDEP-based estimates. For the NYDEC estimates, the correlation (r^2) between TP and NO_3 nutrient optima was 0.58 and the correlation between tolerance values was 0.50. For the NJDEP-based estimates (estimated from the main dataset), the correlation between the two nutrient optima was 0.27 and the correlation between tolerance values was 0.26. For the split of the main dataset, the correlations between nutrient optima and tolerance values were 0.34 and 0.23, respectively.

In all of the chemistry datasets, there were positive correlations between the nitrogen and phosphorus values (Table 2). These values are underestimates of the true correlation between nutrient concentrations, since the estimates are affected by measurement errors. For example, for the diatom subset, the correlation between NJAI nitrogen and phosphorus values was higher than the correlation between the main nutrient values for the NJDEP data. This difference may reflect the combination of data sources and methods for chemistry data for the latter data. Together with the positive correlations between nutrient responses, these resulted in positive correlations between NBI scores for nitrogen and phosphorus at a site (Figure 18). These correlations contribute to the variance in nutrient-NBI scores for each nutrient.

Conclusions

The NBI approach was about as successful in New Jersey waters as in the New York study (Smith et al., 2007), as measured by the relationship between nutrient index values and nutrient concentrations. However, the robustness of these relationships is uncertain, since the relationships in both cases were measured using the same datasets used to estimate nutrient responses of taxa. Application of the nutrient responses to different data produced significant relationships between nutrient index values and nutrient concentrations, but with high variance (low correlation) around the relationships. Furthermore, for individual taxa, estimates of nutrient tolerance values from the New York data were not highly correlated with the tolerance values estimated from New Jersey data. These results indicate that macroinvertebrate assemblages are related to nutrient values, but the relationships are not sufficiently characterized to allow them to be usee to infer nutrient values from assemblage data.

The precision of NBI scores was affected by a number of factors, many of which could be reduced by further study. These include:

1) Variability in nutrient data used to estimate nutrient responses and to evaluate relationships between NBI scores and nutrient values. The variability arose from the necessity to match macroinvertebrate data with chemistry data taken at different times, and possibly from different methods and sources of chemistry data.

2) Presence of taxa in validation data sets for which tolerance values were unavailable (due to their absence in data used to develop tolerance values). As a result, for independent applications of tolerance values, NBI scores for individual sites were based on a subset of taxa present at those sites.

3) Correlations between nitrogen and phosphorus concentrations in data used to develop tolerance values and evaluate NBIs, and correlations between responses of taxa to the nutrients.

4) Taxonomic resolution of macroinvertebrate data used to estimate NBI scores.

The precision of NBI inferences could be improved in several ways, which either reduce or account for these sources of variability:

1) Development of additional data, which provide better temporal and spatial matches between macroinvertebrate and nutrient data, as well as more consistent nutrient estimates. Such data would increase the number of taxa for which tolerance values are estimated, as well as increasing the accuracy of nutrient response estimates. Selection of sites with known enrichment of only one of the nutrients could be used to determine correlation in taxonomic responses and to identify taxa which respond differently to the two nutrients. More comprehensive data could be used to determine optimal levels of taxonomic resolution.

2) Modifications of the definition of NBI values, which can increase accuracy of scores by weighting taxa for the strength or variability of the estimated response to nutrients. Modifications may also allow joint estimation of nitrogen and phosphorus values; these modifications could account for inherent correlations between taxonomic responses to the two nutrients as well as correlations in the levels of the two nutrients. Use of a jack-knife approach to estimating tolerance values and NBIs could also improve estimation of NBIs.

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Figures

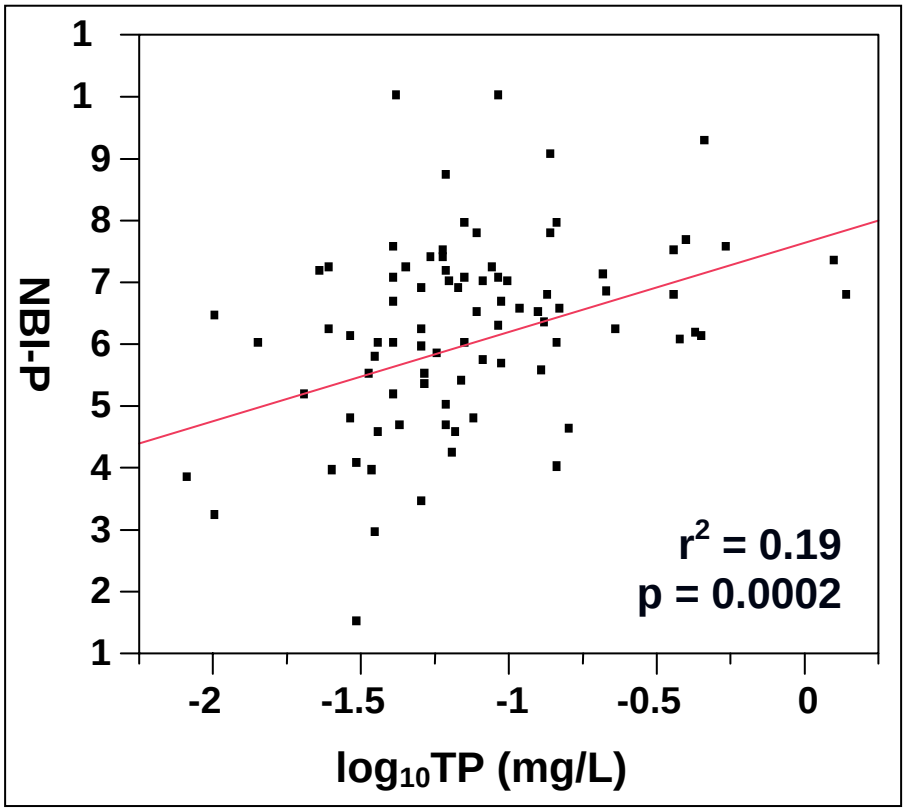

Figure 1. Relationship of NBI calculated using NYDEC tolerance values and total phosphorus concentrations in New Jersey sample sites.

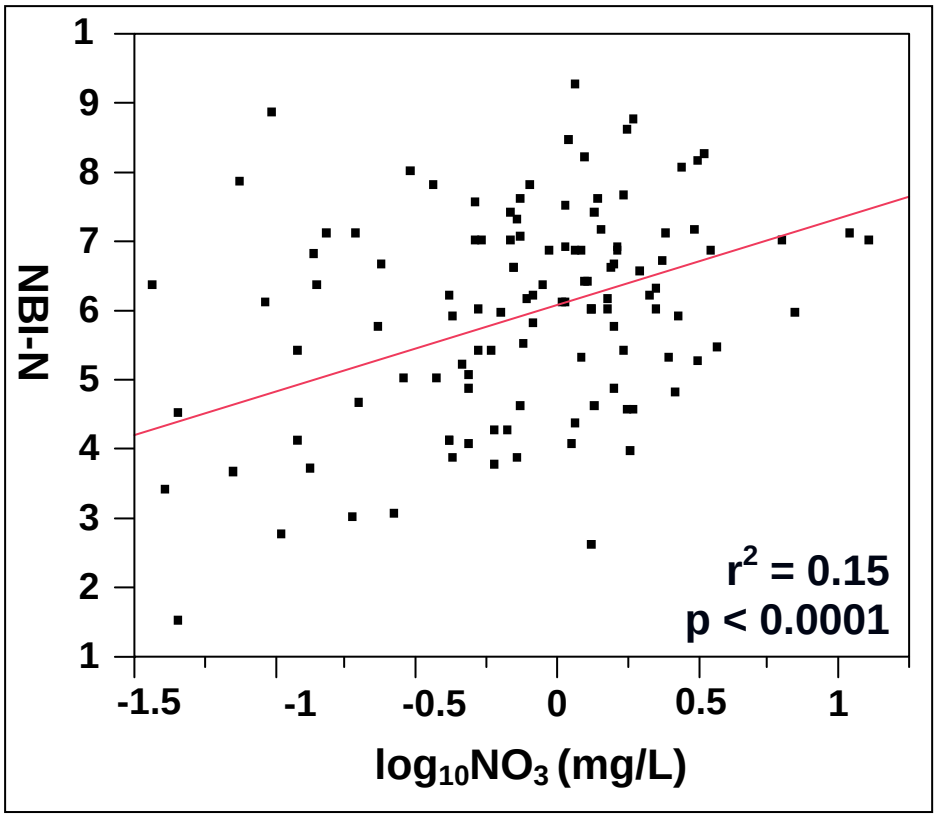

Figure 2. Relationship of NBI calculated using NYDEC tolerance values and nitrogen (nitrate + nitrite) concentrations in New Jersey sample sites.

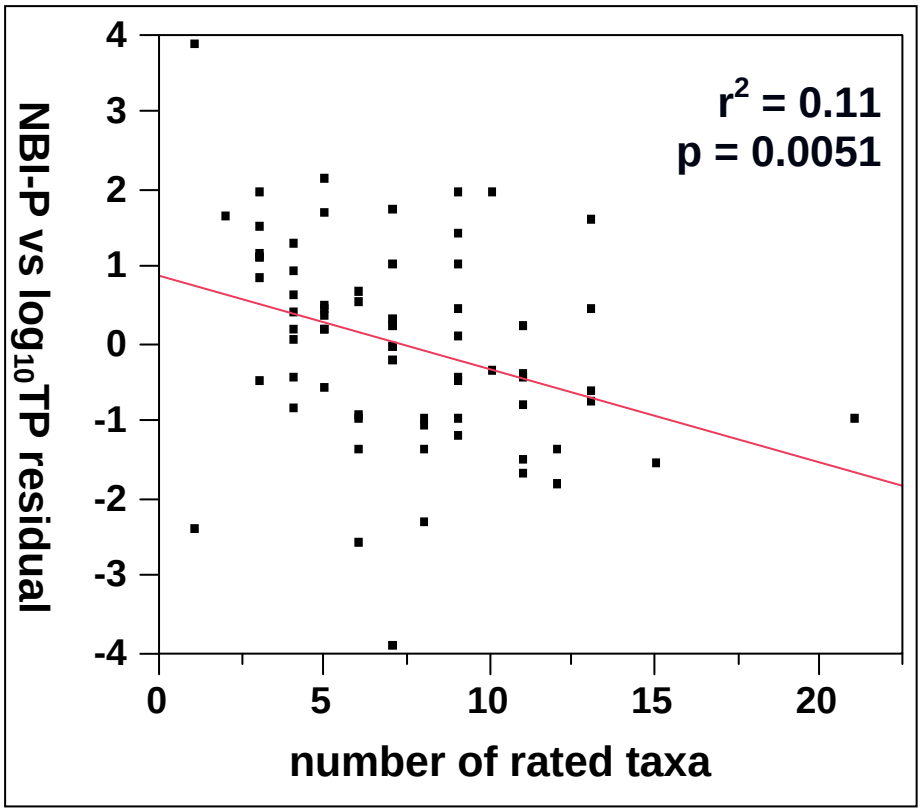

Figure 3. Relationship between residuals of regressions between NBI scores (using NYDEC tolerance values) and total phosphorus concentrations and the number of taxa in each New Jersey sample for which tolerance values were available.

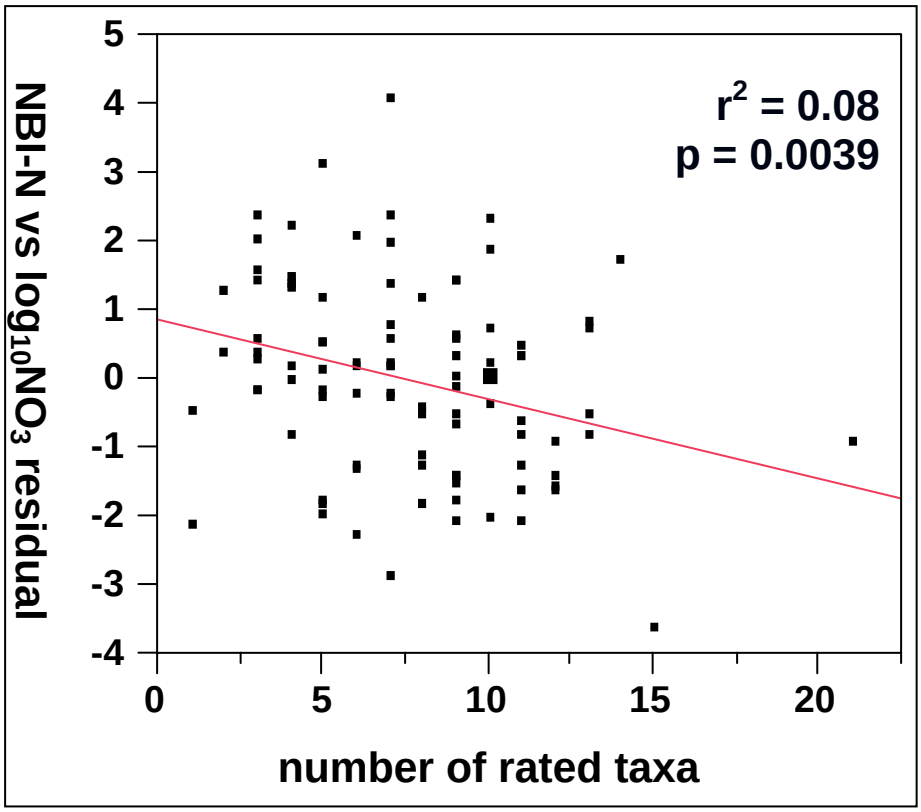

Figure 4. Relationship between residuals of regressions between NBI scores (using NYDEC tolerance values) and nitrogen (nitrate + nitrite) concentrations and the number of taxa in each New Jersey sample for which tolerance values were available.

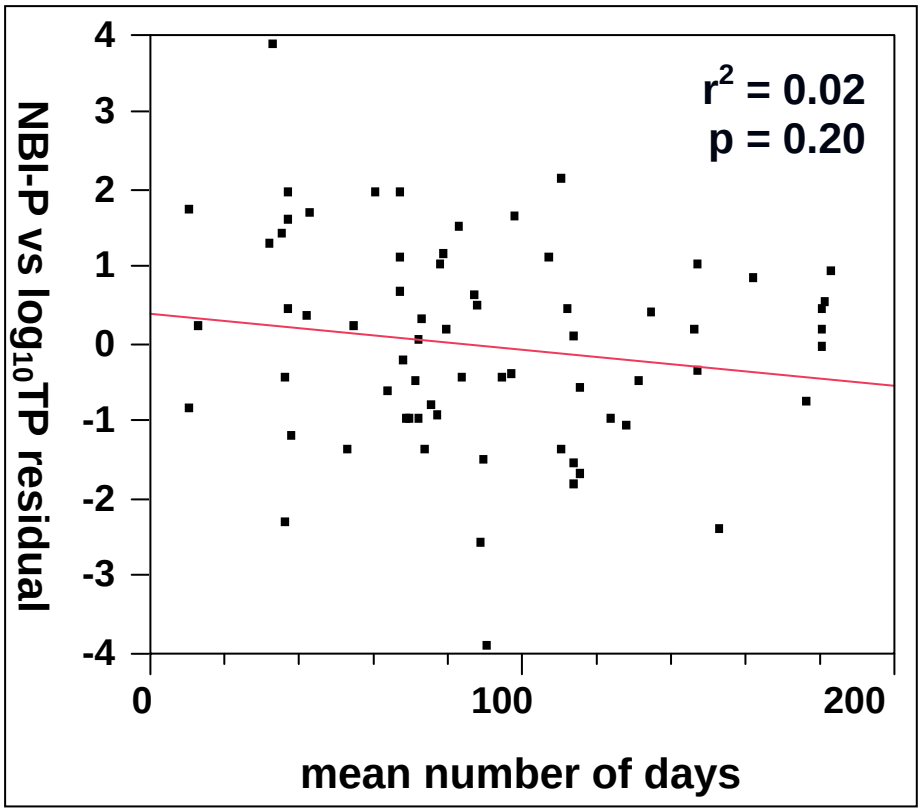

Figure 5. Relationship between residual of NBI score for total phosphorus (estimated using NYDEC tolerance values) and the mean number of days between the date of the macroinvertebrate sample and the nutrient measurements.

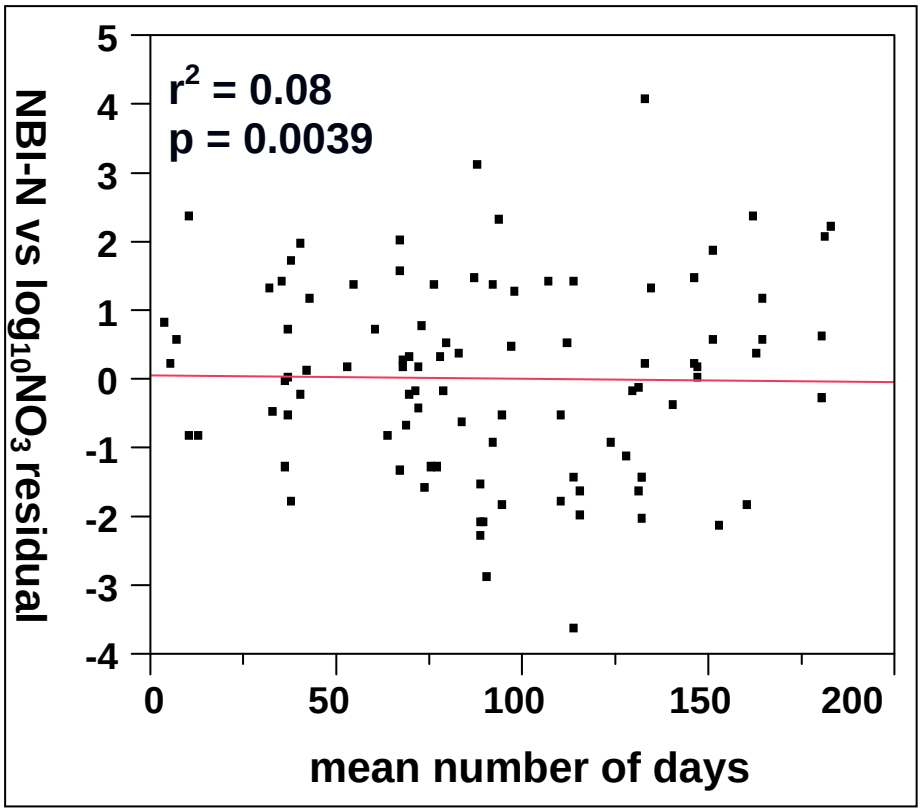

Figure 6. Relationship between residual of NBI score for nitrogen (estimated using NYDEC tolerance values) and the mean number of days between the date of the macroinvertebrate sample and the nutrient measurements.

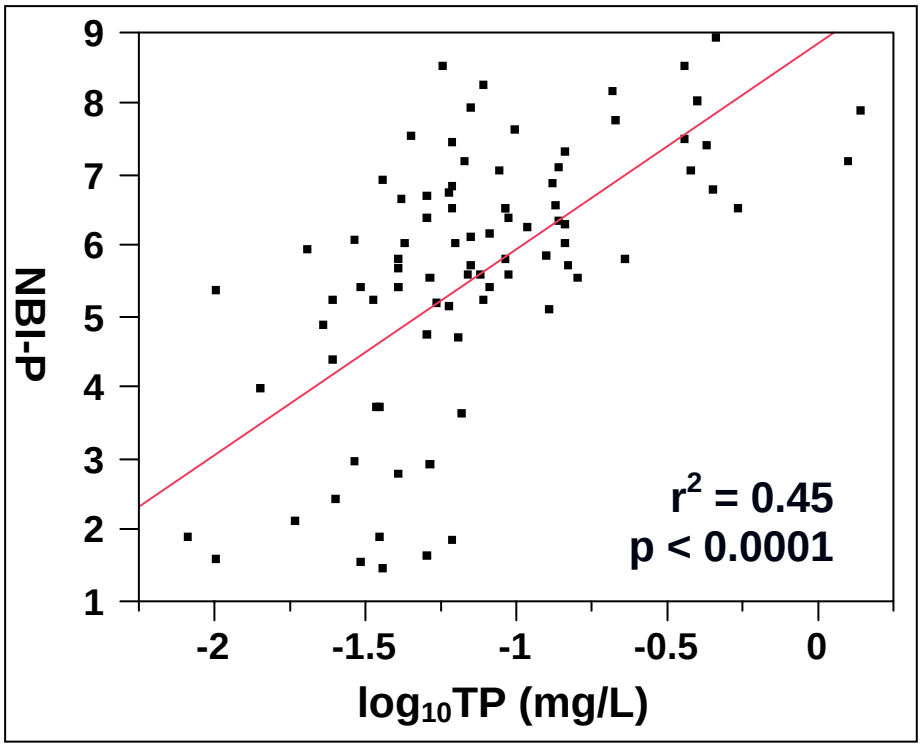

Figure 7. Relationships between NBI scores for phosphorus (estimated from the main dataset of New Jersey data) and total phosphorus concentrations in the same dataset.

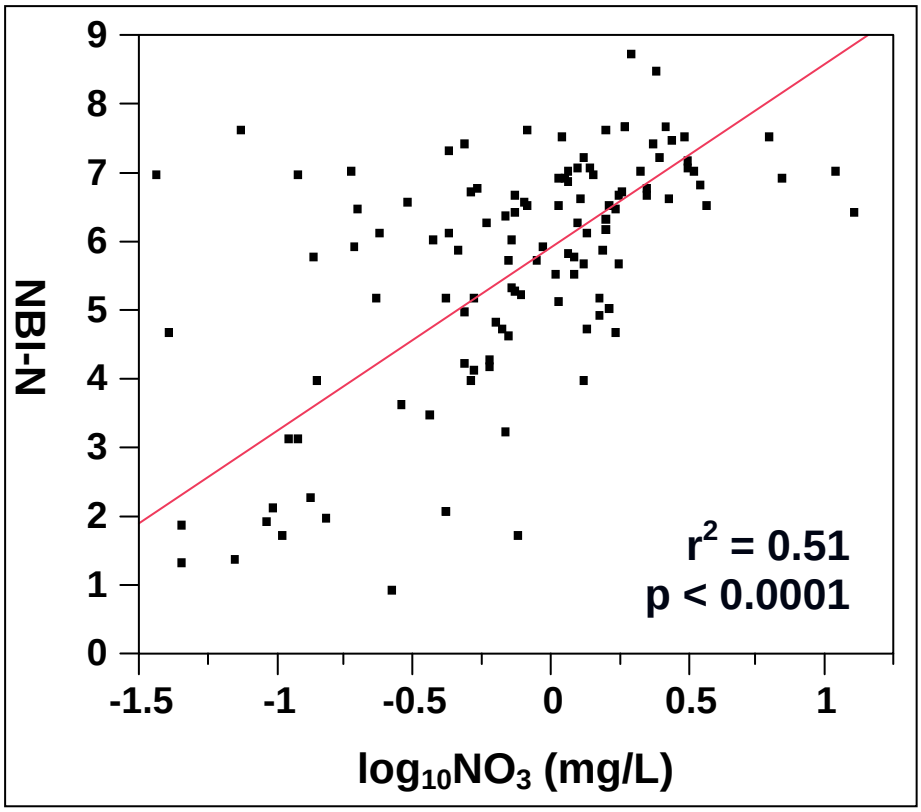

Figure 8. Relationships between NBI scores (estimated from the main dataset of New Jersey data) and nitrogen (nitrate + nitrite) concentrations in the same dataset.

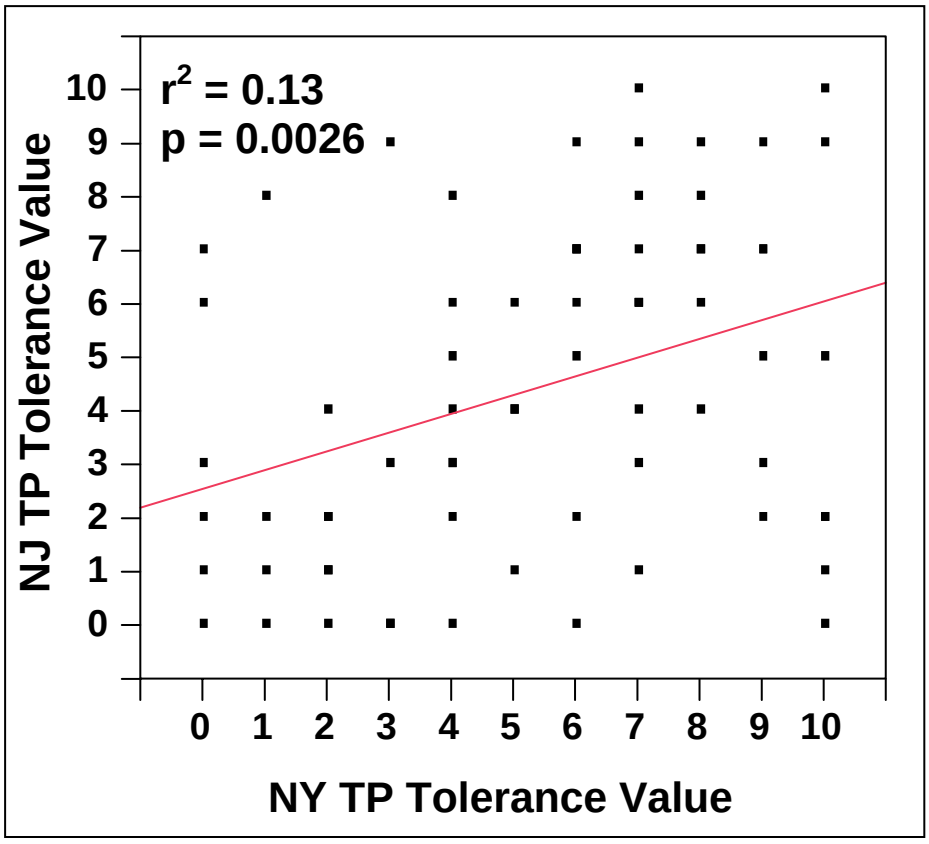

Figure 9. Relationships between the NYDEC estimates of tolerance values for phosphorus (from New York data) and estimates from the NJDEP main dataset.

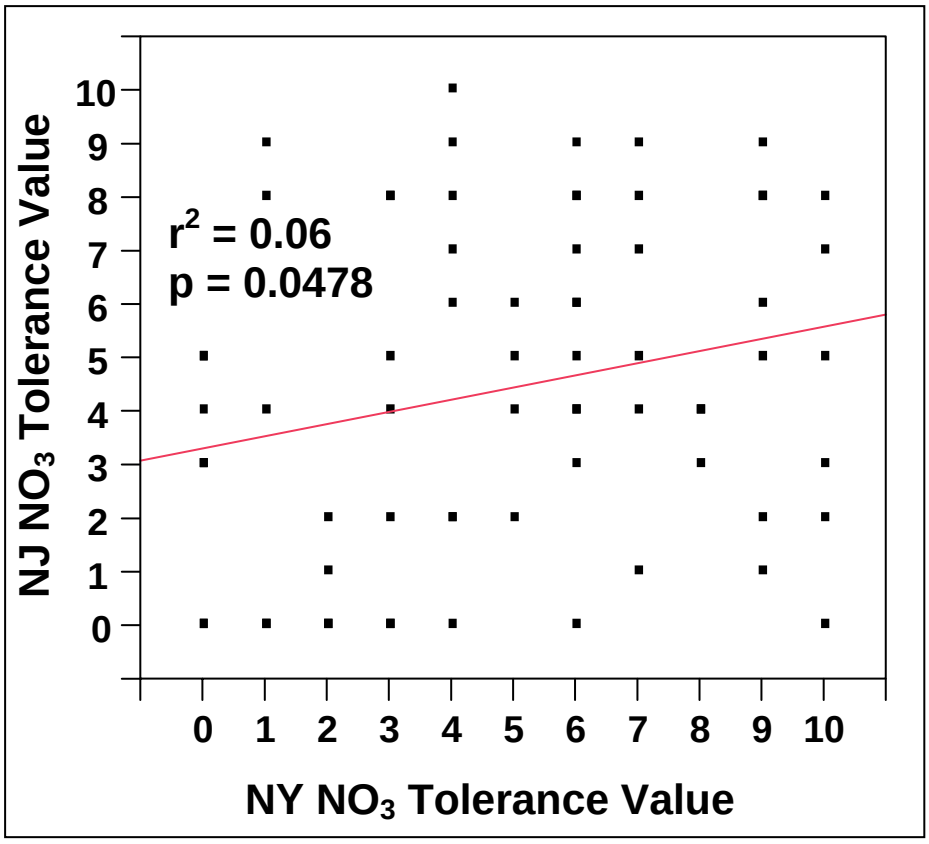

Figure 10. Relationships between the NYDEC estimates of tolerance values for nitrogen (from New York data) and estimates from the NJDEP main dataset.

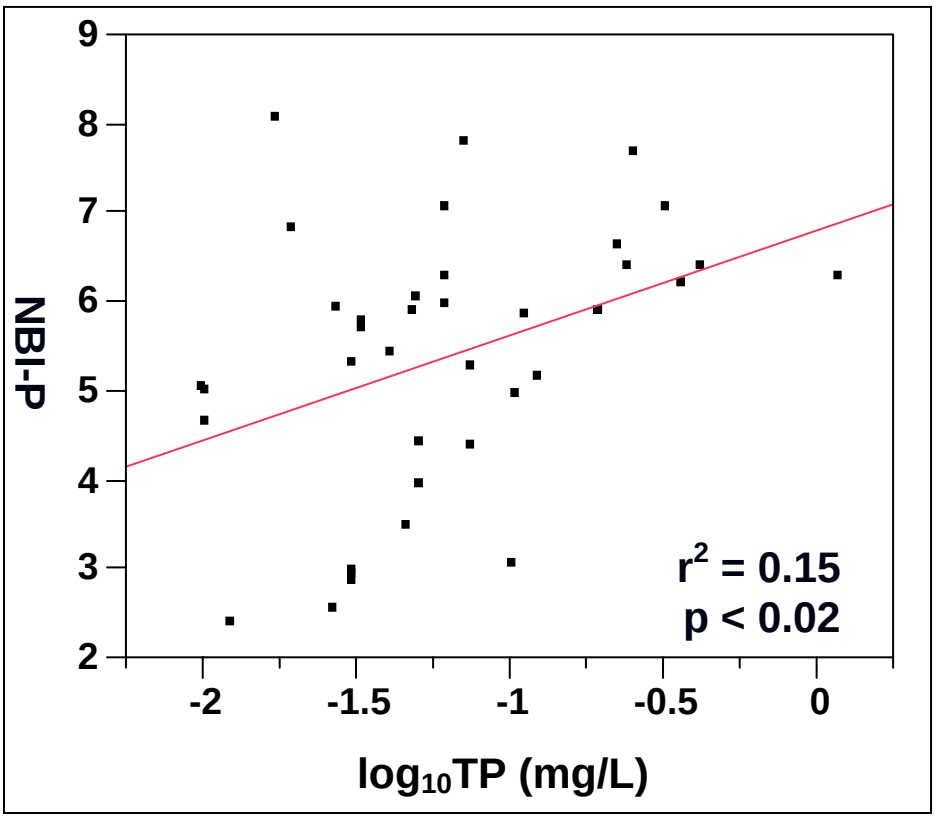

Figure 11. Relationships between NBI scores for phosphorus for sites in the validation dataset and nutrient concentrations. NBI scores are estimated from the main dataset of NJDEP data.

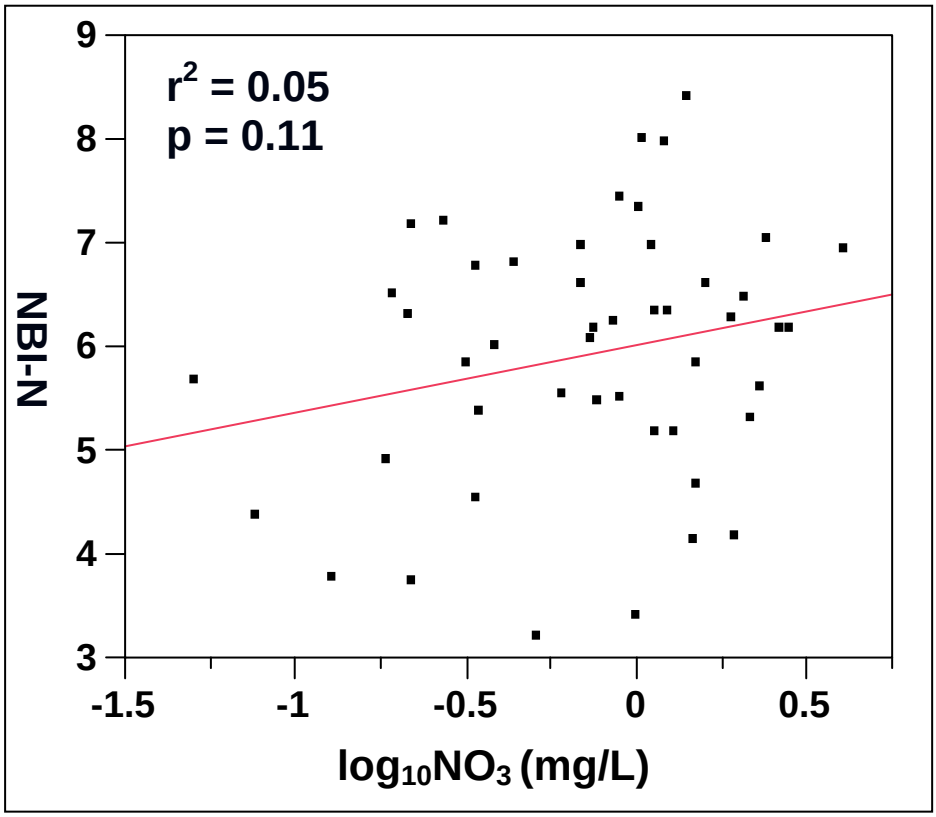

Figure 12.Relationships between NBI scores for nitrogen for sites in the validation dataset and nutrient concentrations. NBI scores are estimated from the main dataset of NJDEP data.

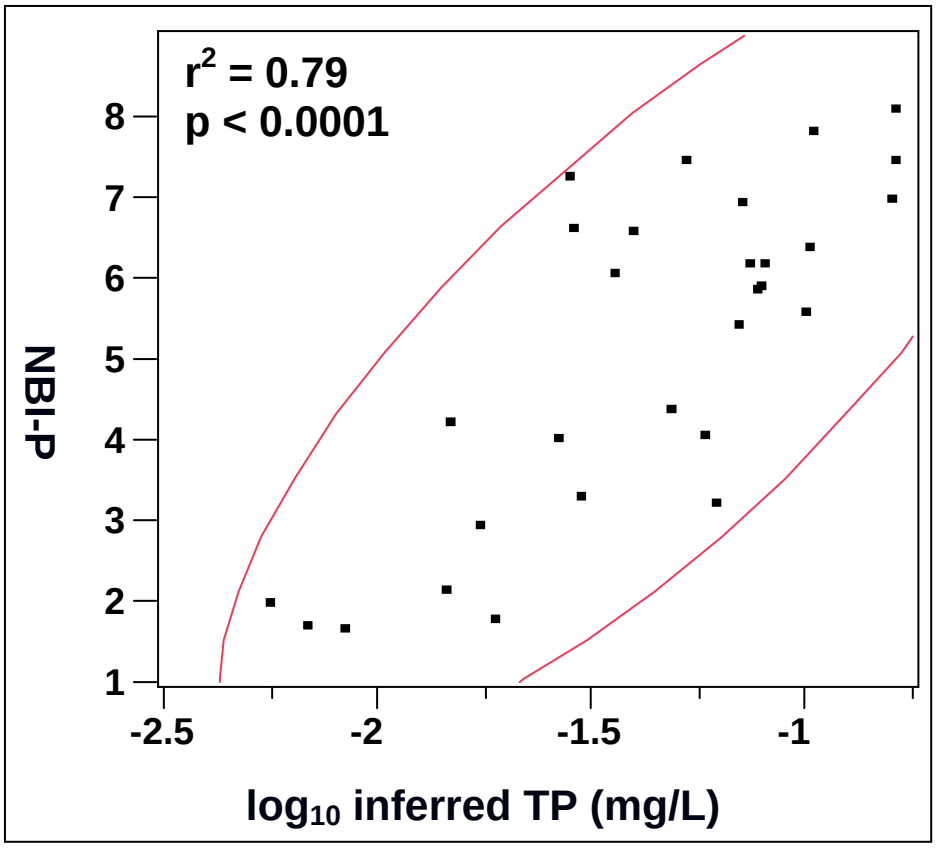

Figure 13. Relationships between NBI scores for phosphorus estimated for diatom subset of New Jersey data and total phosphorus concentrations inferred from diatom assemblage data. NBI scores are based on tolerance values estimated from the main dataset of New Jersey data

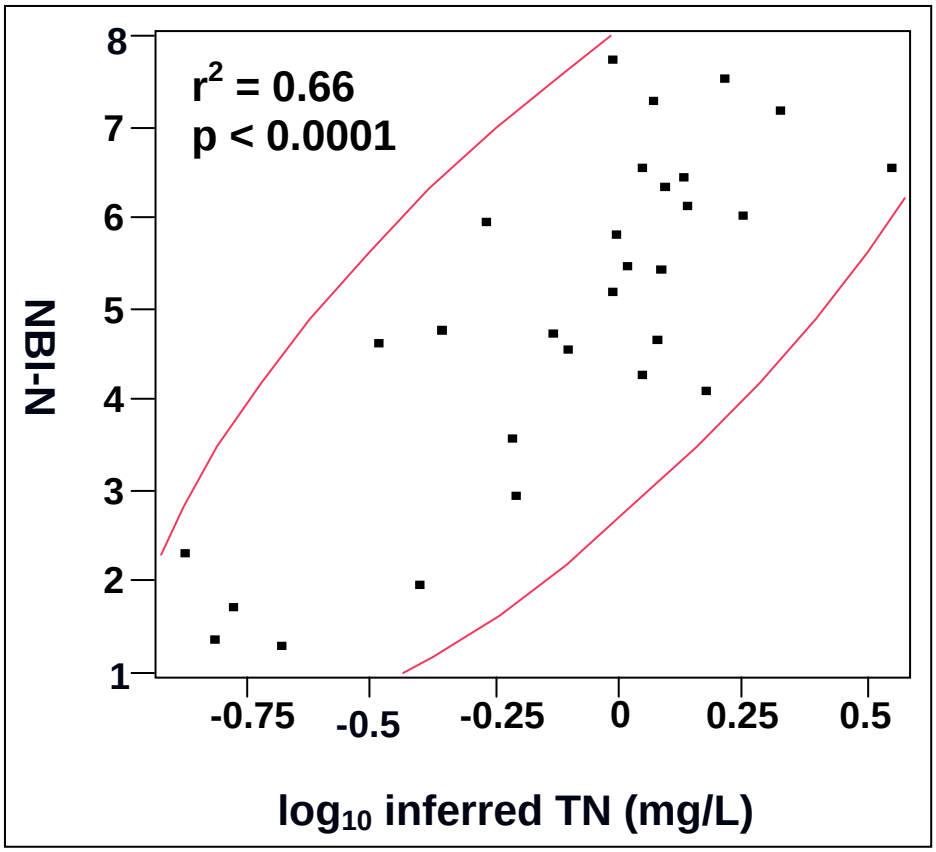

Figure 14. Relationships between NBI scores for nitrogen estimated for diatom subset of New Jersey data and total nitrogen concentrations inferred from diatom assemblage data. NBI scores are based on tolerance values estimated from the main dataset of New Jersey data.

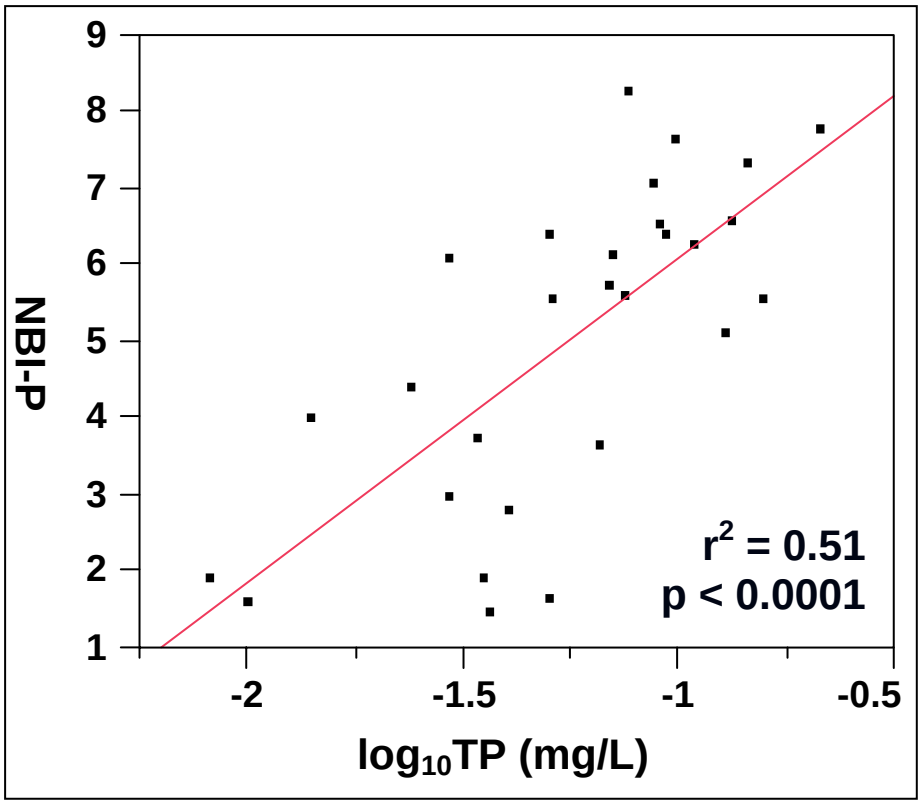

Figure 15. Relationships between NBI scores for phosphorus in the diatom subset and total phosphorus concentrations in the main chemistry dataset.

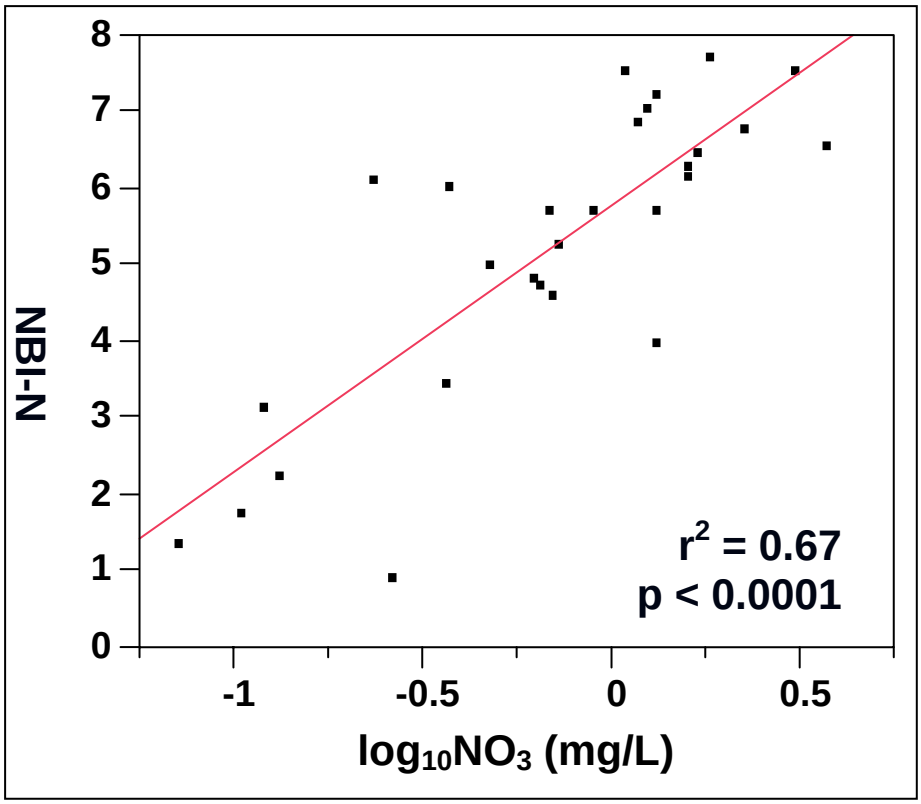

Figure 16. Relationships between NBI scores for nitrogen in the diatom subset and nitrogen (nitrate + nitrite) concentrations in the main chemistry dataset.

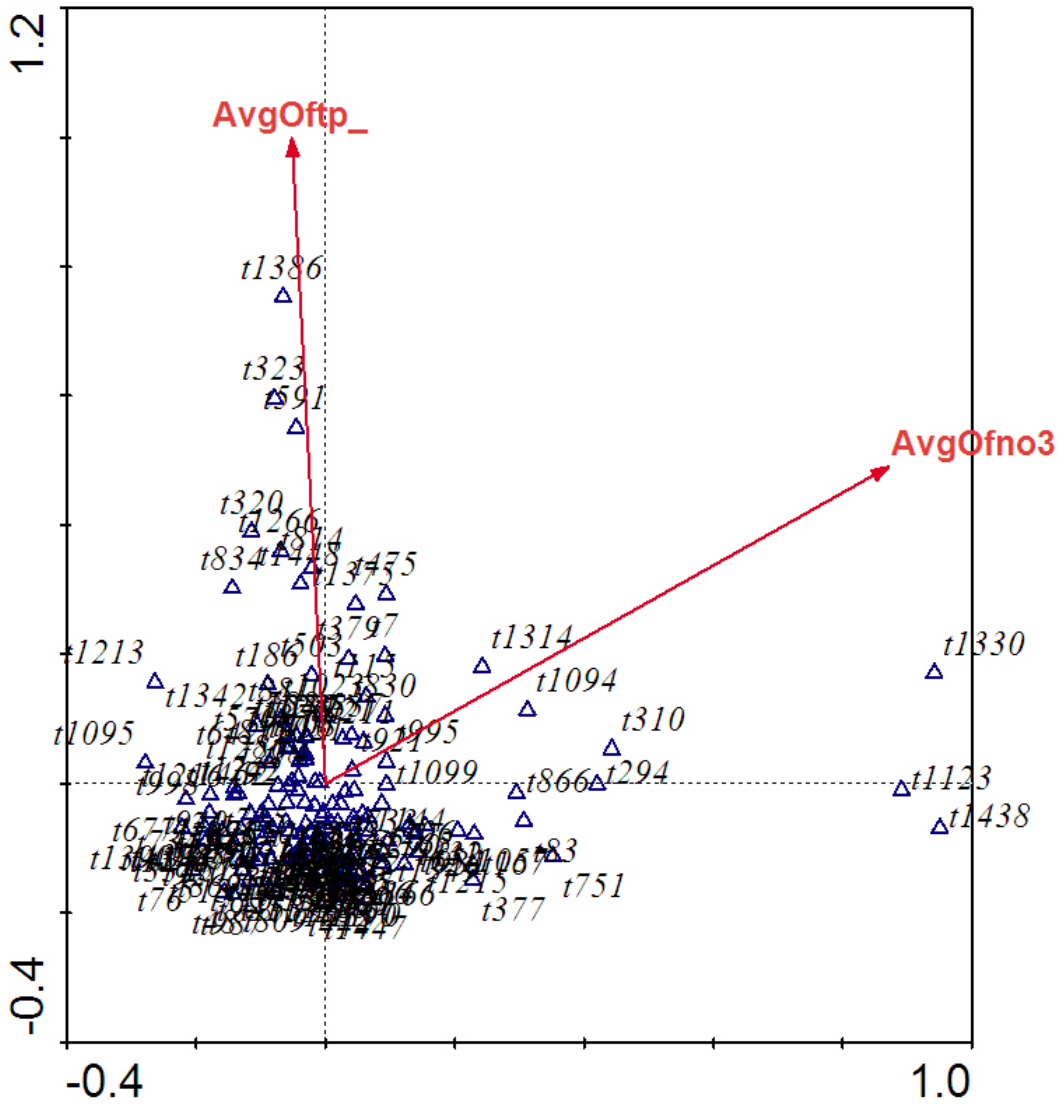

Figure 17. Results of canonical correspondence analysis of macroinvertebrate proportions and nutrient concentrations in the main dataset of New Jersey data. Triangles show centroids of locations of occurrence of individual taxa on the first two ordination axes, and the arrows show relationships of nutrient concentrations to the ordination axes.

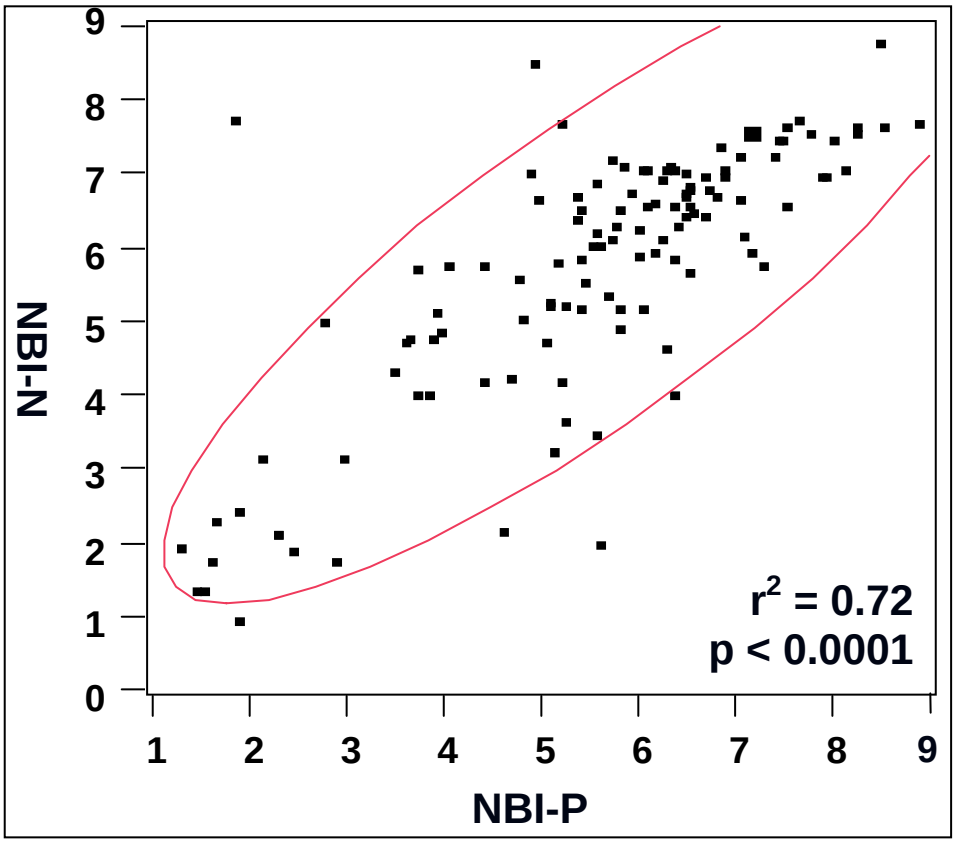

Figure 18. Relationship between nitrate and total phosphorus NBI scores for the main New Jersey dataset.

Tables

Table 1. Parameters and method names for nutrient analyses in NJDEP and NJAI datasets.

Parameter	Occurrence	Source agency	Agency Characteristic Name	Agency Method Code	Agency Method Name
Nitrate + nitrite	NJDEP measurements (main and validation datasets)	USGS	Nitrite plus nitrate, water, filtered, milligrams per liter as nitrogen	I-2545-90	Nitrogen, nitrite plus nitrate, colorimetry, cadmium reduction-diazotization, automated-segmented flow
Nitrate + nitrite	NJDEP measurements (main and validation datasets)	EPA	Nitrogen, Nitrite (NO2) + Nitrate (NO3) as N	353.2	Nitrate (as N) Automated Diazotization w/o Cd Reduction Column
Total Phosphorus	NJDEP measurements (main and validation datasets)	EPA	Phosphorus as P	365.4	Total Phosphorus After Block Digestion
Total Phosphorus	NJDEP measurements (main and validation datasets)	USGS	Phosphorus, water, unfiltered, milligrams per liter	I-4610-91	Determination of total phosphorus by a Kjeldahl digestion method and an automated colorimetric finish that includes dialysis
Nitrate+nitrite	NJDEP measurements (validation dataset only)	USGS	Nitrogen, nitrite plus nitrate, dissolved	I-2546-91	Nitrogen, nitrite plus nitrate, low ionic-strength water, colorimetry, cadmium reduction-diazotization, automated-segmented flow
Total Phosphorus	PCER measurements (main dataset and NJAI study)	EPA	Phosphorus as P	365.2	Phosphorus by single reagent colorimetry
Nitrate+nitrite	PCER measurements (main dataset and NJAI study)	EPA	Nitrogen, Nitrite (NO2) + Nitrate (NO3) as N	353.2	Nitrate-nitrite Nitrogen by Cadmium reduction
Total Kjeldahl Nitrogen	PCER measurements (NJAI only)	EPA	Total Kjeldahl Nitrogen	351.2	Total Kjeldahl Nitrogen by semi-automated colorimetry

Table 2. Relationships between tolerance values, NBI values and nutrient concentrations.

Total Phosphorus								
	Source of values			Regressions			Correlation (r^2)	
Row	Tolerance values	Macroinverte-brate data	Chemistry data	n	r^2	p	logTP & log(NO3 or TN)	Pnbi & Nnbi
1a	NYSDEC	Main dataset	Main dataset	68	0.19	<0.0002	0.38	0.58
2a	Main dataset	Main dataset	Main dataset	68	0.45	<0.0001	0.38	0.72
3a	Main dataset	Validation dataset	Validation dataset	38	0.15	<0.02	0.27	0.60
4a	Main dataset	Diatom subset	Diatom inferred	29	0.62	<0.0001	0.61	0.73
5a	Main dataset	Diatom subset	Diatom study	29	0.58	<0.0001	0.59	0.73
6a	Main dataset	Diatom subset	Diatom subset	28	0.51	<0.0001	0.28	0.73
7a	Half of main dataset	Other half of main dataset	Main dataset	39	0.05	ns	0.18	0.59
Nitrogen ([Nitrate+nitrite] or [Total nitrogen])								
1b	NYSDEC	Main dataset	Main dataset	97	0.15	<0.0001		
2b	Main dataset	Main dataset	Main dataset	97	0.51	<0.0001		
3b	Main dataset	Validation dataset	Validation dataset	48	0.05	<0.11		
4b	Main dataset	Diatom subset	Diatom inferred	29	0.66	<.0001		
5b	Main dataset	Diatom subset	Diatom study	29	0.64	<0.0001		
6b	Main dataset	Diatom subset	Diatom subset	28	0.67	<.0001		
7b	Half of main dataset	Other half of main dataset	Main dataset	55	0.23	<.0002		