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NOTE

RESILIENCE OF FORESTED WETLANDS LOCATED IN THE SOUTHEASTERN UNITED STATES: DEMONSTRATION OF A SOIL PERTURBATION INDEX

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Abstract: This study examined the usefulness of soil organic matter (SOM), total organic carbon (TOC), total Kjeldahl nitrogen (TKN), and total phosphorus (TP) as indicators of resilience in forested wetlands located within southeast Virginia, USA. These data were also examined as standards for reference wetlands before and after timber harvesting and for comparisons of mature and early successional stages. Results indicate that the wetland soils in this study seem to be relatively resilient to perturbation. Soil total phosphorus was significantly greater in the 0- and 0.5-year stages than the 5-, 8-, and 14-year stages ($p < 0.05$). Although there were no significant differences in SOM, TOC, and TKN levels before and after timber harvest or between early and mature successional stages, there were consistent trends that may prove beneficial in determining reference standards. A Soil Perturbation Index was developed by combining all four parameters for soils collected in the Chowan River watershed to determine extent of deviation from the biogeochemical reference. Using the model developed in this study, biogeochemical functions decrease after harvesting, with the low point reached at approximately 8 to 9 years after human alteration. This index predicts that it would take 16–17 years for SOM, TOC, TKN, and TP to return to pre-harvest conditions. Perturbation indices could be used for assessment of human impacts, restoration projects, and mitigation of wetlands. We maintain that a Soil Perturbation Index can be one useful component of an index of biotic integrity for wetland ecosystems.

Key Words: forested wetlands, wetland soils, timber harvest, soil organic matter, total organic carbon, total Kjeldahl nitrogen, total phosphorus, Soil Perturbation Index, biogeochemical reference, index of biotic integrity

INTRODUCTION

Forested wetlands are the most common type of wetlands in the conterminous United States (Dahl et al. 1991). The majority of these wetlands are located along small drainageways, and have been subjected to harvesting. They play an important role in landscape biogeochemical processes because of their position between terrestrial and aquatic ecosystems (Walbridge and Lockaby 1994). The large accumulation and storage capacity for organic matter and highly variable decomposition rates in southeastern forested wetlands are tightly linked to the capacity of the sites to recover from alteration (Griffin et al. 1992, Smith 1997). Recycling of nutrients such as nitrogen and phosphorus, resulting from organic matter decomposition, is a vital link for internal nutrient regeneration in wetlands (Reddy and D'Angelo 1994). The carbon influx into the detrital pool is strongly related to primary production (Cebrian and Duarte 1995).

Organic matter, carbon, nitrogen, and phosphorus are essential in primary productivity and regeneration of ecosystems such as wetlands. Wetland soils integrate the influence of these nutrients from all plant and microbial communities rather than focusing only on a single species or a single nutrient. The biogeochemical functions of forested wetlands are driven mostly by hydrology, biotic processes, and soil chemistry (Walbridge and Lockaby 1994). However, the driving factors regulating decomposition and nutrient processes in forested wetlands are poorly understood (Lockaby et al. 1996).

Forested wetlands are recognized for their importance in maintaining environmental quality, as well as

for their economic value from timber. These environmental and economic interests often conflict, causing the need for best management practices to be scientifically based to provide an optimal balance between environmental quality and economic development (McLaughlin et al. 1996). Considering human population growth and the benefits of wetlands, an increased knowledge of the effects of applied stress and the subsequent resilience, or ability of ecosystems to recover from stress (Holland 1996), is vital for proper management of these resources.

The need for additional baseline information about ecosystem resilience has also been emphasized by Brinson and Rheinhardt (1996). They argue that reference wetlands should be used to develop standards against which impacts to wetlands are evaluated. In their paper, reference wetlands are defined as sites within a specified geographic region that are chosen to encompass the known variation of a group of wetlands, including both those subjected to natural disturbance as well as those that have been altered by human activity. A reference data set in each wetland class should include wetlands ranging in ecological integrity from highly degraded to highly functioning, and from early successional to mature (Brinson and Rheinhardt 1996).

An ideal index for evaluation of wetland ecosystems would be sensitive to all stresses placed on biological systems by humans while also retaining limited sensitivity to natural variation in physical and biological environments. An array of indicators could be combined into one or more simple indices and possibly be used to detect degradation, identify its cause, and determine if improvement results from management actions. An ideal wetland index would apply an appropriate, cost-effective, and user-friendly procedure for general usage that is applicable in a wide range of wetland systems (Karr 1991). This type of approach has proved successful with the Index of Biotic Integrity (IBI) [for freshwater] (Karr 1991).

Using a biogeochemical indicator can provide a systematic approach that includes both the organisms and physical aspects of an ecosystem. The biogeochemical approach can be sensitive to perturbation, user-friendly, and cost-effective. When assessing wetland ecosystems, one might want to include a biogeochemical component, such as the Soil Perturbation Index described here.

This study examined soil organic matter (SOM), total organic carbon (TOC), total Kjeldahl nitrogen (TKN), and total phosphorus (TP) as possible indicators of resilience. Because carbon, nitrogen, and phosphorus are essential components of all living organisms, their availability in soil may prove critical to determining the "health" of that system (Salisbury and Ross 1992). These parameters could be used as standards for reference wetlands before and after alterations such as timber harvest, as well as standards for early and mature successional stages. The objectives of this study were to (1) determine if there are significant differences in SOM, TOC, TKN, and TP concentrations among uncut wetlands and cut wetlands of different successional stages; and (2) draft a Soil Perturbation Index for forested wetlands located within the Mid-Atlantic region.

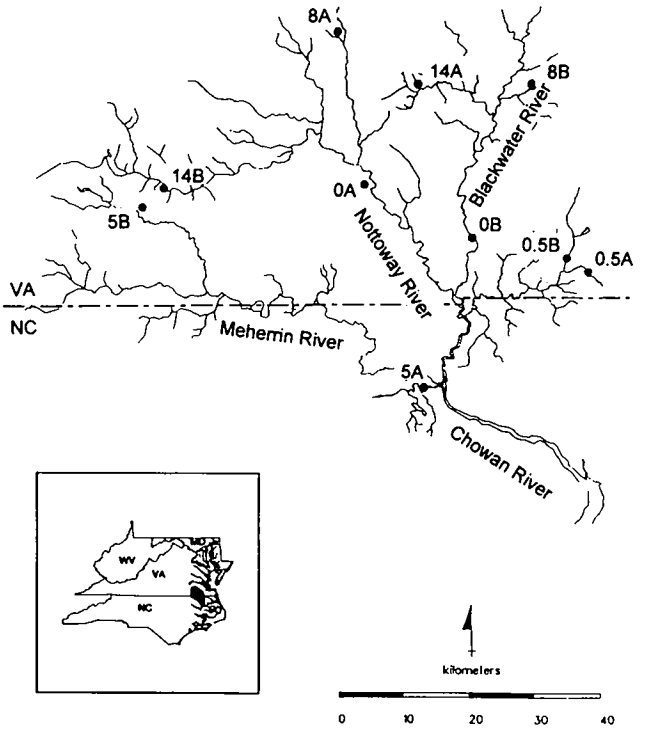

Figure 1. Map showing location of Chowan River watershed and the locations of the individual sites. The study sites include uncut wetlands (0A and 0B) and cut wetlands of various successional stages (years) [0.5A, 0.5B, 5A, 5B, 8A, 8B, 14A, and 14B].

STUDY AREA AND SITE DESCRIPTIONS

The ten forested wetlands examined in this study were located adjacent to the Virginia and North Carolina border within the Chowan River watershed (Figure 1). The paucity of wetlands with similar hydrology, pre-harvest vegetation, soil, and successional stage meant that the number of replicate wetlands was low and was spread out within the Chowan River watershed. The Chowan River watershed consisted of primarily rural land, and all sites were surrounded by agricultural fields. The selected wetlands consisted of two replicates of uncut wetlands (0A and 0B) and cut wetlands of different successional stages. The cut wetlands were timber-harvested by the ground-based,

Table 1. Dominant vegetation of the wetland study sites (Spencer 1998).

Site	Herbaceous	Woody
0A	*Boehmeria cylindrica* L.	*Nyssa aquatica* L.
	Polygonum spp.	*Taxodium distichum* (L.) Rich
0B	*Boehmeria cylindrica* L.	*Nyssa aquatica*
	Polygonum spp.	*Taxodium distichum*
	Impatiens capensis Meerb.	
0.5A	No Vegetation	No Vegetation
0.5B	No Vegetation	No Vegetation
5A	*Boehmeria cylindrica*	*Platanus occidentalis* L.
	Toxicodendron radicans L.	*Salix nigra* Marshall
	Juncus effusus L.	*Acer rubrum* L.
	Impatiens capensis	*Taxodium distichum*
5B	*Boehmeria cylindrica*	*Acer rubrum*
	Scirpus cyperinus (L.) Kunth	*Populus heterophylla* L.
	Juncus effusus	*Fraxinus* spp.
		Salix nigra
8A	*Typha* spp.	*Salix nigra*
	Saururus cernuus L.	*Fraxinus* spp.
	Leersia oryzoides (L.) Sw.	*Acer rubrum*
8B	*Polygonum punctatum* Ell.	*Acer rubrum*
	Saururus cernuus L.	*Fraxinus* spp.
	Sparganium americanum Nuttall	*Alnus rugosa* (DuRoi) Sprengal
	Typha spp.	
14A	*Carex* spp.	*Clethra alnifolia* L.
	Dulichium spp.	*Acer rubrum*
	Woodwardia virginica (L.) Smith	*Fraxinus* spp.
		Magnolia virginiana L.
14B	*Carex* spp.	*Fraxinus* spp.
		Acer rubrum

clear-cut method followed by natural regeneration. The cut sites consisted of wetlands with natural regeneration times of 0.5, 5, 8, and 14 years (0.5A, 0.5B, 5A, 5B, 8A, 8B, 14A, and 14B). The wetland study sites are primarily broad-leaved, deciduous wetlands (Table 1). Soil particle size analysis indicated that textures ranged from loam to clay (Table 2). Monitoring well data were collected biweekly, on average, from 11/95 to 9/96 for the 5-, 8-, and 14-year sites and from 3/96 to 9/96 for the 0- and 0.5-year sites. The majority of the sites were either semipermenantly flooded or seasonally flooded except for sites 5B and 8A, which were flooded (Cowardin et al. 1979) (Figure 2). All sites were sampled in July and August, 1995 except for sites 0.5A and 0.5B, which were sampled in January and March 1996.

Table 2. Soil particle size analysis and textural class of the wetland study sites.

Site	% Sand	% Silt	% Clay	Textural Class
0.5A	11.0	38.0	51.0	Clay
0.5B	12.7	42.4	44.9	Silty clay
5A	7.8	49.4	42.8	Silty clay
5B	10.0	49.6	40.4	Silty clay
8A	45.2	53.7	1.0	Silt loam
8B	77.3	22.5	0.2	Loamy sand
14A	6.5	38.0	55.5	Clay
14B	36.2	40.3	23.5	Loam
0A	36.0	43.0	21.0	Loam
0B	7.5	47.2	45.3	Silty clay

METHODS

Soil

Twenty soil cores were randomly sampled within the wetlands previously selected for the U.S. Environmental Protection Agency project # CD993276–01. Soil cores were 8.5 cm in diameter by 30 cm long. Each soil core was removed intact with loose leaf litter removed. Cores were placed on ice and frozen until processing.

The top 5 cm was chosen to represent the most recent influx of nutrients into the wetland soil. Soil organic matter, TOC, TKN, and TP analyses were performed on the top 5 cm of each soil core. Samples

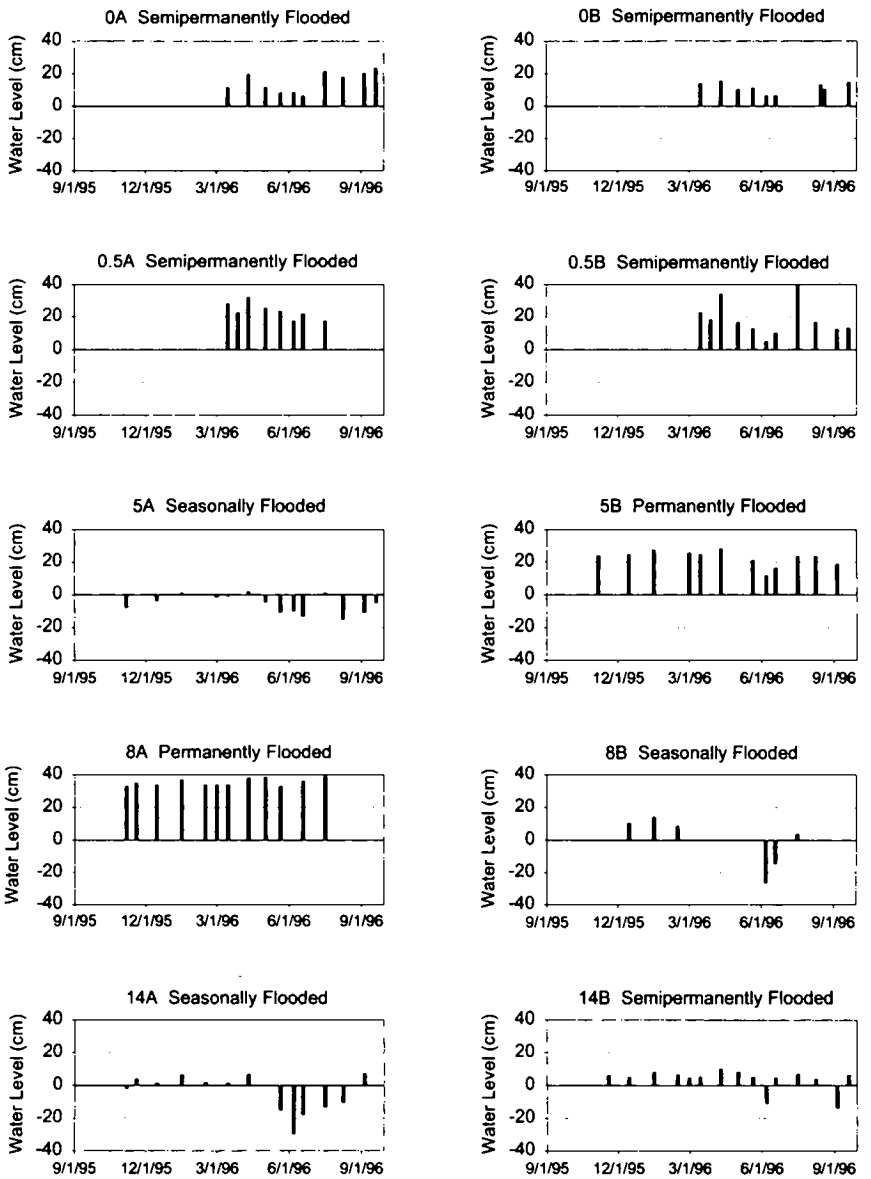

Figure 2. Monitoring well data of study sites from 9/95 to 8/96 for sites 5A, 5B, 8A, 8B, 14A, and 14B and from 3/96 to 8/96 for sites 0A, 0B, 0.5A, and 0.5B (ground level is at 0 cm). The hydroperiod was determined using the Classification of Wetlands and Deepwater Habitats of the United States (Cowardin et al. 1979).

were thawed and air-dried on absorbency paper. Dried samples were weighed, homogenized, and sieved (2.0 mm). The soil passing through the sieve was stored in an air-tight jar in the dark until analyzed. The material passing through the sieve contained decomposed organic matter intermingled with mineral material.

Soil organic matter was measured by loss on ignition at 550°C for 5 hours (Craft et al. 1991). Total organic carbon was analyzed by a CR12 Carbon Analyzer (Leco Corporation 1996). Total Kjeldahl nitrogen and TP were measured by a TRAACS 800 Autoanalyzer (Technicon Industrial Systems Corporation 1987).

Statistical Analyses

Individual Parameter Response. A one-way analysis of variance (ANOVA) was performed on SOM, TOC, TKN, and TP. The treatment was successional stage consisting of five groups ($n = 2$); 0, 0.5, 5, 8, and 14 years. All treatments were normally distributed based on Kolmogorov-Smirnov test for normality (Jandel Scientific 1994). The Levene Median test for homogeneity of variances indicated that variances were unequal among treatments for all four variables (Jandel Scientific 1994). All ANOVAs and Student-Newman-Kuels (SNK) tests ($p < 0.05$) were performed with PC/SAS software (SAS Institute, Inc. 1988).

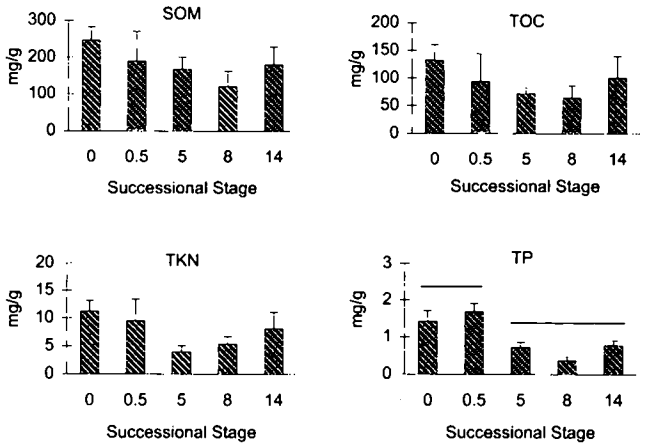

Figure 3. Trends of soil organic matter (SOM), total organic carbon (TOC), total Kjeldahl nitrogen (TKN), and total phosphorus (TP) among different successional stages. Error bars represent one standard error. Significant differences ($p < 0.05$) in TP means are represented by separate horizontal bars.

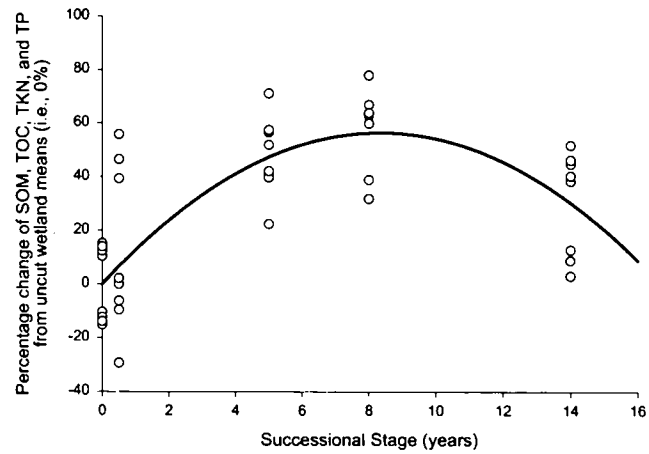

Figure 4. The Soil Perturbation Index shows percent change from a biogeochemical reference determined from uncut wetlands (0 years). This Soil Perturbation Index shows a change in biogeochemical function that is greatest 8–9 years after timber harvesting. This index predicts that it would take 16–17 years for soil organic matter (SOM), total organic carbon (TOC), total Kjeldahl nitrogen (TKN), and total phosphorus (TP) to return pre-harvest conditions.

Soil Perturbation Index. In an effort to develop a simple way to determine overall wetland "health," a Soil Perturbation Index was developed. The Soil Perturbation Index uses the means of SOM, TOC, TKN, and TP data for each wetland to calculate the percent change from the biogeochemical reference. The biogeochemical reference was determined from the uncut wetlands. Since there are two replicate wetlands per successional stage and four parameters analyzed per wetland, eight points (two SOM data points, two TOC data points, etc.) for each successional stage can be plotted. The Soil Perturbation Index consists of data that were transformed to percentage data by the following equation using the parameter TP as an example:

$$[(u - c)/u] \times 100 = \text{perturbation number}$$

where

u = TP mean value for the 0 (uncut) successional stage wetlands and

c = TP mean for the cut wetland in question

The perturbation numbers were plotted for the different successional stages. A second order polynomial equation [($Y = M0 + M1(x) + M2(x)$) where $M0 = 2.943$, $M1 = 12.810$, $M2 = -0.773$, and x = successional stage (years)] provided the best fit line for the index with $r = 0.74$.

RESULTS

Individual Parameter Response

The observable trend for the parameters SOM and TOC was similar. Concentrations decreased until the 8-year stage then increased toward pre-harvest conditions (Figure 3). The 5-year stage was the lowest for TKN. The one-way ANOVA indicated a difference in soil TP among the successional stages ($F_{4,5} = 16.1$, $p = 0.005$) (Figure 3). The SNK test ($p < 0.05$) indicated that the 0- and 0.5-year successional stages were significantly higher in soil TP than the 5-, 8-, and 14-year stages.

Soil Perturbation Index

The Soil Perturbation Index suggests that timber harvesting causes a change in biogeochemical functions that is greatest at eight to nine years after alteration. This index predicts that it would take 16–17 years for SOM, TOC, TKN, and TP to return to pre-harvest conditions (Figure 4).

DISCUSSION

Individual Parameter Response

Previous work suggested that the initial effects of timber harvesting on forested wetlands result in loss of organic matter and carbon because of the increased microbial activity associated with higher temperatures (Gambrell and Patrick 1978, White 1995) due to the removal of canopy cover (Trettin et al. 1996). The results of this study, as shown in the 0.5-, 5-, and 8-year successional stages, corroborate the earlier studies. The lower SOM and C content is in agreement with the findings of Mader et al. (1989), McLaughlin et al.

(1996), and Trettin et al. (1996). At the 5- and the 8-year stages, there is a decrease of organic input compared to the annual leaf litter in a mature wetland or the immediately available harvest debris (above- and belowground) left from timber harvest in a 0.5-year wetland. This lowered availability of organic matter could account for a decrease in SOM and TOC (Smith et al. 1996). The 8-year stage may be the low point at which the wetland begins to return to pre-harvest conditions. Comparisons of the individual parameters did not suggest that SOM and TOC are reliable indicators of wetland resilience.

Nitrogen concentrations were highest in the uncut wetlands. This may be due to the high organic matter content of the soil resulting from annual input of leaf litter and root production over many decades. Although there is an immediate influx of N and P from leaves (Lockaby and Walbridge 1998) and canopy fragments (Harmon et al. 1986) after harvesting, the soil N level may not increase significantly in the 0.5-year sites because N is lost to the atmosphere (Lindau et al. 1994). Unlike SOM and TOC, TKN means are the lowest at the 5-year stage. However, the 8-year stage contained red alder, *Alnus rugosa,* which is a nitrogen-fixing shrub or small tree. The roots of nitrogen-fixing plants excrete nitrogen from nodules into surrounding soil (Goldman 1961), thus possibly causing the increased TKN shown in the 8-year stage. In forested wetlands, plant uptake with respect to overall rates of N and P retention can be significant but may vary with successional stage. Rates may be higher in young aggrading stands but decrease as wetlands mature (Lockaby and Walbridge 1998).

Phosphorus levels were the highest in the 0.5-year successional group. Canopy fragments and roots left from timber harvest, as well as leaf litter, could contribute to these high levels. Harmon et al. (1986) stated that there is a lack of data to even roughly gauge the importance of P stored in coarse woody debris. According to Salisbury and Ross (1992), leaves in general contain significantly more P and N than do whole shoot systems. Unlike N, P remains in the wetland system, since there are no removal mechanisms corresponding to denitrification. The major mechanism for soil P removal is plant uptake (Patrick 1992). At the 0.5-year stage, there is no vegetation to extract P from the soil. By the 5- and 8-year successional stages, herbaceous and woody sapling vegetation have become established to absorb P and start the recycling process of P commonly found in mature wetland systems.

Clear-cut timber harvesting in this study induces similar trends for SOM, TOC, and TKN that decrease until vegetation has reestablished, then return toward pre-harvest conditions. Total phosphorus demonstrated significant differences ($p < 0.05$) among successional stages. Phosphorus storage and subsequent release is much more likely to occur within wetlands since the P cycle is not as biogeochemically open as N (Patrick 1992).

Holling (1986) defines a stable ecosystem as having low variability, the ability to resist and absorb change, and the ability to maintain an equilibrium. Resilient systems withstand events far from equilibrium. These systems have high variability and can adapt to change (Holling 1986). In our study, the 0.5-year successional stage wetlands have the highest variability for three of the four parameters. As the years pass, the variability of the Chowan River study sites can be expected to return back to pre-alteration conditions. Trends seen in means and variability indicate that bottomland hardwood wetlands are relatively resilient. More studies are needed to explore variability within and between similar types of wetlands and successional stages.

Soil Perturbation Index

The Soil Perturbation Index evaluates how the different successional stages compare to the uncut mature wetlands from a biogeochemical standpoint. The Brooks and Hughes (1988) premise is that profiles of biotic communities within an ecoregion framework provide the most appropriate data for evaluating the functions and values associated with a wetland. An aquatic ecoregion represents an area within which one can expect similar wetland types to vary less than they would between different ecoregions. Relatively undisturbed wetlands in an ecoregion represent the attainable integrity of that ecoregion's wetlands (Brooks and Hughes 1988). With the model created in our study, zero percent change is the mean of the uncut wetlands and is considered the biogeochemical reference because it has zero perturbation. This perturbation index displays the wetlands demonstrating the lowest biogeochemical functions as deviating most from the biogeochemical reference. The greatest effects are not apparent immediately following timber harvest. Using the model developed in this study, biogeochemical functions decrease after harvesting, with the low point reached at approximately 8 to 9 years after human alteration, as indicated by the higher perturbation index number. This index predicts that it would take 16–17 years for SOM, TOC, TKN, and TP to return to pre-harvest conditions (Figure 4).

CONCLUSION

A biogeochemical assessment would provide a systems approach to wetland functional integrity since many biotic and abiotic factors affect soil nutrients.

These data would provide an indication of biogeochemical reference for other wetlands of similar type within the same geographic region. Over time, a set of reference data points may be assembled, against which sample wetlands can be compared. Different successional stage wetlands within the Chowan River watershed, as well as in other watersheds of the Mid-Atlantic region, should be added to this index to increase validity. Comparisons could be made to wetlands in other regions, wetlands of different types, and wetlands exposed to different perturbations. Soil Perturbation Indices could be used for assessment of human impacts, restoration projects, and mitigation of wetlands. We maintain that a Soil Perturbation Index can be one useful component of an index of biotic integrity for wetland ecosystems.

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