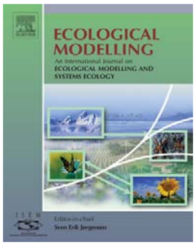
ECOLOGICAL MODELLING 195 (2006) 281–295

available at www.sciencedirect.com

journal homepage: www.elsevier.com/locate/ecolmodel



GIS and biogeochemical models for examining the legacy of forest disturbance in the Adirondack Park, NY, USA

Brenden E. McNeil, Richard E. Martell, Jane M. Read*

Syracuse University, Maxwell School of Citizenship and Public Affairs, Department of Geography,
144 Eggers Hall, Syracuse, NY 13244, USA

A R T I C L E I N F O

Article history:
Received 25 August 2004
Received in revised form 26 October 2005
Accepted 15 November 2005
Published on line 7 February 2006

Keywords:
Model resolution
GIS
PnET
Nitrogen
Disturbance history
Logging
Adirondack mountains
New York

A B S T R A C T

Human dominance over the spatial patterns of nitrogen (N) cycling in forested ecosystems of the northeast United States is regulated through the locally variable legacy of historic forest disturbance, and the regionally variable effects of chronic atmospheric N deposition. In order to effectively use ecosystem models to understand the combined influence of these perturbations, the level of detail, or resolution, of input data must be carefully matched to the scale of analysis. By interpreting historic accounts of anthropogenic forest disturbances in the Adirondack Park between 1860 and 1916 into GIS models, we developed two realistic disturbance history scenarios of differing resolution. Using these models, we found predictions of present-day N cycling obtained from an ecosystem process model, PnET-CN, to be sensitive to the resolution of century-old disturbance input data. PnET-CN predictions obtained using the higher-resolution (more complex) disturbance scenario produced significantly different predictions of N cycling for selective-cut versus clear-cut disturbance regimes. Our experience with the combined use of GIS and a biogeochemical model suggests that the development of spatially explicit disturbance history information from historic accounts may enable future research to: (1) develop more precise quantitative disturbance history inputs at appropriate resolutions for ecosystem process models, and (2) more adequately characterize field-testable differences in old-growth, selective-cut, and clear-cut disturbance regimes.

1. Introduction

The legacy of historic disturbance is a crucial factor in understanding ecological pattern and process (Foster et al., 2003). Unfortunately, the logistics, time, and monetary expense of obtaining disturbance history information rapidly increase with the resolution (i.e., level of information) of the data. As researchers leverage the combined technologies of GIS, remote sensing, and ecosystem process models to understand broad-scale ecological problems at increasingly fine spatial and temporal resolutions (e.g., Ollinger et al., 2002; Schulze et al., 2002; Steffen et al., 2004; Turner et al., 2004; Keller et al., in press), the large costs of obtaining high-resolution disturbance information (e.g., via land record archives, dendrochronology, pollen analysis, pedologic analysis) will require environmental scientists to carefully match the resolution of forest disturbance information to the scale and method of analysis.

This research considers the role of disturbance history within the problem of nitrogen (N) pollution in the northeast United States (NE US, Driscoll et al., 2003). The cycling of N in the NE US is a human dominated system; almost every portion of this region has undergone extensive land-cover change during the past 200 years (Foster and Aber, 2004) and, on average, currently receives over 18 times more anthropogenically

---

* *Corresponding author*. Tel.: +1 315 382 5429.
E-mail address: bemcneil@syr.edu (B.E. McNeil).

0304-3800/$ – see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.ecolmodel.2005.11.028

fixed N than natural inputs (Boyer et al., 2002). Across this historically human dominated landscape, the current large amount of additional N can cause serious environmental consequences to the quality and health of air, forests, surface waters, and estuaries in the NE US (Driscoll et al., 2003). As human activity continues to assert its dominant role in this system, there is an increasing need to identify and describe the character of our past and present contributions to the functioning of this system. Most importantly, human contributions must be understood across scales of analysis, ranging from localized, acute land-cover change (Foster and Aber, 2004) to the regional, chronic effects of atmospheric N deposition to ecosystems throughout the region (Aber et al., 2003).

Researchers in the NE US have long recognized this need for a multi-scale, regional understanding of the anthropogenic manipulation of N cycling. Over 10 years ago, Aber et al. (1993) developed a modelling approach to understand the functioning of forests across the region. This approach combined geographic information systems (GIS) and simple statistical models to parameterize a simple, lumped-parameter forested ecosystem model, PnET (Photosynthesis and EvapoTranspiration). Since the development of this approach, the PnET family of models have been tested and validated extensively at sites throughout the region, and shown to be capable of assisting in the development of policies concerning acid deposition (Driscoll et al., 2001) and N pollution (Driscoll et al., 2003).

As identified by studies using the PnET-CN version of the model (Aber et al., 1997), a major consideration within the PnET approach to understanding N cycling in ecosystems lies within its parameterization of disturbance history (Aber et al., 1997; Goodale et al., 2002). In the NE US, disturbance causes N to be leached from the forest ecosystem, and counteracts the accumulation of atmospherically deposited N (Aber et al., 1998). The linkage between disturbance and leaching of N from ecosystems has been recognized for some time (Likens et al., 1970; Vitousek et al., 1979), but the potential long-term (i.e., 100–300 years) legacy of disturbance on N cycling has only recently been recognized by researchers in the NE US. As suggested by field studies (Goodale et al., 2000; Goodale and Aber, 2001) and evident within past PnET-CN modelling studies (e.g., Aber and Driscoll, 1997), the magnitude of the measurable legacy of disturbance upon current rates of N cycling may be dependent on the type, timing, frequency, intensity, and spatial extent of disturbance.

In PnET-CN, disturbance history is parameterized as a yearly record of forest biomass mortality and removal. For previous validations of PnET-CN, the level of detail, or resolution, of disturbance history information has been highly dependent upon the scale of analysis. Aber et al. (1997) validated and applied PnET-CN in small watersheds (10^{-2} km^2) using high-resolution disturbance data obtained with substantial localized historical knowledge. Goodale et al. (2002) validated and applied PnET-CN in large watersheds (10^3 to 10^4 km^2) of the eastern United States by using county-level United States Forest Service (USFS) Forest Inventory and Analysis (FIA) data on forest age-class structure, and state-level US census information on agricultural abandonment. While successful at their respective scales of measurement, implementation of either methodology at intermediate scales (i.e., 10^{-1} to 10^2 km^2) presents substantial difficulty: county-level FIA and state-level census information are typically too coarse, and fine-resolution, localized knowledge of disturbance history is extremely difficult to obtain for large areas.

The purpose of this research is to test the sensitivity of PnET-CN predictions of present-day N cycling using two resolutions of historically documented anthropogenic disturbance within a large region of the NE US, the Adirondack Park, New York. In our description of this sensitivity analysis, we will (1) discuss the use of GIS for "interpreting" historic records and modelling realistic scenarios of disturbance, (2) describe the use of these disturbance models as input to PnET-CN, and (3) answer the research question: are PnET-CN predictions of present-day N cycling sensitive to the different anthropogenic disturbance regimes that occurred within the Adirondack Park during 1860–1916?

2. Methods

2.1. Study area

2.1.1. Physical geography and N cycling

Originally protected by an 1894 amendment to the constitution of New York State requiring forest preserve lands to be "forever kept as wild forest lands", the current 2.4 million hectare Adirondack Park of northern New York State, USA (Fig. 1), contains a globally unique mountainous landscape of wetlands, northern hardwood and boreal forests, alpine tundra, and over 3000 lakes (Driscoll et al., 1991; Jenkins and Keal, 2004). The Park's downwind location from the industrialized

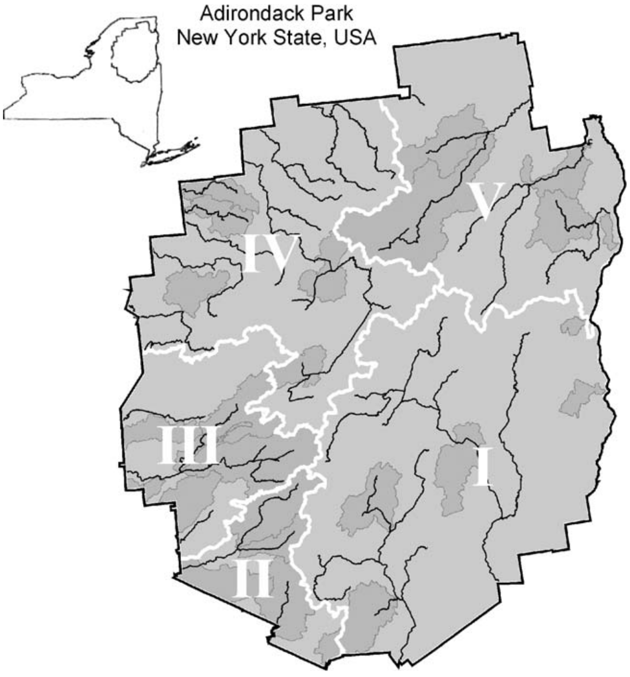


Fig. 1 – Study area map. The five regions discussed in the text are designated by the white boundaries and roman numerals (I = Hudson, II = East Canada Creek, III = West Canada Creek, IV = St. Lawrence, and V = Champlain). The five sample watersheds within each region are displayed in dark grey. Major rivers draining each region are also shown.

Ohio River valley and proximity to major east coast urban centers cause portions of the Park to receive some of the highest rates of nitrate (NO_3^-) and ammonium (NH_4) deposition in the NE US (NADP, 2004). As measured with N input and output budgets by Ito et al. (2005), watersheds in the Adirondack Park currently exhibit highly variable rates of N retention. There are five principal spatially variable factors in the Adirondack Park that could influence this variability in N retention: watershed topography/hydrological pathways, climate, nitrate deposition, species composition, and site disturbance history (Aber et al., 2003). Techniques to efficiently model or remotely observe the spatial variability of the first four factors are readily available, and include hydrological analysis of available USGS 10 m DEMs, determination of climate and nitrate deposition values using regression equations incorporating latitude, longitude, and elevation (Ito et al., 2002) and the use of remote sensing to determine species composition (e.g., Martin et al., 1998). However, existing techniques to map the spatial patterns of disturbance history (e.g., pollen analysis, land-deed surveys) are comparatively difficult – if not impossible – to implement across the large expanse of the Adirondack Park.

2.1.2. *Disturbance history*

Unlike the majority of forest lands within the United States, USFS FIA forest age-class structure data are not recorded on the "forever wild" designated lands of much of the Adirondack Park. Nevertheless, the Adirondack Park has a substantial recorded history of both natural and anthropogenic disturbance, available in the form of a thoroughly researched written history (McMartin, 1994), historic maps from 1885 and 1916 (Jenkins and Keal, 2004), and several GIS datasets (APA, 2001). These sources document many natural disturbances, including an extensive 1998 ice storm, large blowdown events in 1950 and 1995, and slash fires following logging in the early 20th century. Anthropogenic disturbance was minimal through the pre-European period, and then limited to small farming communities in the eastern lowlands of the Park from the European settlement period until the mid 19th century (McMartin, 1994). However, the anthropogenic disturbances to Adirondack forests during the late 19th century and early 20th century mark the region's most intensive period of disturbance since the ice age (McMartin, 1994).

An emergent trend within the historic record during 1860–1916 is the uneven distribution of disturbance across different parts of the present day Adirondack Park. Unlike the more omni-present agricultural clearing that occurred across much of New England during the 19th century (Foster and Aber, 2004) our interpretation of McMartin's historic record lead us to characterize disturbance regimes in the Adirondacks into five distinct regions (Fig. 1), with each region generally delineated by principal watershed boundaries. The one exception to this delineation was in the Hudson region, where we considered the lands draining into Lake George – part of the Lake Champlain watershed – (see Fig. 2) to have disturbance patterns more similar to the adjacent Hudson valley. The disturbance regimes that diffused within each of these regions were characterized by unique mixes of three disturbance types: agricultural clearing, clear-cut logging for charcoal production, and selective-cut spruce harvests (Table 1). Agricultural land uses began in the early to mid 19th century, and

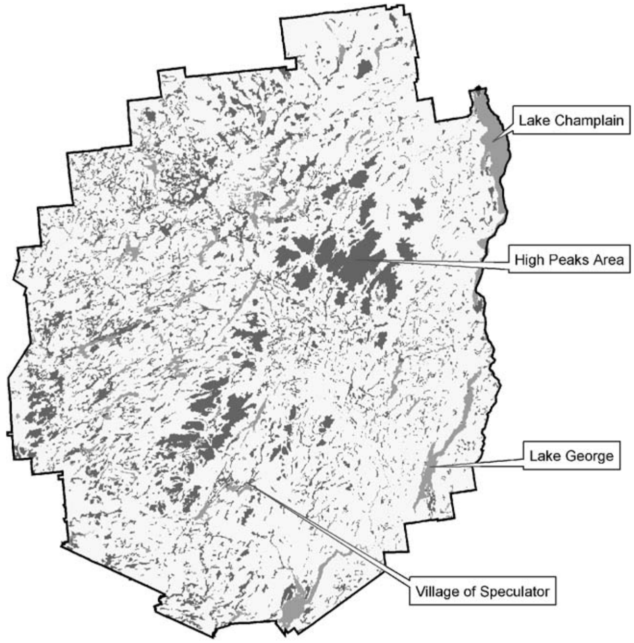


Fig. 2 – Modelled primeval land cover map, with selected geographic features mentioned in the text. Predicted spruce areas are shown in dark grey and major water bodies are shown in light grey. All other areas were predicted as mixed northern hardwood forest.

Table 1 – Regional disturbance histories[a], as identified by disturbance type[b] at each mapped time snapshot within the study period

	Hudson	East Canada creek	West Canada creek	St. Lawrence	Lake Champlain
1860	Ag	Ag	M	M	Ag
1885	M	M	F	L	Ch
1892	L	L	M	P	Ch
1909	P	P	L	R	P
1916	R	R	P	M	R

[a] Regions correspond to those identified in Fig. 1.

[b] Agriculture (Ag), selective-cut spruce harvests of mast (M), lumber (L), pulp (P), and high-elevation/remote (R) logs, clear-cut fuel harvests for charcoal production (Ch); see text for detail.

were confined to lowland areas within the eastern regions of the Park. Due to the ease of transport onto nearby Lake Champlain, the clear-cutting of both hard and softwood forests for the production of charcoal (used in iron smithing) was rampant in the northeastern region of the Adirondack Park during the mid-late 19th century. Selective-cut logging (i.e., harvest of spruce trees for lumber or pulp) was the most widespread and recurring disturbance type during the 1860–1916 time period; affecting almost every part of the Park. Unlike the widespread clear-cut logging in the White Mountains of New Hampshire (Goodale and Aber, 2001), logging was predominately focused on the selective harvest of spruce trees. As technology and demand increased throughout the 1860–1916 time period, logging became progressively more intensive and spatially extensive. Much of the Adirondacks was logged repeatedly (McMartin, 1994): first for large "mast" logs (>12″ in diameter), then for lumber logs (>8″ in diameter), and finally for pulp logs (>4″ in diameter). Following these three harvests of easily accessible forests, more intensive selective logging occurred on high slopes (e.g., High Peaks area; see Fig. 2) and remote areas. According to McMartin's account, the timing and spatial extent of logging was primarily dictated by the developing transportation networks. The arteries of the logging trade in each of the five regions were first and foremost along the rivers manipulated for the "driving" of logs, but later included the newly constructed railroads. Roads and wagon trails served to transport logs to these main arteries.

Coevolving with the increasing intensity of logging and construction of railroads during the 1890s, the State of New York earnestly began to acquire tracts for designation as "forever wild" land within the newly created Adirondack Forest Preserve. The story of the competition for land between state preservationist interests and logging interests during the years of 1890–1910 is quite unique to the Adirondacks and beautifully described by McMartin (1994). The result of this competition is a highly variable pattern of land disturbance history across the Adirondack Park, but one driven by consistent, broad-scale trends.

2.2. GIS models

2.2.1. *Background*

The theoretical background for our spatial interpretation of the disturbance history trends in the Adirondacks is found from the work of David Foster and his colleagues at Harvard Forest, Massachusetts (e.g., Foster, 1992, 1995; Motzkin et al., 1996; McLachlan et al., 2000). As measured by pollen analysis, historical land ownership records, historic air photos, and dendrochronology, Foster and his colleagues find patterns of anthropogenic disturbance history for central New England to be closely linked to environmental controls (e.g., distance from roads, slope, and soil drainage). With this guiding theoretical background, and through implementation in a GIS, we developed the hypothesis that, for each region in the Adirondacks, it would be possible to "translate" historical records (e.g., McMartin, 1994) into models describing spatio-temporal patterns of disturbance history through the 1860–1916 time period of intensive disturbance.

Based on available historical records of forest disturbance, which only allowed us evaluate GIS models at discreet time intervals, we created five "snapshot" maps (Langran, 1992), which depict the spatial extent of forest disturbance occurring between two dates. We selected the end dates of 1860, 1885, 1892, 1909, and 1916 based on availability of historic records and their proximity to key events. The year 1860 was chosen to spatially represent all the extant agricultural activity that preceded our time period. A commission was granted in 1885 by New York State to survey the land for its value as a Park; the resulting map of this commission describes a rough picture of the extent of logging activity in the Park until that time (see map in Jenkins and Keal, 2004). The year 1892 witnessed the construction of the Adirondack division of the New York central line in the western portion of the Park – the only railroad ever to cross the park – and the beginning of state land acquisitions. These two factors dramatically changed the spatial pattern of disturbance in the Park. Finally, we chose 1909 and 1916 based on the availability of historic maps. The 1909 map (Wood and Smith, 1909) documented the extent of the rail and road transportation network, an important input to our models. The 1916 fire response map (APA, 2001) gave a rough picture of the land cover status of each tract of land within the Park.

2.2.2. *Input data*

We obtained nine input datasets from the Adirondack Park Agency (2001) with spatial coverage throughout our study area: (1) a United States Geological Survey (USGS) 1 arc second Digital Elevation Model (DEM); (2) a percent slope map derived from the DEM; (3) a dataset describing the location and year of each state land acquisition; (4) a nine-class, 1:250,000 scale soil drainage map; (5) delineations of the 14-digit USGS Hydroloic Unit Code (HUC) level watersheds; (6) USGS Digital Line Graph (DLG) data of current roads; (7) USGS DLG rivers data; (8) USGS DLG towns data; (9) USGS Digital Raster Graphic (DRG) 1:24,000 topographic map data. We also obtained a hardcopy 1:126,720 scale map describing the historic rail and road transportation network (Wood and Smith, 1909). From these data, and following descriptions found in McMartin (1994), we derived two further input datasets for use in our GIS models: primeval forest lands cover, and transportation network, described below.

The primeval forest land cover dataset classifies every 1 arc second pixel within the Adirondack Park boundary into one of three land cover types: spruce forest (100% spruce), mixed forest (25% spruce, 75% hardwoods), and water (Fig. 2). The basis of our classification was a diagram and description of the primeval land cover found in McMartin (1994, p. 38), which predicts pure spruce forests on poorly drained soils or elevations above 2500 ft (762 m). The remainder of the land area is assumed to be primeval mixed northern hardwoods, which, on average, included approximately 25% spruce (Pinchot, 1898). Using a 1 arc-second soil type map and DEM available digitally from the Adirondack Park Agency (APA, 2001), we classified pure spruce stands as all pixels having either: (a) soil attribute of "somewhat-poorly drained" to "very poorly drained" or (b) an elevation attribute of greater than 762 m (2500 ft). Water areas were selected as all pixels having a soil drainage attribute of "water". The mixed forest areas were defined as all areas neither classified as water nor spruce.

The transportation network dataset describes the transportation type (i.e., river navigable for log driving, road, or railroad) and date of construction (when obtainable) for each mode of transport used during the 1860–1916 time period. Each segment of navigable river was selected from the DLG rivers data, and, according to the descriptions found in McMartin (1994), attributed with the year it became available for log driving. Each segment of road was selected from the DLG roads data based on its presence on Wood and Smith's (1909) map. We did not find a reliable means to attribute the year of construction for each road segment. Each segment of railroad was digitized according to Wood and Smith's (1909) map and attributed with the year of its construction using the descriptions of McMartin (1994). We digitized the spatial location of each railroad using the DLG towns and DRG data as background layers.

2.2.3. *Model development*

Our purpose in developing the GIS models of disturbance history was to provide realistic inputs for testing the sensitivity of the PnET-CN model. We developed two GIS models of differing resolution. Each model produced five snapshots of the spatial extent of disturbance occurring within our study period. Model 1 was a simple, low-resolution model, simulating the spatial diffusion of one disturbance regime across the entire study area. Model 2 was a more complex, high-resolution model (i.e., increased information content), simulating the spatial diffusion of the disturbance regimes unique to each of the five regions within the study area.

For both models, the spatial diffusion of disturbance from transportation networks was modelled across a cost-distance surface. We developed the cost distance surface in order to: (1) impede the diffusion of disturbance as the gradient of slope increased, and (2) prohibit disturbance from entering land acquired by the state, or lands known to be "virgin" prior to state acquisition (McMartin, 1994; Jenkins and Keal, 2004). Since McMartin (1994) described logging as diffusing more rapidly on easily accessible areas with gentle terrain, and only later on steeper areas, we reclassified the slope map using logarithmic weighting as follows: 0–15% slope = 1; >15–30% slope = 10; >30% slope = 100). The effect of this reclassification, for example, made diffusing through a pixel containing a 35% slope 100 times more difficult relative to a pixel with a 5% slope. Pixels within areas acquired by the state were excluded from the diffusion process. Since state land acquisition was dynamic through our time period, we created a different cost-distance surface for each time interval. Similarly, we created a different transportation network map for each time interval based on the attributed time of construction for each transportation segment. In this way, our predictions of the spatial diffusion of disturbance were specific to each time interval. For both models, we determined the buffer length (i.e., distance of diffusion from either side of the transportation network) for each time interval (and each region in model 2) by interpreting the written history of McMartin (1994). Specifically, variation in buffer length expresses the unevenness in space and time of the technology, demand, and capital that drove the logging industry during our study period. For example, logging in the Hudson region occurred sooner, and extended farther into the forest (relative to other regions) due to the ease of transporting logs down the major Hudson River to the rapidly industrializing east coast urban centers, and financial backing of wealthy New York city entrepreneurs. The unevenness of the human factors of technology, capital, and demand driving logging in the Adirondacks during our study period has recently received an elegant cartographic description by Jenkins and Keal (2004).

Table 2 – Model 1 buffer widths (in km) about the transportation network

	Rivers	Roads	Railroad
1860	5	1	[a]
1885	7	1	5
1892	7	2	5
1909	7	3	5
1916	15	5	5

[a] Railroad not present.

The output of both GIS models was a binary, snapshot map for each time interval (i.e., for each time interval, areas predicted to be disturbed = 1, not disturbed = 0). Model 1 simulated the spatial diffusion (along transportation networks) of once-over (i.e., no repeat harvests of the same area) logging for spruce. For each time iteration of this simple model, disturbance diffused at the same rate across the entire study area from each type of transportation (Table 2). Our final predictions of the spatial extent of logged areas during each time interval were achieved by masking the areas predicted to be cut in all previous iterations (Fig. 3).

Model 2 simulated the more complex, region-specific differences in disturbance regimes. As seen in Table 3, we determined the spatial extent of the diffusion of disturbance on a per-region basis. In this model, we allowed repeated harvests of the same area, and generally only masked areas that had been previously clear-cut or completely exhausted of all spruce timber. There was only one exception to this practice of masking in model 2; for the 1909 time interval we allowed a pulp harvest of spruce re-growth from charcoal clear-cuts in the Champlain valley.

2.2.4. *Calculation of PnET-CN input from the GIS predictions of disturbance extent*

The PnET-CN model is commonly run in order to model the forest processes occurring within a watershed. Within each of the five regions within the study area, we randomly selected five HUC watersheds to use in our PnET-CN analysis, for a total of 25 watersheds within the study area (Fig. 1). For each time interval in models 1 and 2, we calculated the percent biomass removed in each watershed using: (1) the predicted spatial extent of disturbance in the watershed; (2) the proportion of each primeval forest cover type within this spatial extent; (3) the type of disturbance predicted for each time interval (Fig. 3). After clipping the binary GIS model output and the primeval forest cover type map to each HUC watershed extent, we multiplied the binary map by the primeval forest cover type map to produce a disturbance/cover type map. This disturbance/cover type map displayed, for example, the location of disturbed pure spruce forests within the watershed. Using the disturbance/cover type map, we calculated the proportional area of each disturbed forest cover type within the watershed. For the

Table 3 – Model 2 buffer widths (in km) about the transportation network, given by region

	Hudson			East Canada creek			West Canada creek			St. Lawrence			Lake Champlain		
	Rivers	Roads	Railroad	Rivers	Roads	Railroad	Rivers	Roads	Railroad	Rivers	Roads	Railroad	Rivers	Roads	Railroad
1860	2	2	[a]	1	1	[a]	2	1	[a]	2	1	[a]	2	1	[a]
1885	7	3	5	3	3	[a]	2	1	[a]	2	1	[a]	3	2	5
1892	7	3	5	3	3	[a]	6	3	5	5	3	5	4	3	5
1909	7	3	5	3	3	[a]	6	3	5	5	3	5	4	3	5
1916	15	5	5	7	7	7	10	5	7	10	5	7	15	5	5

[a] Railroad not present.

spruce logging disturbance regime in model 1, we assumed a 99% biomass removal from disturbed pure spruce forests, and a 25% biomass removal from disturbed mixed forests. Our assumptions of the percent biomass removal in each disturbed cover type differed by the regional disturbance regime and time interval in model 2 (Table 4). Similar to our interpretation of buffer distances in space and time, we based our assumptions of forest removal on the disturbance type (Table 1) and the extensive data available in McMartin (1994) describing the spatio-temporal patterns in technology, capital, and demand. For both models 1 and 2, the PnET-CN input value for each watershed at the end date of each time interval was the sum total of the watershed proportional area multiplied by the percent biomass removal within each disturbed cover type (Fig. 3).

2.2.5. *GIS model validation*

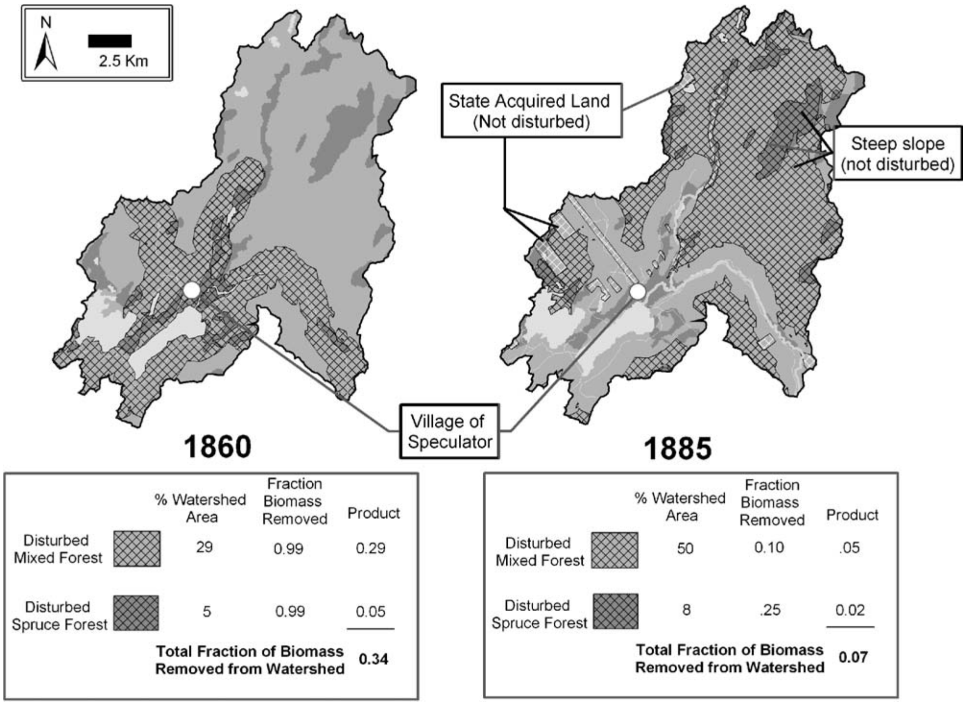
We validated the realism of our GIS models through visual comparison with the 1916 Fire Hazard Map (APA, 2001), which depicts the land cover the end of our study period. A quantitative evaluation of our models against this historic map was not possible due to the fact that the historic map's land cover classes could not be directly matched to the results of our models. For our visual comparison, we aggregated four categories on the original historic map (open land, waste and denuded lands, burned over area, and logged for both softwood and hardwood) into the category "cleared". We also reclassified the categories of "logged for softwood only", and "green timber—virgin and second growth" as "selective-cut" and "old-growth", respectively.

In order to compare the predictions of our quantitative models with the categorical 1916 map, we reclassified both GIS models into categorical land cover maps. To generate the map, we summed the five snapshot predictions of biomass fraction removed from each pixel (which varied by land cover type in model 1 and land cover type, region, and year in model 2) and classified this summed fraction into three categories: old growth (no biomass removed), selective-cut (0.01–0.49), and cleared (0.5–0.99).

2.3. *PnET-CN modelling*

The PnET-CN model (Aber et al., 1997) is a generalized, lumped-parameter model designed to simulate the cycling of water, carbon (C), and nitrogen (N), in forest ecosystems. The model was parameterized and validated in forests within the NE US (Aber et al., 1997), and has been applied toward the study of the legacy of forest disturbance upon N cycling in NE US forest ecosystems (Aber and Driscoll, 1997; Goodale et al., 2002). In order to generate yearly output predictions of water balance and C and N cycling, PnET-CN requires monthly climate and N deposition data. Rates of photosynthesis (Pn), evapotranspiration (ET), and C and N cycling respond to the monthly input data, but also are controlled by the size of internal pools of water, carbon, and nitrogen. Disturbance (i.e., biomass mortality and removal) serves to reduce the pools of C and N within the model, and subsequently has a long-term affect upon rates of Pn, ET, and C and N cycling.

We used PnET-CN version 5.1-1.4vb, as downloaded from the PnET website (http://www.pnet.sr.unh.edu) on April 10, 2003. The purpose of our PnET-CN analysis was to test the



1860

	% Watershed Area	Fraction Biomass Removed	Product
Disturbed Mixed Forest ▨	29	0.99	0.29
Disturbed Spruce Forest ▩	5	0.99	0.05
Total Fraction of Biomass Removed from Watershed			0.34

1885

	% Watershed Area	Fraction Biomass Removed	Product
Disturbed Mixed Forest ▨	50	0.10	.05
Disturbed Spruce Forest ▩	8	.25	0.02
Total Fraction of Biomass Removed from Watershed			0.07

Fig. 3 – Example watershed-level determination of PnET-CN input from GIS model predictions of disturbance history. Model 2 predictions of areas cleared in 1860 and 1885 (black cross-hatching) are superimposed on the primeval landcover map (light to dark gray tones indicating water, mixed, and spruce cover types, respectively). Description of model rational, buffer widths, and cover-type fraction removed are available in the text and Tables 1, 3 and 4.

sensitivity of the model to disturbance history, which was calculated from the GIS models (see Section 2.2.4) and entered for each model run as the % biomass mortality and % biomass removal from a watershed in each of the five end years of the time intervals in our study period. Since the disturbances we modelled were extractive in nature, we assumed the biomass mortality and biomass removal values to be equal. In order to isolate the effects of disturbance history within our sensitivity analysis, we held all other inputs and parameters consistent between runs. We used the climate and nitrogen deposition parameter set developed by Aber and Driscoll (1997) for their mean-climate disturbance analyses at Hubbard Brook Experimental Forest, New Hampshire. The use of this previously validated parameter set is unrealistic insofar as climate and deposition in the Adirondacks differ from that of New Hampshire; however, it had the advantage of enabling us to directly compare the N-cycling outcomes of our modelled disturbance histories against the well-documented disturbance histories examined within the model runs of Aber and Driscoll (1997). The assumptions in the parameter set of Aber and Driscoll (1997) include: mean climate (monthly mean values for each climate parameter), an N deposition ramp from 0 in 1600 to 2001 actual values (measured at Hubbard Brook), constant N deposition after 2001, Northern Hardwoods vegetation, and no effects of CO_2 or O_3. Using this consistent parameter set and the disturbance scenarios generated by models 1 and 2 for each of the 25 sample watersheds, we used PnET-CN to generate 50 predictions of the 2003 rates of N cycling (N uptake, N mineralization, nitrification, N leaching, and foliar N concentration). Due to the fact that it demonstrated a consistent legacy response to disturbance in the study conducted by Aber and Driscoll (1997), we focused our statistical analysis on the

Table 4 – Cover-type specific biomass removal percentages from model 2 predicted disturbed areas, given by region

	Hudson		East Canada creek		West Canada creek		St. Lawrence		Lake Champlain	
	Spruce	Mixed	Spruce	Mixed	Spruce	Mixed	Spruce	Mixed	Spruce	Mixed
1860	99	99	99	99	25	5	25	5	99	99
1885	25	10	25	10	75	20	75	20	99	99
1892	25	5	25	5	75	20	75	20	99	99
1909	50	10	50	10	25	5	25	5	99	25
1916	75	25	99	25	99	25	99	25	75	25

2003 rates of plant N uptake, a value that responds to the availability of ammonium and nitrate in the soil (outcomes from N mineralization and nitrification, respectively) but also directly relates to a plant's relative demand for N (Aber et al., 1997).

Though agriculture was present in some regions of the Adirondacks, the current structure of PnET-CN does not allow its agriculture routine by to be used within our methodology used to derive spatially explicit biomass removal percentages from GIS models. As developed by Aber and Driscoll (1997), the agriculture routine in PnET-CN necessitates the assumption that the entire watershed was converted to agriculture, and biomass removals are made yearly. To partially circumvent this limitation of our methodology, we input a clear-cut occurring in the first year of our disturbance models for all lands we predicted to have been converted to agriculture prior to 1860. While this did incorporate some of the intensive disturbance effects inherent within agricultural disturbance, it in no way can represent the legacy of prolonged effects of agriculture upon N cycling (300+ years) as measured in Aber et al. (1997).

As a means to place the sensitivity analysis afforded by our disturbance scenarios within a more general and simplified context, we also ran a series of PnET-CN model runs designed show the effect of increasing the percent biomass removed in a single year. We performed five model runs for this purpose, using inputs of 0%, 25%, 50%, 75% and 99% biomass loss and removal in 1890, which was near the median year of our time period.

2.4. *Statistical analyses*

The primary data used for statistical analysis consisted of 50 biomass inputs (expressed as the five time-interval sum of the % biomass removed) and output PnET-CN N uptake predictions obtained from 25 sample watersheds and the two disturbance history models of differing resolution. We used the non-parametric Kolmogorov–Smirnov (K–S) two-sample test in order to test the null hypothesis that disturbance history resolution would have no effect on PnET-CN N uptake predictions. Using only the 25 N uptake predictions derived from the more complex (model 2) GIS disturbance history model, we used repeated K–S two-sample tests in order to test the null hypothesis that regional differences in disturbance regime would have no effect on PnET-CN uptake predictions. Also, in order to test that our GIS models did produce significant differences in disturbance regime, we performed the same series of K–S tests on the fraction biomass removed from the 50 watersheds. We chose the non-parametric K–S two-sample test instead of the parametric two-sample *T*-test because our data (biomass inputs and N uptake outputs) violated the assumption of normality (as tested with the Shapiro-wilk statistic and evaluated on Q–Q plots), and also violated the assumption of equality of variance (as tested with Levene's and the folded *F* statistic). The K–S test assesses the hypothesis that two samples are drawn from different populations (or distributions), which is adequate to evaluate the sensitivity of the PnET-CN model predictions to the resolution of disturbance information and differing disturbance regimes.

3. Results and discussion

3.1. *GIS models*

Our purpose in using GIS to model disturbance history was to, in effect, "translate" a historic account of disturbance (McMartin, 1994) into *realistic scenarios* capable of testing the sensitivity of PnET-CN N cycling predictions to the resolution of disturbance history information. Here, after presenting the results and validation of the two models, we discuss the use of GIS models with regards to: (1) their utility in describing, interpreting and visualizing historic accounts of disturbance, and (2) their utility for providing spatially explicit inputs to ecological process models.

3.1.1. *Results and validation*

As we anticipated, the transportation network dataset was very important in determining the spatial extent of disturbance predicted by both models 1 and 2 in each time interval (Fig. 4). For example, during 1892 time interval, the completion of the Adirondack division of the New York central railroad caused both models to predict large increases in disturbed area for the western portion of the Park. Both models predict the occurrence of forests that were not disturbed during our time period, which is primarily due to the model constraint of excluding disturbance from state acquired lands. Most importantly, as an artifact of our simple and complex interpretations of McMartin's (1994) historical account, models 1 and 2 differed sharply in the timing and spatial pattern of the diffusion of disturbance between 1885 and 1916 (Fig. 4). Especially obvious in Fig. 4 is the observation of a much more extensive and continuous pattern of areas affected by disturbance in the model 2 time series. However, this observation should not be taken to suggest that model 2 always simulated a more severe disturbance regime. As seen in Fig. 3, our models assume that, in addition to the spatial extent of disturbed areas, the land-cover change (quantified as % biomass removed) in a watershed at a given time interval is heavily contingent upon the fractional biomass removed from each land cover type, and the proportion of each land cover type in the disturbed area.

The land-cover changes resulting from the disturbance regimes predicted within models 1 and 2 was visualized in the categorical land cover maps produced for validation against the 1916 historic map (Fig. 5). As observed in Fig. 5, both the low- and high-resolution models predicted similar areas of old growth forest, which generally coincided with areas classified as old growth on the historic map. Since most of the modelled old growth areas occurred on state acquired lands, this result highlights the importance and value of the simple constraints we included in both diffusionary models. The effect of model resolution became important in predicting areas that were cleared, and is expressed by the inability for model 1 to predict the extensive cleared areas in the Hudson and Champlain regions. This finding also supports the general assumption made within the more complex model: that there were important regional differences in the disturbance regimes within the Adirondack Park.

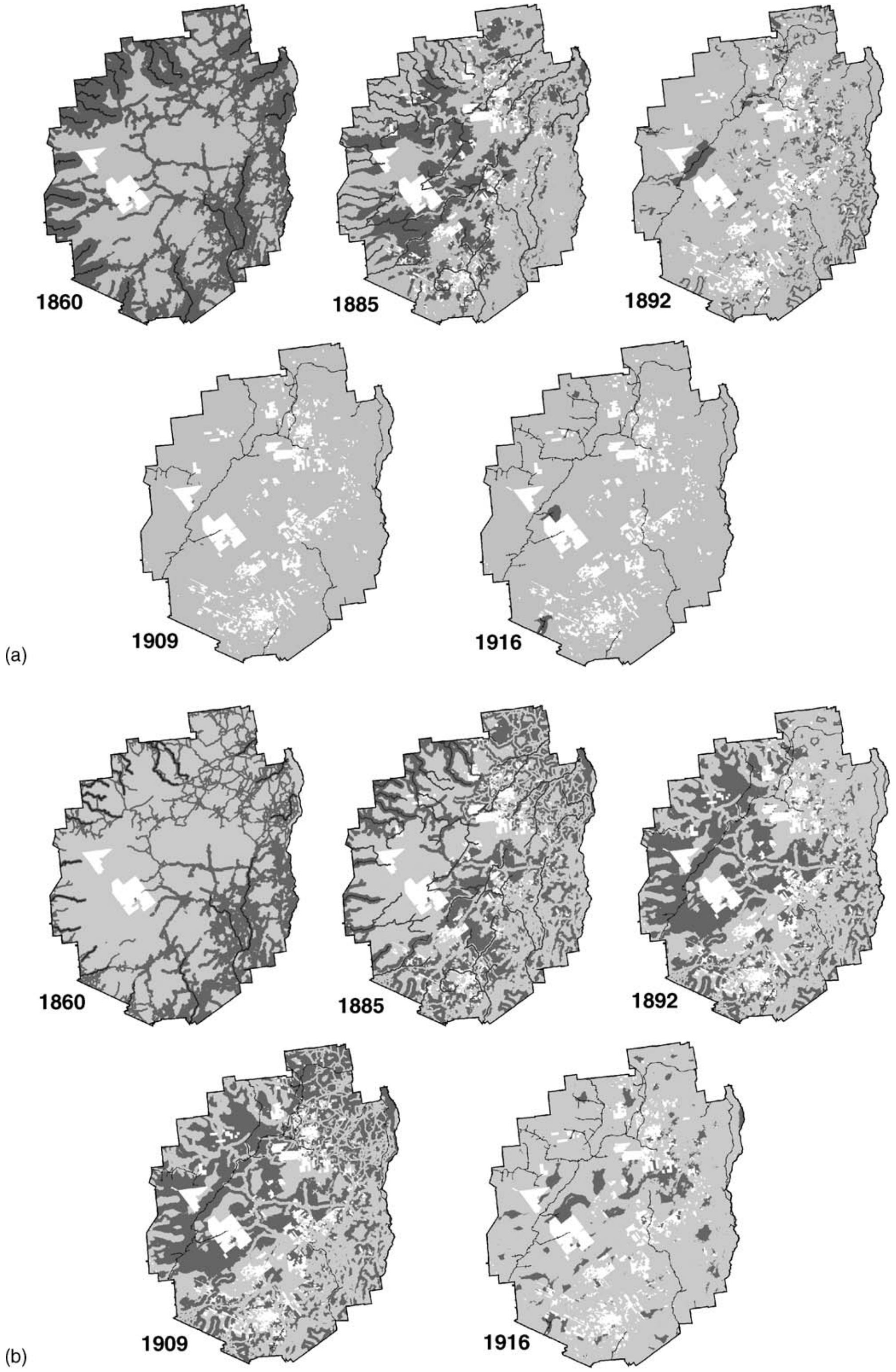


Fig. 4 – Disturbance time series maps, as predicted by model 1 (a) and model 2 (b). For each year, the models predict new areas affected by anthropogenic disturbance (dark grey), as buffered from the transportation network (black lines), and constrained by state land acquisitions (white areas). The 1860 and 1884 maps show the chronosequence of the opening of rivers for log driving, and the 1892, 1909, and 1916 maps show the construction of the rail network. Roads were assumed to be used in all years and are not shown.

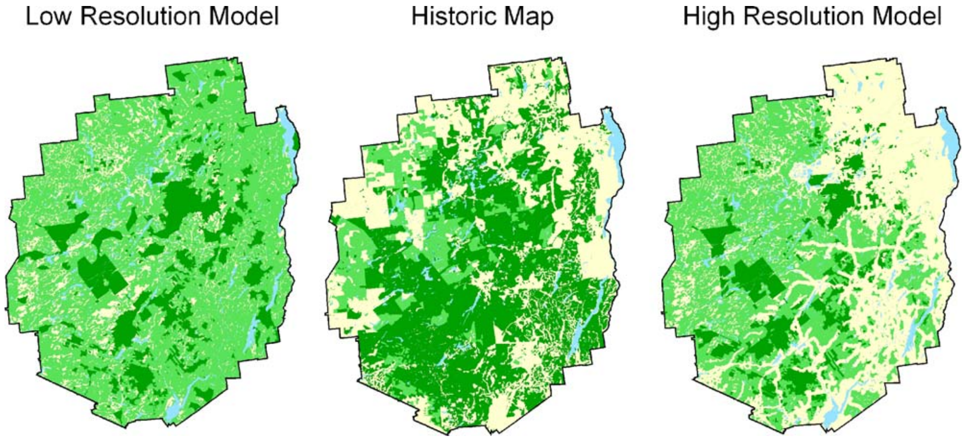


Fig. 5 – Land cover in 1916, as defined by a four-class system: old growth (dark green); selective cut (light green); cleared (light tan); water (blue), as depicted on the 1916 Fire Protection Map (APA, 2001), and predicted using high resolution (model 2) and low resolution (model 1) GIS models.

The predictions of model 2 in particular are likely more reflective of real conditions than suggested by direct visual comparison against the historic map. A large component of the apparent inaccuracy between model 2 and the 1916 map may be due to the ambiguity of classifications on the original 1916 fire map. On the historic map, the areas we reclassified as "old growth" were areas that were originally designated as "green timber—virgin and second growth". Since a large portion of this "green timber" was on areas mapped as selectively cut or cleared on the 1885 historic map (Jenkins and Keal, 2004), these would have been predicted to be "selective-cut" or "cleared" by the classification criteria used with our models.

An alternative view of the difficulty in comparing our model predictions to the historic maps suggests that the derivation of land cover from our models is perhaps most limited by the inability of our models to express the re-growth of forests during our time period. Our models' inability to predict the onset of the fires, which occurred following logging in the early 20th century also resulted in errors of omission of cleared areas (relative to the 1916 map), particularly in the western areas of the park adjacent to the Adirondack line railroad. Future modelling efforts would do well to include improved treatments of these sources of inaccuracy.

3.1.2. *GIS models for reconstructing disturbance history*

Despite its limitations, we found the use of GIS models to be a relatively quick and effective means to reconstruct realistic disturbance history scenarios in the Adirondack Park during our time period. The visual validation of our relatively simple models highlight many important outcomes, and collectively suggest promise for other researchers seeking to use historic information to reconstruct regional patterns of land-cover change. Overall, the use and validation of GIS models allows for the creation and testing of hypotheses regarding the drivers, mechanisms, and outcomes of land-cover change. This type of process-based understanding can add to existing knowledge (e.g., historic maps), which is often sparse, or of low quality. In our study, the capacity to model the drivers and mechanisms of land-cover change enabled us to use informed predictions to increase the quantification and temporal resolution (e.g., predict land cover for years not covered by historic maps) of century-old disturbance history information.

Nevertheless, the use of GIS models for predicting disturbance history, or any other outcome of human–environment interactions, should be executed cautiously. Specifically, this type of modelling should carefully consider the environment and phenomena being modelled. Our models relied upon a context- and scale-dependent assumption of humans acting as a singular disturbance "agent" through space and time. At finer scales or in other contexts, more explicit modelling of the interactions of diverse human agents (e.g., loggers versus farmers), may be necessary to achieve realistic scenarios of disturbance histories (Parker et al., 2003). Our study also had a relatively simplistic focus on logging; land-cover change driven by more complex human–environment interactions may necessitate more complex socio-economic models (Weber et al., 2001). Finally, our GIS modelling approach was conducted almost entirely within the GIS itself; but combining GIS with other tools may be more appropriate for modelling human–environment interactions within other applications or contexts. For instance, previous work presented within the pages of *Ecological Modelling* has demonstrated the synergy obtained through combining GIS with tools such as sequential Gaussian simulation (Mowrer, 1997), discriminant analysis (Tappeiner et al., 1998), artificial neural networks (Hilbert and Ostendorf, 2001), remote sensing (Matějíček et al., 2003), or wind models (Blennow and Sallnäs, 2004).

Ultimately, the decisions of how to interpret and model the spatio-temporal geography of any human–environment interaction must come from a careful examination of available data. We attribute the successes of our modelling strategy to the availability Barbara McMartin's (1994) thorough and consistent historical account of the processes governing forest disturbance in the Adirondack Park from 1860 to 1916. There were four principal factors in McMartin's account which aided our spatial interpretation: (1) the clear identification of vectors of diffusion; (2) an insightful description of the uneven spatial distribution of motivating factors (i.e., the regional differences in the availability of technology, capital, and demand); (3) locational knowledge of the resource to be extracted; (4) delineation of the constraints to diffusion. To the extent that written and/or oral histories of other regions contain information on one more of these factors, the GIS-enabled geographic interpretation of historic accounts of disturbance may provide fruitful paths for reconstructing disturbance histories and educating understanding of ecological pattern and process.

3.1.3. *GIS models as inputs for ecological process models*

The methodology we used to derive inputs to PnET-CN from the GIS models provided a flexible means to quantify the many components of a disturbance regime; namely, the type, timing, frequency, intensity and spatial extent. Our characterization of a total spruce harvest disturbance regime in the low-resolution model (model 1) resulted in an average total removal of 32% and a standard deviation of 6.1% (Table 5), which is consistent with accounts of the relative percentage of spruce in the primeval Adirondack forest (Pinchot, 1898; McMartin, 1994). The variation between the 25 watersheds is attributable to one of two factors: differences in the relative percentage of pure spruce stands, or differences in the relative percentage of predicted old growth stands.

The regionally specific disturbance regimes we characterized in model 2 resulted in an average total removal of 58.1% and standard deviation of 29.6%, which was statistically different from model 1 ($p = 0.0023$). As seen in Table 5, the regionally specific average total removals ranged from 32% ($1\sigma = 1.9\%$) in the case of the total spruce harvest simulated in the St. Lawrence region to 103% ($1\sigma = 14.5\%$) for the charcoal harvest and re-harvesting of secondary growth simulated in the Champlain region. This simulated disturbance regime in the Champlain region was statistically different ($p = 0.0135$) from all the regions except Hudson, suggesting that our methodology was capable of distinguishing this intensive disturbance regime from spruce harvests (St. Lawrence and West Canada Creek), and spruce harvests with small amounts of agriculture (East Canada Creek). However, our methodology exhibited mixed results in distinguishing the combined agriculture/spruce harvest from a simple spruce harvest. The East Canada Creek region was not significantly different from any of the regions (besides Champlain), but the Hudson region was statistically different from the spruce harvest regimes of the St. Lawrence and West Canada Creek ($p = 0.0135$). Collectively, these results suggest that our GIS methodology for providing inputs to the PnET-CN model distinguished very different disturbance regimes, but could not statistically distinguish more similar disturbance regimes due to its poor sensitivity to small differences in the disturbance type.

The inability of our methodology to draw categorical distinctions between similar disturbance regimes does not simplify the difficult task of characterizing disturbance. Rather, our simple models reinforce the idea that disturbance regimes must be measured along a gradient of severity. Characterizing the gradient of severity in disturbance may be best achieved through spatially and temporally explicit measurement of each individual component within a disturbance regime (e.g., type, intensity, spatial extent). Towards this end, our methodology should be viewed as groundwork for future improvement; our ability to separately measure components of a disturbance regime was limited due to the requirement of conforming to the structural constraints of the PnET-CN model (i.e., the requirement of an aggregate (point based) value for the fraction biomass lost in a year). We suggest that further interpretation and use of similarly quantified, and spatio-temporally explicit disturbance inputs may improve

Table 5 – Summary of PnET-CN biomass removal inputs and selected 2003 N cycling predictions

	Input[a]	Output				
	% Biomass removed 1860–1920	N uptake ($kg\,ha^{-1}\,yr^{-1}$)	N mineralization ($kg\,ha^{-1}\,yr^{-1}$)	Nitrification ($kg\,ha^{-1}\,yr^{-1}$)	N leaching ($kg\,ha^{-1}\,yr^{-1}$)	Foliar N (leaf % N)
1890 single-cut scenarios						
0% cut	0	106.2	103.7	18.8	5.6	2.41
25% cut	25	104.7	100.1	15.7	5.0	2.39
50% cut	50	103.0	99.2	12.7	4.3	2.37
75% cut	75	100.8	96.3	9.0	3.4	2.34
99% cut	99	96.6	90.9	3.4	2.3	2.27
Model 1						
All watersheds[b]	32.4 (6.1)	104.5 (0.3)	101.3 (0.5)	15.7 (0.7)	4.9 (0.1)	2.39 (0.01)
Model 2						
All watersheds[b]	58.1 (29.6)	103.0 (1.6)	99.3 (2.2)	13.0 (2.9)	4.4 (0.6)	2.37 (0.02)
Hudson[c]	71.2 (19.8)	102.1 (1.9)	98.0 (2.5)	11.3 (3.2)	4.0 (0.7)	2.36 (0.03)
East Canada creek[c]	47.2 (18.0)	103.7 (0.9)	100.3 (1.3)	14.2 (1.7)	4.6 (0.4)	2.38 (0.02)
West Canada creek[c]	36.8 (8.5)	104.1 (0.4)	100.8 (0.6)	14.9 (0.9)	4.8 (0.2)	2.39 (0.01)
St. Lawrence[c]	32.6 (1.9)	104.4 (0.1)	101.2 (0.2)	15.3 (0.4)	4.9 (0.1)	2.39 (<0.01)
Lake Champlain[c]	103.0 (14.5)	101.0 (0.7)	96.5 (1.1)	9.3 (1.3)	3.6 (0.3)	2.34 (0.01)

[a] Model 1 and model 2 values represent the sum of the 1860, 1885, 1892, 1909, and 1916 % biomass removal input values.

[b] Values represent the mean (and 1σ) for 25 watersheds.

[c] Values represent the mean (and 1σ) for five watersheds.

the characterization of disturbance regimes for the PnET-CN model, and for other contexts, scales, and methods of analysis.

3.2. *Sensitivity analysis of the PnET-CN model*

In accordance with previous research (Aber and Driscoll, 1997), our model runs demonstrate that PnET-CN model predictions of 2003 N uptake are sensitive to century-old disturbances (Table 5). Predicted N uptake values ranged from 106.2 kg ha^{-1} yr^{-1} for the case of the 1890 no biomass removal scenario to 96.6 kg ha^{-1} yr^{-1} in the 1890 clear-cut harvest case. We caution that these and the rest of our predicted values (e.g., Table 5) are intended to be useful in relation to each other, or in relation to other model results obtained with the same inputs of deposition and climate (i.e., mean-climate model runs of Aber and Driscoll, 1997). Actual N uptake values would differ from our estimates according to climatic and N deposition differences between New Hampshire (the validation site of our parameter set) and the Adirondack Park. While there is great variability of climate and N deposition within the Adirondack Park (Ito et al., 2002), as a whole, the Adirondacks have a similar mean climate, but receive more N deposition than New Hampshire (NADP, 2004). Increased deposition would generally be expected to raise N uptake values, but the interactive effects of climate, disturbance, and N deposition can lead to complex, and counter-intuitive N cycling dynamics (Aber et al., 2002). Our decision to use a previously validated input parameter set enabled us remove uncertainty potentially caused by these complex dynamics and focus on testing the sensitivity of the PnET-CN model to realistic scenarios of disturbance. In all model runs, increased disturbance resulted in lower 2003 N uptake values. This result is aligned with the N saturation hypotheses of Aber et al. (1998), whereby disturbance is understood to counteract increases in N uptake caused by accumulating atmospheric N deposition.

The N cycling values from our sensitivity analysis were within those obtained with the same PnET-CN parameter set and inputs of disturbance history from several well-studied locations in the White Mountains of New Hampshire (Aber and Driscoll, 1997). Comparison of our predictions with the New Hampshire locations suggests that our method of parameterizing PnET-CN from GIS models of disturbance history was relatively conservative compared to parameterization of the model with these more detailed histories. For example, our method likely underestimated the legacy of the extensive clear-cut logging and fires that spread through the Adirondack Park in the early 1900s (McMartin, 1994). Aber and Driscoll simulated the effects of a severe fire in 1820 at the Cone Pond watershed in New Hampshire, and obtained N cycling values markedly lower than any of our simulations of clear-cuts during the 1860–1916 time period. The enhanced legacy of fire within Aber and Driscoll's model runs was simulated through a one-time reduction of the PnET-CN pools of soil C and N pool. These effects of fire could be incorporated into future implementations of our methodology by adding a sub-routine predicting the spatio-temporal diffusion of fire.

The inputs to PnET-CN provided by the models 1 and 2 GIS disturbance scenarios, resulted in 2003 N uptake predictions that are within the range of our 1890 single-year harvest model runs (Fig. 6). Using inputs from the simpler GIS model, model 1, the 25 runs of PnET-CN predicted a mean watershed N uptake value of 104.5 kg ha^{-1} yr^{-1} and a very small range of values about the mean (0.3 kg ha^{-1} yr^{-1}). Overall, the model 1 inputs to PnET-CN resulted in N uptake values that were highly clustered around the value predicted by the 25% biomass removal single-cut model run (104.7 kg ha^{-1} yr^{-1}). Using inputs from the more complex GIS model, model 2, the 25 PnET-CN model runs predicted a mean N uptake value of 103.0 kg ha^{-1} yr^{-1}, which is equivalent to that predicted by the 50% biomass removal single-cut model run. Unlike the highly clustered values of model 1 predictions, the range of values obtained from the model 2 inputs to PnET-CN was analogous to the range predicted between the 25% and 75% single-year harvest model runs.

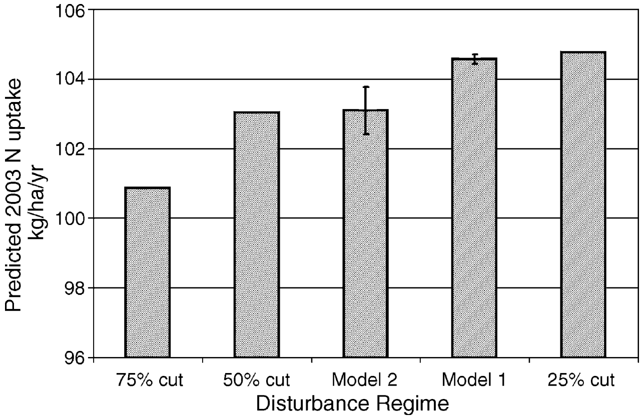


Fig. 6 – Sensitivity of the PnET-CN model predictions of 2003 N uptake to the resolution of disturbance history input. The height of the models 1 and 2 bars represent the mean of PnET-CN predictions from the 25 sample watersheds (see Fig. 1). PnET-CN predictions obtained using the models 1 and 2 disturbance history inputs are placed within PnET-CN predictions of 2003 N cycling obtained from input values of 0% ($y_{\max}$), 25%, 50%, 75%, and 99% ($y_{\min}$) biomass removal in 1890. Error bars on models 1 and 2 indicate the upper and lower 95% confidence intervals of the mean. Means of models 1 and 2 are significant at $p < 0.0001$.

3.2.1. *Sensitivity of the PnET-CN model to the resolution of historic disturbance information*

The sample of the 25 watershed N uptake values predicted from the inputs derived from the simple, lower resolution model 1 to PnET-CN were significantly different ($p = 0.0002$) from those obtained from the more complex, higher resolution model 2 (Fig. 5). This result suggests that our PnET-CN predictions of 2003 N uptake are sensitive to the resolution of disturbance history input data for this time period in the Adirondack Park.

3.2.2. *Sensitivity of the PnET-CN model to Adirondack Park disturbance regimes*

In our disturbance history scenarios, we increased the resolution of disturbance history input in model 2 by increasing the complexity (i.e., information content) within our description

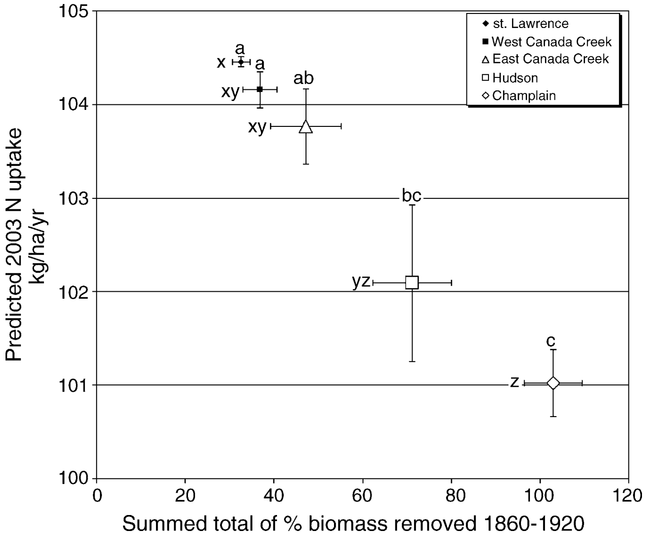


Fig. 7 – Sensitivity of PnET-CN predictions of 2003 N uptake to simulated region-specific disturbance regimes. Mean values (of five watersheds) for regions including clear-cut type disturbance are shown in open symbols, and those with only selective-cut type disturbance are shown in closed symbols. X and Y error bars represent +/− the standard error of the mean. Different letters (a, b, c or x, y, z) indicate significant differences ($p = 0.0135$ in all cases, see text) in biomass input (horizontal bars) and PnET-CN model predictions (vertical bars).

of the disturbance regimes affecting different regions of the study area. In comparing these regions, we observed a wide variation in PnET-CN N cycling predictions (Table 5) and significant differences between many of the regional samples (five watersheds) of N uptake values (Fig. 7). The PnET-CN predictions of 2003 N uptake from the two regions that experienced clear-cut type disturbance, the Hudson River and Lake Champlain drainages, were significantly different ($p = 0.0135$) from the two regions that only experienced spruce harvests (Fig. 7), which suggests that PnET-CN is sensitive to differences between clear-cut, and selective-cut disturbance regimes. The disturbance regime of the East Canada Creek drainage included limited clear-cut type disturbance, but was not significantly different than the spruce harvest disturbance regimes of the West Canada Creek and St. Lawrence River drainages, nor was it significantly different from the more extensive clear-cutting in the Hudson drainage. This result, and the increased variability of PnET-CN predictions within the East Canada Creek drainage (Table 5) suggest that the N cycling legacy of its disturbance regime lies between that of clear-cut and selective cut disturbance types.

Generally, N uptake predictions decreased linearly with the severity of the simulated disturbance regime within a region (Fig. 7). However, the variability in N uptake predictions within the sample of five watersheds in a region (Fig. 7) tended to increase relative to the biomass inputs (Fig. 7, horizontal error bars) in the regions that experienced the early agricultural removals (Hudson and East Canada Creek). The cause of the variability lies within the fact that the sample watersheds within these two regions experienced different amounts of simulated agricultural influence, which may be directly attributed to relative differences in spatial extent of diffusion within a watershed. However, the increased variability relative to the biomass inputs suggests that PnET-CN was especially sensitive to the extensive early clear-cut harvests in some watersheds.

Previous field and modelling research exploring the effect of historical anthropogenic forest clearing on current patterns of N cycling in the NE US have demonstrated significant differences between agriculture, clear-cut, and old growth forests disturbance regimes (Aber and Driscoll, 1997; Goodale and Aber, 2001; Goodale et al., 2002; Foster and Aber, 2004). Our model results reinforce the importance of agricultural and clear-cut logging, but also suggest that selective-cut disturbance regimes may leave a distinguishable legacy upon modelled, and possibly field-observed patterns of N cycling.

However, since some selective-cut disturbance regimes may leave a similar legacy to the characteristic natural disturbances that have occurred even within the old-growth forests in the Adirondack Park (see Section 2.1.2 and Jenkins and Keal, 2004), distinguishing these two disturbance regimes in modelling and field studies may prove to be difficult. Including natural disturbances within a model sensitivity analysis such as we have presented would be a valuable opportunity to evaluate the distinctiveness of selective-cut and naturally disturbed old-growth disturbance regimes.

4. Conclusions

We conclude that PnET-CN predictions of present-day nitrogen cycling are sensitive to the resolution of realistic, century-old anthropogenic disturbance scenarios within the Adirondack Park. When coupled to a complex, spatially-explicit scenario of anthropogenic disturbance history between 1860 and 1916 in the Adirondack Park, PnET-CN predicts significant differences in nitrogen cycling rates between clear-cut and selective-cut disturbance regimes. Further use of written historical records, maps, and government documents for developing spatially explicit disturbance history information may be used to quantify precise inputs to biogeochemical ecosystem process models such as PnET-CN, and enable researchers to more adequately characterize field-testable differences in disturbance regimes.

Acknowledgements

This research was developed as part of the course requirements in GEO 583, Environmental GIS, Spring 2003, instructed by J.M. Read. Preliminary GIS model development was carried out by the undergraduate students of J.M. Read's GEO 383, Principles of GIS course, Fall 2002. The authors would like to thank Joe Stoll for cartographic advice. Funding for this research was provided by the W.M. Keck Foundation with logistical support from the Syracuse University Department of Geography.

REFERENCES

Aber, J.D., Driscoll, C.T., 1997. Effects of land use, climate variation, and N deposition on N cycling and C storage in northern hardwood forests. Global Biogeochem. Cycl. 11, 639–648.

Aber, J.D., Driscoll, C.T., Federer, C.A., Lathrop, R.G., Lovett, G.M., Melillo, J.M., Steudler, P., Vogelmann, J., 1993. A strategy for the regional analysis of the effects of physical and chemical climate change on biogeochemical cycles in northeastern US forests. Ecol. Model. 67, 37–47.

Aber, J.D., Goodale, C.L., Ollinger, S.V., Smith, M.L., Magill, A.H., Martin, M.E., Hallett, R.A., Stoddard, J.L., 2003. Is Nitrogen deposition altering the nitrogen status of northeastern forests? BioScience 53, 375–389.

Aber, J.D., McDowell, W.H., Nadelhoffer, K.J., Magill, A., Berntson, G., Kamakea, M., McNulty, S.G., Currie, W., Rustad, L., Fernandez, I., 1998. Nitrogen saturation in temperate forest ecosystems: hypotheses revisited. BioScience 48, 921–934.

Aber, J.D., Ollinger, S.V., Driscoll, C.T., 1997. Modelling nitrogen saturation in forest ecosystems in response to land use and atmospheric deposition. Ecol. Model. 101, 61–78.

Aber, J.D., Ollinger, S.V., Driscoll, C.T., Likens, G.E., Holmes, R.T., Freuder, R.J., Goodale, C.L., 2002. Inorganic N losses from a forested ecosystem in response to physical, chemical, biotic, and climatic perturbations. Ecosystems 5, 648–658.

APA (Adirondack Park Agency), 2001. Shared Adirondack Park Geographic Information CD-ROM ver.1.0. NYS Adirondack Park Agency, Ray Brook, NY.

Blennow, K., Sallnäs, O., 2004. WINDA—a system of models for assessing the probability of wind damage to forest stands within a landscape. Ecol. Model. 175, 87–99.

Boyer, E.W., Goodale, C.L., Jaworski, N.A., Howarth, R.W., 2002. Anthropogenic nitrogen sources and relationships to riverine nitrogen export in the northeastern USA. Biogeochemistry 57/58, 137–169.

Driscoll, C.T., Lawrence, G.B., Bulger, A.J., Butler, T.J., Cronan, C.S., Eager, C., Lambert, K.F., Likens, G.E., Stoddard, J.L., Weathers, K.C., 2001. Acidic deposition in the northeastern United States: sources and inputs, ecosystem effects, and management strategies. BioScience 51, 180–198.

Driscoll, C.T., Newton, R.M., Gubala, C.P., Baker, J.P., Christensen, S.W., 1991. Adirondack mountains. In: Charles, D.F. (Ed.), Acidic Deposition and Aquatic Ecosystems. Springer-Verlag, New York, pp. 133–202.

Driscoll, C.T., Whitall, D., Aber, J.D., Boyer, E.W., Castro, M., Cronan, C., Goodale, C.L., Groffman, P., Hopkinson, C., Lambert, K., Lawrence, G., Ollinger, S.V., 2003. Nitrogen pollution in the northeastern United States: sources, effects, and management options. BioScience 53, 357–374.

Foster, D.R., 1992. Land-use history (1730–1990) and vegetation dynamics in central New England, USA. J. Ecol. 80, 753–771.

Foster, D.R., 1995. Land-use history and four hundred years of vegetation change in New England. In: Turner, B.L.I., Gomez Sal, A., Gonzalez Bernaldez, F., di Castri, F. (Eds.), Global Land Use Change: A Perspective From the Columbian Encounter. Consejo Superior de Investegaciones Cientificas, Madrid, Spain.

Foster, D.R., Aber, J.D., 2004. Forests in Time. Yale University Press, New Haven.

Foster, D.R., Swanson, F., Aber, J., Burke, I., Brokaw, N., Tilman, D., Knapp, A., 2003. The importance of land-use and its legacies to ecology and environmental management. BioScience 53, 77–88.

Goodale, C.L., Aber, J.D., 2001. The long-term effects of land-use history on nitrogen cycling in northern hardwood forests. Ecol. Appl. 11, 253–267.

Goodale, C.L., Aber, J.D., McDowell, W.H., 2000. The long-term effects of disturbance on organic and inorgainic nitrogen export in the White Mountains, New Hampshire. Ecosystems 3, 433–450.

Goodale, C.L., Lajtha, K., Nadelhoffer, K.J., Boyer, E.W., Jaworski, N.A., 2002. Forest nitrogen sinks in large eastern US watersheds: estimates from forest inventory and an ecosystem model. Biogeochemistry 57/58, 239–266.

Hilbert, D.W., Ostendorf, B., 2001. The utility of artificial neural networks for modelling the distribution of vegetation in past, present and future climates. Ecol. Model. 146, 311–327.

Ito, M., Mitchell, M.J., Driscoll, C.T., 2002. Spatial patterns of precipitation quantity and chemistry and air temperature in the Adirondack region of New York. Atmos. Environ. 36, 1051–1062.

Ito, M., Mitchell, M.J., Driscoll, C.T., Roy, K.M., 2005. Nitrogen input–output budgets for lake watersheds in the Adirondack region of New York. Biogeochemistry 72, 283–314.

Jenkins, J., Keal, A., 2004. The Adirondack Atlas. Syracuse University Press, Syracuse, NY.

Keller, M., Ane Alencar, A., Asner, G.P., Braswell, B., Bustamante, M., Davidson, E., Feldpausch, T., Fernandes, E., Goulden, M., Kabat, P., Kruijt, B., Luizão, F., Miller, S., Markewitz, D., Nobre, A., Nobre, C., Priante-Filho, N., Rocha, H., Silva-Dias, P., Randow, C., Vourlitis, G.L., (in press). Ecological research in the large-scale biosphere atmosphere experiment in Amazonia (LBA): a discussion of early results. Ecol. Appl.

Langran, G., 1992. Time in Geographic Information Systems. Taylor and Francis, London.

Likens, G.E., Bormann, F.H., Johnson, N.M., Fisher, D.W., Pierce, R.S., 1970. Effects of forest cutting and herbicide treatment on nutrient budgets in the Hubbard Brook watershed-ecosystem. Ecol. Monogr. 40, 23–47.

Martin, M.E., Newman, S.D., Aber, J.D., Congalton, R.G., 1998. Determining forest species composition using high spectral remote sensing data. Remote Sens. Environ. 65, 249–254.

Matějíček, L., Benešová, L., Tonika, J., 2003. Ecological modelling of nitrate pollution in small river basins by spreadsheets and GIS. Ecol. Model. 170, 245–263.

McLachlan, J.S., Foster, D.R., Menalled, F., 2000. Anthropogenic ties to late successional structure and composition in four New England hemlock stands. Ecology 81, 717–733.

McMartin, B., 1994. The Great Forest of the Adirondacks. North Country Books, Utica, New York.

Motzkin, G., Foster, D.R., Allen, A., Harrod, J., Boone, R.D., 1996. Controlling site to evaluate history: vegetation patterns of a New England sand plain. Ecol. Monogr. 66, 345–365.

Mowrer, H.T., 1997. Propagating uncertainty through spatial estimation processes for old-growth subalpine forests using sequential Gaussian simulation in GIS. Ecol. Model. 98, 73–86.

NADP (National Atmospheric Deposition Program), 2004. National Atmospheric Deposition Program 2003 Annual Summary. NADP Data Report 2004-01. Illinois State Water Survey, Champaign, IL.

Ollinger, S.V., Smith, M.L., Martin, M.E., Hallett, R.A., Goodale, C.L., Aber, J.D., 2002. Regional variation in foliar chemistry and soil nitrogen status among forests of diverse history and composition. Ecology 83, 339–355.

Parker, D.C., Manson, S.M., Janssen, M., Hoffmann, M.J., Deadman, P.J., 2003. Multi-agent systems for the simulation of land use and land-cover change: a review. Annal. Assoc. Am. Geogr. 93, 316–340.

Pinchot, G., 1898. Adirondack Spruce: A Study of the Forest in NE–HA–SA–NE Park, With Tables of Volume and Yield and a

Working Plan for Conservative Lumbering. The Critic Company, New York.

Schulze, E.D., Vygodskaya, N.N., Tchebakova, N.M., Czimczik, C.I., Kozlov, D.N., Lloyd, J., Mollicone, D., Parfenova, E., Sidorov, K.N., Varlagin, A.V., Wirth, C., 2002. The Eurosiberian transect: an introduction to the experimental region. Tellus B 54, 421–428.

Steffen, W., Sanderson, A., Tyson, P.D., Jäger, J., Matson, P.A., Moore, B., Oldfield, F., Richardson, K., Schellnhuber, H.-J., Turner, B.L., Wasson, R.J., 2004. Global Change and the Earth System. Springer, Berlin.

Tappeiner, U., Tasser, E., Tappeiner, G., 1998. Modelling vegetation patterns using natural and anthropogenic influence factors: preliminary experience with a GIS based model applied to an Alpine area. Ecol. Model. 113, 225–237.

Turner, B.L., Geoghegen, J., Foster, D.R., 2004. Integrated Land Change Science and Tropical Deforestation in Southern Yucatan: Final Frontiers. Clarendon Press of Oxford University Press, Oxford.

Vitousek, P.M., Gosz, J.R., Grier, C.C., Melillo, J.M., Reiners, W.A., Todd, R.L., 1979. Nitrate losses from disturbed ecosystems. Science 204, 469–474.

Weber, A., Foher, N., Möller, D., 2001. Long-term land use changes in a mesoscale watershed due to socio-economic factors—effects on landscape structures and functions. Ecol. Model. 140, 125–140.

Wood, M.O., Smith, G.S., 1909. Map of Adirondack Forest and Adjoining Territory. J.B. Lyon Company, Albany.