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Modeling the Carbon and Nitrogen Dynamics Following Disturbance in Eastern U.S. Forests

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Modeling the Carbon and Nitrogen Dynamics Following Disturbance in Eastern U.S.

Forests

By

Shree Ram Sharma Dangal

A Thesis

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MODELING THE CARBON AND NITROGEN DYNAMICS FOLLOWING
DISTURBANCE IN EASTERN U.S. FORESTS
SHREE RAM SHARMA DANGAL

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Date Approved

_____

Benjamin S. Felzer

Advisor

_____

Bruce R. Hargreaves

Supervisory Committee Member

_____

Zicheng Yu

Supervisory Committee Member

_____

Frank J. Pazzaglia

Department Chair

Acknowledgements

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Abstract

Previous studies show that disturbances such as hurricanes, logging, and agricultural abandonment have a significant effect on vegetation and the carbon and nitrogen dynamics of terrestrial ecosystems. In this study, we use a biogeochemical model (TEM-Hydro) to explore the effects of disturbance, climate change, and elevated CO_2 on annual carbon, and water fluxes in the U.S. eastern temperate forest by comparing it with Net Ecosystem Exchange (NEE) measurements using eddy covariance (EC) and biometric methods. Simulated evapotranspiration (ET) and net ecosystem productivity (NEP) match well with EC and biometric measurements for all sites. Disturbance history shows that an ecosystem is a net carbon source immediately after disturbance and that it becomes a carbon sink over longer periods. Simulations with and without disturbance suggest that land use history is crucial to determine the correct carbon sequestration rates of terrestrial ecosystems.

Key words: Disturbance, Net Ecosystem Productivity (NEP), Biometric NEP, Eddy Co-variance.

1. Introduction

Natural and anthropogenic disturbance such as hurricanes, fires, logging, and insect damage have a significant effect on vegetation and the carbon and nitrogen dynamics of terrestrial ecosystems (Foster et al. 1997; Thornton et al. 2002; Li et al. 2003; Grant et al. 2007; Clark et al. 2010). While some disturbances (hurricanes, fires) cause large scale tree mortality, other (ground fires, selective logging) affect community structure and organization without causing massive mortality (Dale et al. 2000). Currently, temperate forests are accumulating carbon in large enough quantities to affect the net global carbon sink (Goodale et al. 2002; Sabine et al. 2004). Enhanced carbon sequestration is likely due to recovery from historical disturbance, CO_2 fertilization of photosynthesis, nitrogen deposition, and warming (Caspersen et al. 2000).

Understanding how disturbance affects the overall carbon balance of forest is poorly understood primarily because of difficulties in separating the various contributions of autotrophic and heterotrophic carbon efflux, temperature dependence of Gross Primary Productivity (GPP), and the physiological differences in plant functional types (Thornton et al. 2002). Detailed understanding of the constraints on forest carbon sequestration requires knowledge of previous land use (Foster et al, 2003; Chen et al, 2003; Pregitzer and Euskirchen 2004; Magnani et al. 2007). In disturbed sites, soil respiration exceeds the carbon sequestration rates for several years (Amiro 2001; Pypker and Fredeen 2002b; Kowalski et al. 2003) and recovery of biomass, detritus mass, and carbon balance to pre-disturbance conditions takes more than 5 years (Thornton et al. 2002; Binford et al. 2006; Humphreys et al. 2006) . Disturbance history can provide detailed information of the changes in carbon stocks and fluxes, and response of plants to different types and

intensities of disturbance, and finally help us to predict the effect of future disturbance on net carbon sequestration (McGuire et al. 1992; Schimel et al. 2000; Smithwick et al. 2009).

Numerous studies have been conducted on former agricultural fields and cleared forests (Billings 1938; Oosting 1942; Smith 1968; Christen and Peet 1981; Shankman 1990; Post and Kwon 2000; Lafon et al. 2000). However, there has been little focus on understanding the implication of land-use history on carbon and nitrogen dynamics of ecosystems (Hamburg and Sanford 1986). It is important to characterize the effect of disturbance on carbon sequestration of these forested ecosystems. While studies reveal that productivity reaches a maximum early in the stand age and then gradually declines as it approaches maturity (Gower et al. 1996; Amiro et al. 2010), Luyssaert et al. (2008) have shown that mature stands are a global sink of carbon contrary to the existing belief that they are carbon neutral.

1.1. Effects of Hurricane on Forest Recovery

In eastern North America, hurricanes are the primary type of coarse-scale wind disturbance of temperate forests (Canham and Loucks, 1984). Hurricanes and other violent storms can create large patch disturbances with strong ecological impacts (Greenberg and McNab, 1997; Frelich, 2002; Woods, 2004). They affect above-ground forest biomass by defoliating and uprooting trees, and by damaging branches and stems (Walker, 1991). Extensive blow down by strong wind is an important factor that regulates hydrological, carbon and nutrient cycles (Whigman et al. 1991; Lugo and Scatena 1996). In 1938, a hurricane at Harvard Forest removed 70% of the crown area, disturbing the soil, hydrological, and carbon cycle (Barford et al., 2001). Studies carried out in Harvard

forest suggest that productivity declined immediately following disturbance, but recovered rapidly within 4 years, and increased net nitrogen mineralization as well as nitrogen leaching, and emission of trace gases (Foster et al., 1997). Goward et al. (2008) suggested that it might take several decades to respire the detritus after which the ecosystem starts to behave as a net sink of carbon. Studies show that net ecosystem productivity (NEP) was negative in North Carolina immediately following Hurricane Fran due to decomposition of new wood, resulting in losses exceeding carbon gains (Busing et al., 2008). Boose et al. (1994) show that the experimental blow down causes major reorganization of forest structure along with rapid redevelopment of canopy cover.

1.2. Effects of Logging on Forest Recovery

Logging can have a potential impact on the ecosystem structure and function. The forest floor is a major reservoir of organic matter and nutrients (Dominski, 1972; Gosz et al. 1976) and plays an essential role in the recovery of vegetation after disturbance. Covington (1981) shows that forest floor organic matter in clear cut stands declines by 50% within 20 years after harvest, and this decline is attributed to accelerated decomposition of surface litter (Yanai et al. 2003). However, other studies have shown that changes in decomposition rates due to logging are uncertain, and depend on species composition and organic matter content (Spurr and barnes, 1980; Blair and Crossley, 1988; Wallace and Freedman, 1986). Disturbances such as clear cutting will alter the ecosystem balance, leading to an increase of nutrient and organic matter storage due to increased addition of organic matter to the soil (Dominski, 1972). A simulation study carried out by Grant et al. (2007) suggests that decomposition of fine litter with small C:N ratios (35:1) enhances net N mineralization and plant N uptake, causing an early rise

in CO_2 fixation and leaf area index (LAI). On the other hand, decomposition of coarse woody litter with large C:N (250:1) does not release enough dissolved organic nitrogen (DON), causing immobilization of mineral N, and decreasing nitrogen uptake. Furthermore, Grant et al. (2007) show that the NEP of a 12 year logging cycle was larger than that of a 60 year cycle for about 20 years, but after that, declined with forest age. The conversion of long-lived forests into young stands changes the forest from a sink to a source of carbon for several decades because the lower leaf area in regenerating forests limits photosynthesis, while the residual carbon in soils and woody debris continues to respire (Chen et al., 2004).

1.3. Effects of Agricultural Abandonment on Forest Recovery

In the eastern United States, more than 80% of the original forest was cleared for farmland in the late 1800s (Glitzenstein et al. 1990; Foster 1992). Unlike natural disturbance, agriculture has a different effect on the carbon and nutrient dynamics of an ecosystem. Singleton et al. (2001) show that logging and repeated plowing of the soil removes both the plant and litter and hence recovery depends upon colonization from outside seed sources or artificial regeneration. Following agricultural abandonment, pH and nutrient concentrations of soil increases, while soil organic matter decreases (Koerner et al. 1997). Recovery of vegetation to pre-disturbance levels may take over 100 years after disturbance (Dupouey et al. 2002). Studies carried out at New York show that there are differences in species composition and diversity between former farmland and undisturbed forest (Nyland et al. 1986). However, Bossuyt et al. (1999), in his study of ancient and deciduous forests in Belgium, found no differences in overall species abundance or diversity following agriculture. Johnson (1992) found that soils recovering

from abandonment lose their carbon by an average of 30%. Experimental studies at North Carolina show that all the carbon went into the standing biomass immediately following regrowth while soil carbon did not recover well during the period of 30 years (Richter et al. 1995). While Hamburg (1983) predicted a minimum of 200 years necessary to obtain soil carbon to pre-disturbance level, Houghton et al. (1983) found that temperate soil carbon recovers to 90% within 50 year. Compton and Boone (2000) show an increase of 13-16% soil carbon and not many changes in soil nitrogen in the nearby woodlots compared to cultivated sites. Studies focused on the effects of agriculture disturbance show that factors such as soil and topography might play an essential role in the recovery of vegetation following disturbance (Singleton, 2001).

1.4. Effects of Nitrogen Limitation on Forest Recovery

Disturbance can alter the nutrient dynamics of forest ecosystems especially in places where nitrogen cycling is rapid (Iseman et al. 1999). Several studies have documented increases in nitrogen availability and net nitrogen mineralization following disturbance (Knoepp and Swank 1997; Prescott 1997). Studies suggest that nitrate leaching increase following harvest, but rates are similar to pre-harvest levels after 2-5 years (Hornbeck and Kropelin. 1982; Mann et al. 1988; Iseman et al. 1999). Nye and Greenland (1961) observed rapid movement of nitrate and cations through soils in England. Studies carried out in Coweeta Hydrological Laboratory following clear-cutting, deforestation, fertilization, and natural disturbance such as insect outbreaks suggest that nitrate losses in Coweeta streams increased more after disturbance than those of other ions, and was prevalent up to 20 years following disturbance (Swank and Douglass 1977). However, nitrogen uptake decreases after disturbance due to reduced plant biomass but accelerated

growth leads to nitrogen uptake that exceeds pre-disturbance rates within 4-5 years

(Gholz et al. 1985). While disturbance enhances nitrogen mineralization rates and

reduces plant nitrogen uptake in the temperate forests, the annual nitrogen mineralization

and plant nitrogen uptake are unpredictable prior to disturbance (Vitousek and Melillo.

1979). Increased soil nitrogen availability after disturbance increases the root length with

a net decrease in the overall contribution of roots to total soil respiration (Pregitzer et al.

1995). Similarly, Finzi et al. (2006) have shown that increased fine root production under

elevated CO_2 allows enhanced nitrogen uptake in his study carried out at Duke, Oak

Ridge National Laboratory, and Rhinelander. Although elevated CO_2 increased litter

production (Finzi et al. 2001; King et al. 2001; Norby et al. 2002), microbial processes

did not increase (Zak et al. 2003). However, several studies have shown that microbial

communities are metabolically active under elevated CO_2 (Insane et al. 1999; Phillips et

al. 2002), making more nitrogen available to plants.

In this study, we use the Terrestrial Ecosystem Model (TEM-Hydro) to explore the

effects of disturbances like hurricanes, logging, and agricultural abandonment on net

carbon sequestration of the US eastern temperate forests. Estimation of growth and

recovery from disturbance is key to understanding the carbon and nitrogen dynamics of

an ecosystem. We use eddy covariance (EC) data from the temperate forest sites at

Harvard Forest, Massachusetts to improve our ability to understand hydrology and

carbon-nitrogen dynamics during recovery from disturbance. The model is tested against

EC and site level biometric data and leaf area index (LAI) comparing the

evapotranspiration (ET) and Net Ecosystem Productivity (NEP) measurements at three

other temperate forest sites. The EC measurements produce Net Ecosystem Exchange (=

- Net Ecosystem Productivity). A positive NEP is a sink of carbon to the atmosphere while a negative NEP is a source to the atmosphere. The purpose of this study is to test our ability to model the seasonal and annual dynamics of water, carbon, and nutrient cycling in the U.S. eastern temperate forests; to evaluate how site history, stand-age dynamics, climate, and elevated carbon dioxide affect recovery following disturbance; and to understand the interaction of climate, vegetation, and disturbances on the regional carbon sink.

2. Methods

2.1. Site Description

Harvard Forest, MA is a source of data to calibrate our model to site-specific carbon and nitrogen stocks and fluxes. It consists of 70% deciduous and 30% coniferous trees dominated by oak, maple, birch, pine, and hemlock. A hurricane occurred in 1938 and blew down all the trees. Currently, the stands are approximately 81 years old and have not yet reached maturity (Barford et al. 2001). After calibrating Harvard Forest, we use sites listed in Table 1 to validate our model with gap-filled meteorological data. The location, elevation, mean annual temperature (T_{ann}), precipitation (Prec) and soil texture (proportion of sand, silt, and clay) are listed in Table 1. We combine meteorological forcing data from the Climate Research Unit (CRU) and eddy covariance data based on the years of availability of data for all sites to validate the model.

Table 1. Description of four different sites of the Eastern Temperate Forests.

Site	Location	Elevation(m)	Tann (°C)	Prec(mm yr^{-1})	Sand (%)	Silt (%)	Clay (%)
Harvard Forest, MA	42° 32'N 72° 10'W	340	8.3	1120	65	29	6
Duke Forest, NC	35° 58'N 79° 06'W	163	15.0	1147	49	42	9
Willow Creek, WI	45° 48'N 90° 05'E	515	4.6	810	56	33	11
Walker Branch, TN	35°57'N 84°17'E	343	14.69	1312	34	3	63

2.2. The Terrestrial Ecosystem Model

The Terrestrial Ecosystem Model (TEM) is a biogeochemical model that considers the complex interaction of carbon and nitrogen dynamics within an ecosystem and uses information on climate, elevation, soils and vegetation to estimate the important carbon and nitrogen fluxes of the ecosystem (Fig. 1). TEM has been used to examine the patterns of terrestrial carbon dynamics and how CO_2 fertilization, climate change, disturbance and air pollution affect the global carbon cycle (Raich et al., 1991; Tian et al., 1999; Felzer et al., 2004). As many biogeochemical models do not take account carbon-nitrogen interactions (Plattner et al., 2008), these models over-estimate the response of plant production and carbon sequestration to increasing atmospheric CO_2 concentrations and disturbance associated with climate change (Hungate et al., 2003). They are also too sensitive to the effects of warming on carbon (Sokolov et al., 2008). However, TEM has always considered the complex interaction of carbon and nitrogen cycle to regulate the

net primary production and decomposition (McGuire et al., 1997, Pan et al., 1998, Sokolov et al., 2008). The modified version, TEM-Hydro, has improved the physics governing water and energy fluxes between the surface and atmosphere.
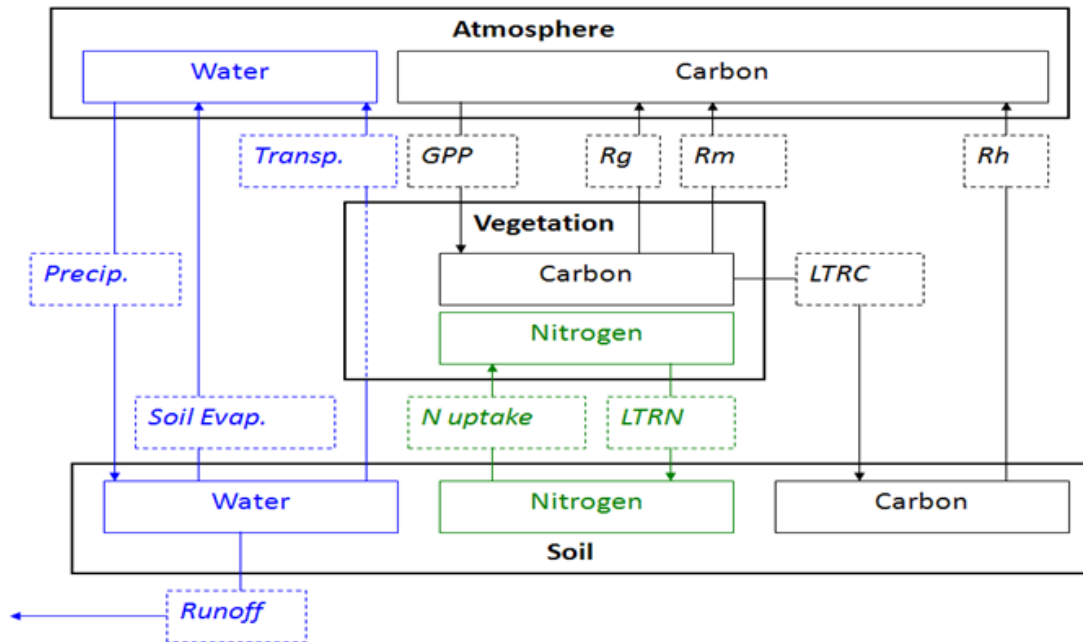
Figure 1. TEM-Hydro (Felzer et al. 2009). A Generalized figure showing the carbon, nitrogen, and water cycling in TEM-Hydro. The solid box represents the stocks and the dashed box represents the fluxes in and out of the ecosystem.

The vegetation pool in TEM-Hydro consists of four plant structural compartments and one storage compartment; each of these contains a carbon and nitrogen pool. The four structural compartments consist of leaves, active stem tissue (sapwood), inactive stem tissue (heartwood) and fine roots and carbon storage compartment (labile pool) which is used to grow new tissue or maintain existing tissue. Active stem tissue is meant for the storage and transport of resources, while inactive stem tissue plays a structural role and is non-functional. In our current model, there are ten variables that define the vegetation pool, which are labile carbon, labile nitrogen, leaf carbon, leaf nitrogen, stem carbon

(active), stem nitrogen (active), stem carbon (inactive), stem nitrogen (inactive), root

carbon, and root nitrogen (figure 2).
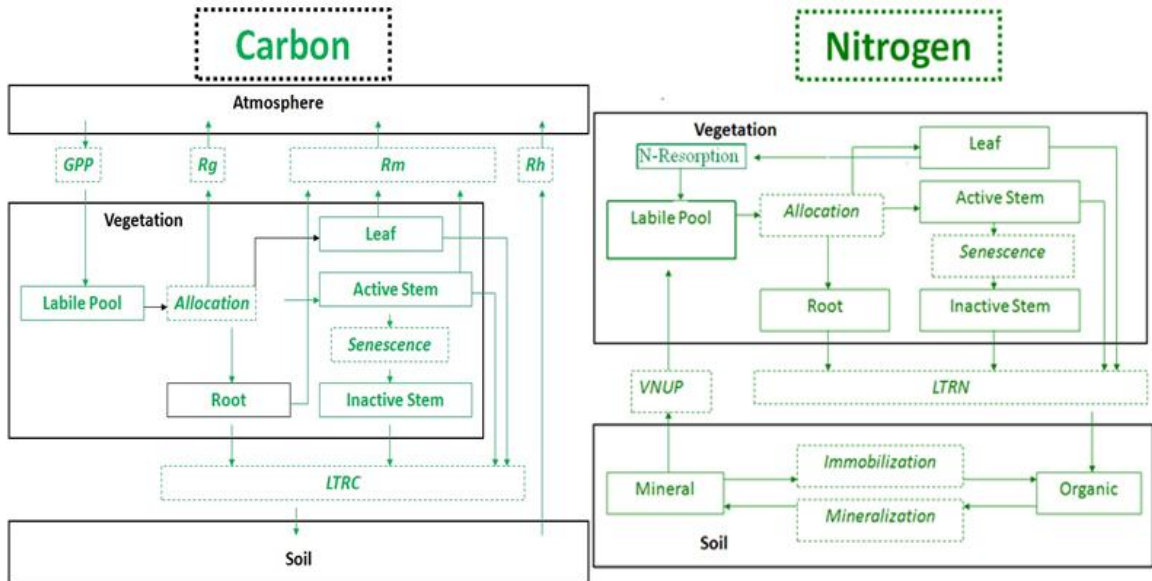
Figure 2 Carbon and Nitrogen allocation in TEM-Hydro. Following photosynthesis, carbon is stored temporally in labile pool. The labile pool then allocates carbon to leaf, active and inactive stems, and roots based on a cost benefit analysis.

2.3. Simulation Procedure

2.3.1. Evapotranspiration

In TEM-Hydro, we model evapotranspiration(ET) based on a simple bucket model

approach developed by Vorosmarty et al. (1989) that explicitly uses the Shuttleworth and

Wallace (1985) formulation to calculate soil evaporation and plant transpiration. The

Shuttleworth and Wallace approach (1985) is a flow-resistance model that determines

water vapor fluxes based on aerodynamic resistance among the soil, canopy, canopy air

space, and atmosphere. Similarly, the soil moisture function is calculated based on the

ratio of the amount of plant extractable water in the soil column to the maximum possible

amount of extractable water in the given soil profile. We no longer use the previous

dependence of soil moisture on the ratio of estimated to potential evapotranspiration.

2.3.2. Photosynthesis

TEM-Hydro uses a semi empirical equation for gross primary production (GPP) and

represents the total assimilation of CO_2 (C_{max}) reduced by factors of light, temperature,

moisture, carbon dioxide, ozone, and nutrient availability. We explicitly use Leaf Area

Index (LAI) to calculate GPP, and C_{max} represents a maximum leaf-level compared to

canopy-level photosynthetic rate. LAI is prognostically determined from the leaf carbon

and a biome-dependent specific leaf area. In TEM-Hydro, GPP is estimated as a

parabolic function of temperature, a linear function of photosynthetically active radiation

(PAR), a hyperbolic function of internal carbon dioxide concentration (C_i), and a linear

function of ozone.

2.3.3. Respiration

In TEM-Hydro, respiration is divided between growth and maintenance rates. Growth

respiration is assumed equal to 25% of the total carbon allocated to tissues while

maintenance rates are based on temperature and tissue nitrogen. The temperature

dependence of respiration is based on the LaRS (Hanson et al. 2004) function for

autotrophic respiration and the Lloyd and Taylor (1994) approach for heterotrophic

respiration. Respiration is modeled as Q10 function where rates double for a temperature

increase of 10^oC. However, TEM-Hydro assumes that autotrophic respiration

downregulates with increasing temperature, enabling complete acclimation with

warming.

The soil pool in TEM-Hydro consists of a single layer, where decomposition of organic matter explicitly depends on the Lloyd and Taylor (1994) approach and assumes no acclimation to increasing temperatures. While Stromgren (2001) and Luo et al. (2001) have shown acclimation of heterotrophic respiration with increased warming, Kirschbaum (2004) has pointed out that such an increase in soil carbon efflux is temporary and can be modeled easily using a two-pool soil carbon model. The limited decomposition with increased warming is due to depletion of readily decomposable substrate. By incorporating a single layer soil pool and assuming no acclimation, we are over-estimating the soil carbon efflux in our current version of TEM. This over-estimation of soil carbon efflux can be counter-balanced by adding a transient term that will allow the soil pool to equilibrate over longer time scales.

2.3.4. Carbon and Nitrogen Dynamics

Our carbon allocation routine is based on a cost-benefit analysis where the plant will add leaves if the expected marginal benefit exceeds the expected marginal cost. Since, nitrogen allocation does not occur in the same proportion as carbon allocation, the nitrogen allocation is based on carbon allocation and the carbon nitrogen ratio of each structural plant component. Some of the litterfall organic nitrogen is mineralized by bacteria converting it into inorganic nitrogen, that in turn is taken up by plants directly. We don't explicitly model individual compounds of nitrogen such as nitrate or ammonium. Under nitrogen-limiting conditions, our model assumes that prior to litter fall, some of the nitrogen is sent back into the labile nitrogen pool (nitrogen resorption), allowing the nitrogen pool to regain nitrogen.

2.4. Experimental Setup

2.4.1. Reference Datasets

We use three major sources of data to calibrate and validate our model. While reference datasets for calibration includes carbon and nitrogen stocks and fluxes measured over a long period of time at Harvard Forest, validation is done against Eddy Covariance NEE and ET, Biometric NEP, and LAI obtained from literature. The carbon and nitrogen stocks and fluxes obtained at Harvard Forest (Appendix A) are altered to account for a completely mature forest.

Eddy covariance data are obtained from the flux tower located at four specific sites of our study. The eddy covariance method uses wind speed and CO_2 or H_2O concentrations to measure the exchange of CO_2 and latent heat fluxes within atmospheric boundaries, and the measurements are done on half-hourly basis. To compare our modeled ET to eddy covariance water vapor fluxes, I need to convert the latent heat fluxes obtained from the flux tower to ET.

The biometric NEP's used in this study are obtained from literature. Biometric NEP's are calculated using different approach. Most common methods include measuring the diameter at breast height (dbh) of several trees, using allometric relationships to estimate the amount of above-ground biomass and then estimating the change in total carbon from the standing biomass. Similarly, changes in soil carbon is estimated by using loss on ignition (LOC), which involves taking a known mass of soil and heating it at a known temperature and measuring the change in mass per unit of time.

The LAIs, which are measured as the ratio of total upper surface area of the tree to the surface area of land on which the tree grows, are obtained from the literature. We compare the year on which the LAI is available to the month of July for that particular year from the model.

2.4.2. Factors Affecting Recovery Rates

We adjust different variables that affect the recovery rates of vegetation following natural and anthropogenic disturbance. These variables (Table 2) include factors like optimum temperature for plant growth, nitrogen uptake by plants, root respiration, wind-fall carbon allocation, and labile nutrient supply. In order to accurately model the recovery rates, we use an iterative approach of recalibrating and checking against the target Net Ecosystem Productivity (NEP) with each subsequent change in code.

Table 2. Parameters that affects the carbon and nitrogen stocks and fluxes in TEM

Variables	Description of variables	Effect	Remarks
VegC	Carbon stored in in leaves, active and inactive stems, and roots	ltrc	Ltrc is the litter fall carbon rate, and affects the amount of carbon stored in plants.
SoilC	Carbon in soil	kd	Kd is the decomposition rates of organic matter in the soil.
Windfall Allocation	Allocation to seed pool and occurs only when labile pool grows larger than its allowed storage space	Investment Allocation	Investment allocation is the allocation of carbon to stems, leaves, roots, and labile pool and hence any changes in the windfall allocation will affect the size of investment allocation pool.
Q10	temperature dependent function	root respiration	higher Q10 means higher respiration
krnup	half saturation constant	vegetation nitrogen uptake	Affects the nitrogen uptake by plants depending on the amount of inorganic nitrogen available in soil.
topt	Optimum temperature for plant growth	GPP	GPP is highest at topt and decreased parabolically with change in temperature.
N resorption	leaf nitrogen resorption	Labile nutrient supply senescence	Affects the amount of nitrogen available in labile pool.

In TEM- Hydro, vegetation is allowed to store carbon in leaves, stems (active and inactive), roots, and seeds. Changing the litter fall carbon rates could allow vegetation carbon to equilibrate over longer time scales, affecting the rates of recovery. Similarly, by allowing decomposition of soil organic matter (kd) to vary, we can adjust the equilibrium time of the soil pool affecting the recovery rates. Cost-benefit analysis approach of carbon allocation involves investment and windfall allocation. Since investment allocation returns more than it consumes, a certain portion of the allocation goes to windfall allocation (allocation to seeds), which occurs only when the labile pool exceeds the allowed storage space in structural tissues. Changing the size of labile carbon storage pool could affect the carbon allocation to different structural compartments and hence the recovery rates.

Plant respiration is modeled as an exponential function of Q10, where respiration doubles for a short-term temperature increase of 10^oC. Changes in the Q10 function will allow respiration rates of plants to vary significantly, affecting the recovery rates. Vegetation nitrogen uptake (VNUP) is the total uptake of nitrogen from soil, and all uptake of nitrogen is assumed to be from the available inorganic nitrogen pool. Temperate forests under nitrogen-limiting conditions show decreased carbon assimilation, allowing plants to allocate less carbon to different structural components. Currently, our VNUP function is explicitly based on fine root biomass where increased fine root biomass will allow enhanced uptake of nitrogen. Increase in temperature will enhance plant respiration and allow higher VNUP. The temperature function (t_{opt}) of GPP (alternatively referred to as optimum temperature of GPP) is based on the average temperature of the growing season compared to the warmest temperature of the growing

season. Optimum temperature is the temperature where assimilation rates are highest and decreases parabolically with temperature change. Because plants have a certain range of temperature where maximum assimilation of carbon occurs, any change in t_{opt} leads to change in the carbon sequestration by plants and hence the allocation of carbon to different vegetation compartments.

2.4.3. Historical Simulation

TEM-Hydro is simulated for each site assuming that the land is covered with the original natural vegetation. The model is then run in transient mode for 120 years using historical climate data (CRU 2.0), where the first 40 years initialize terrestrial carbon and nitrogen dynamics to a dynamic equilibrium state. We use CRU2.0 historical cloudiness, air temperature, precipitation, temperature range, and vapor pressure, and substitute the gap-filled data for the specific years we are modeling for the site level runs. Annual atmospheric carbon dioxide concentrations are from Keeling et al. (1995). Historical ozone levels (AOT40 index) are derived from the Environmental Protection Agency's (EPA) Clean Air Status and Trends Network (CASTNET; http://www.epa.gov/castnet). The model also uses spatially-explicit data sets of soil texture (GSDTG, 2000), elevation (GLOBE, 1999), and pre-disturbance natural vegetation (McGuire et al., 2001).

I ran historical simulations for four sites: Harvard Forest, Duke Forest, Willow Creek, and Walker Branch. While Harvard Forest recovers from a hurricane, Duke and Willow Creek recover from clear-cut, and Walker Branch recovers from agricultural abandonment. Because there is lack of data on the fertilization history at Walker Branch during the period of agriculture, I did not include fertilization.

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2.4.4. Model Calibration and Validation

I calibrated TEM-Hydro without disturbance by adjusting several parameters to get the target carbon and nitrogen stocks and fluxes such as gross primary productivity (GPP), nitrogen-limited net primary production (NPP), nitrogen-saturated NPP, available inorganic nitrogen (N_{av}), and nitrogen uptake rates (N_{up}). Calibration involves adjusting the carbon assimilation rate (C_{max}) for saturated NPP, maintenance respiration (K_{ra}) for GPP, nitrogen assimilation rate (N_{max}) for saturated NPP, stem mortality ($\tau_{heartwood}$) for vegetation carbon, heterotrophic respiration (kd) for soil carbon, and nitrogen mineralization (M_{nup}) for available nitrogen.

While validating the model against EC carbon and water fluxes, I replace CRU climate with EC climate from the years EC data are available and carry out a hundred year simulation for that particular grid. Then I compare the model output (ET and NEP) with Eddy Covariance ET and NEE (=-NEP), and biometric NEP to validate our model at Harvard Forest, Duke Forest, and Willow Creek. In case of Walker Branch I compared both NEP and Net Carbon Exchange (NCE) based on McGuire et al. 2001 to see the change in carbon fluxes. NCE is calculated as the total of NEP, the conversion fluxes, and the product decay pools. I also validated the modeled LAI for the month of July with site specific LAI obtained from literature.

$$NCE = NEP + E_{NAD} + E_{AD} + E_p \qquad \text{--- (i)}$$

E_{NAD} = emission from non anthropogenic disturbance

E_{AD} = emission from anthropogenic disturbance

E_p = decomposition of production harvested for human use

Table 3. Disturbance history at four eddy covariance sites of the eastern temperate forests.

Site	EC Data available	Disturbance	Stand age	Forest type	References
Harvard Forest, MA	1993-2004	Hurricane (1937)	81 years	Oak, maple, birch, pine, hemlock	(Wofsy et al., 1993), Ameriflux; Davidson, & Savage.
Duke Forest, NC	2000 – 2005	Clear-cut (2002)	25 Years	Loblolly Pine	Stoy et al., 2006
Walker Branch, TN	1994 – 1998	Agriculture (1901)	50-120 years	Mixed broadleaf and deciduous forest	Baldocchi and Wilson, 2001
Willow Creek, WI	1998 – 2006	Clear cut (late 1800 and 1993)	55-90 years	Sugar-maple-aspen birch forest	Desai et al., 2005

After calibrating TEM-Hydro, I simulate carbon and water fluxes using climate, atmospheric CO_2, and ozone data for the four EC sites (Table 3). I considered three different disturbance types for this study: hurricane, logging, and agricultural abandonment. In the model, following each disturbance, I assign a certain portion of above-ground biomass for conversion and slash depending upon the type of disturbance. The recovery rate depends on the amount of above-ground biomass added to the soil or released back to the atmosphere. The disturbance history simulations at each site are 100 years long, allowing for changes in climate, carbon dioxide, and ozone.

2.4.5. Historical Disturbance and Recovery Following Disturbance

The TEM-Hydro uses a dynamic cohort approach to account for land use and land cover change. In this approach, it assumes that the grid is initially covered by undisturbed potential vegetation. When disturbance occurs, a new cohort is formed and a certain amount of land area is subtracted from the original cohort and added to the new disturbed cohort. Each time disturbance occurs, a new cohort is added to the old one and part of original cohort is subtracted to assign to the new one. TEM-Hydro is then used to

simulate the recovery of terrestrial carbon dynamics after a disturbance within a context

of local environmental conditions.
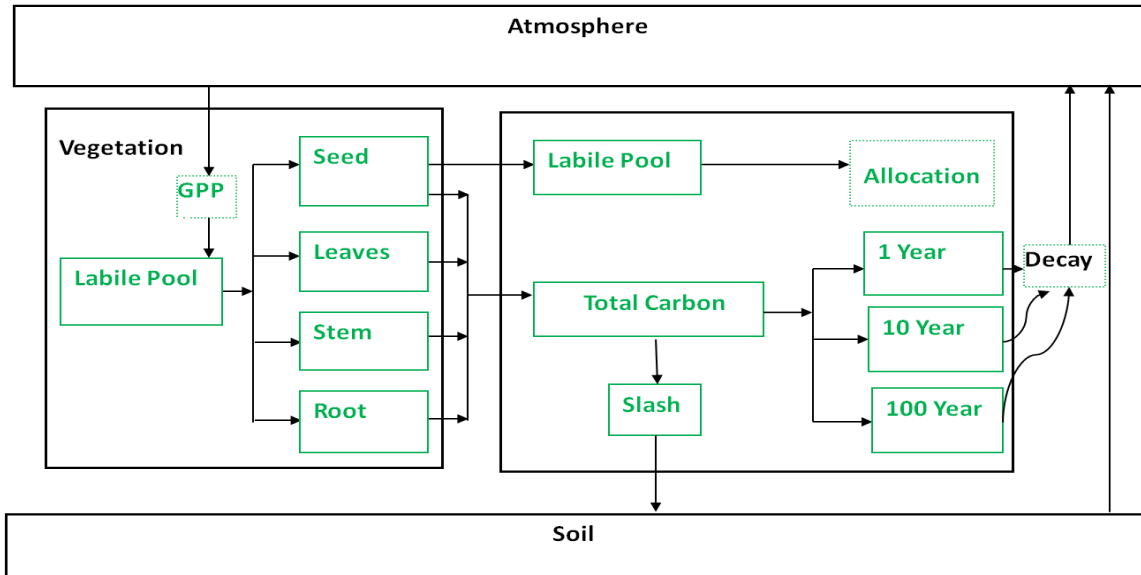
Figure 3. Disturbance in TEM-Hydro. Following disturbance, non living biomass is transferred to a four different product pool (Houghton et al., 1983). The non living biomass is added to the soil in the form of slash or converted to the one (fuelwood and crops), ten (paper and pulp), and hundred (furniture and long lasting products) year product pool.

After disturbance, all the above-ground biomass that including leaf and active and

inactive stems, is transferred into a different year product pool (Houghton et al, 1983)

(Fig. 3). Disturbances other than agricultural abandonment are simulated under similar

environmental conditions where above-ground biomass is transferred to slash, one-, ten-,

and hundred-year product pool (McGuire et al., 2001). For instance, we allow 99% of the

above ground biomass to be added into the soil in the case of Harvard forest which was

cleared by a hurricane in 1938, while a larger percentage of the above-ground biomass

goes into the one, ten, and hundred year product pools when clear-cut. In the case of

agricultural abandonment, the biomass goes into a one year product pool or into slash.

Recovery of vegetation following disturbance is based on the transfer of a certain

proportion of seed carbon to the labile pool. While reverting to forest from agricultural abandonment, we allow for the update of rooting depth as appropriate to potential plant functional types (PFT). The release of carbon from the three pools is calculated as a linear function of the initial carbon input to these pools. For example, the release of carbon from the 100 year product pool represents 1% of the initial carbon released into the atmosphere annually over a period of 100 years. Part of nitrogen from the seed pool is transferred to the labile pool to allow for vegetation re-growth after disturbance. In the current version of TEM, I do not allow nitrogen deposition and leaching, and calculate the available nitrogen based on C:N ratio and the carbon content in plants. The nitrogen from leaves and stems are either lost from the soil or goes into the organic or inorganic pool.

I also carried out historical simulations with and without disturbance to separate out the effects of disturbance on the carbon sink at each site. The difference between the two runs will help to determine the recovery rates of NEP for these sites. I then compared the length of recovery of NEP after disturbance with the mean annual temperature of all sites to see the effect of temperature on forest recovery.

2.4.6. Model Comparison, Forest Recovery, and Nitrogen Limitation

I first compare our modeled ET values with site specific EC estimates of ET and discuss how energy imbalance at various EC sites results in under-estimation of ET. Similarly, I compare simulated NEP with NEP calculated from observed EC and from biometric estimates and analyze the differences between simulated, EC, and biometric NEP at each site. I then compare annual leaf area index (LAI) from literature based on actual field measurements to the modeled LAI for the month of July.

I also explore the model response to the type of disturbance, and how it changes the

carbon stocks and fluxes at each site, comparing it with observed estimates from various

sources. I then determine the length of recovery period of NEP for all sites and compare

it with the mean annual temperature to determine if changes in temperature affect the

recovery time. Finally, I explore the model response of nitrogen limitation on NEP at

each site.

3. Results

3.1. Evapotranspiration

After model calibration, the modeled evapotranspiration (ET) shows strong agreement

with the observed values for all sites, though the bias is larger at Harvard and Walker

Branch (Fig 4; Table 4). The modeled ET is larger at Harvard Forest by 109 mm yr^{-1} and

at Walker Branch by 88 mm yr^{-1}. Duke and Willow Creek show strong agreement with

the observed values obtained from eddy flux measurements. The root mean square errors

(RMSE) at all sites are within ±17 mm yr^{-1}, indicating that TEM-Hydro captures monthly

variability well compared to EC fluxes (Table 4). Differences between the EC and

simulated ET might be due to energy imbalance at EC sites, which are described in the

discussion.
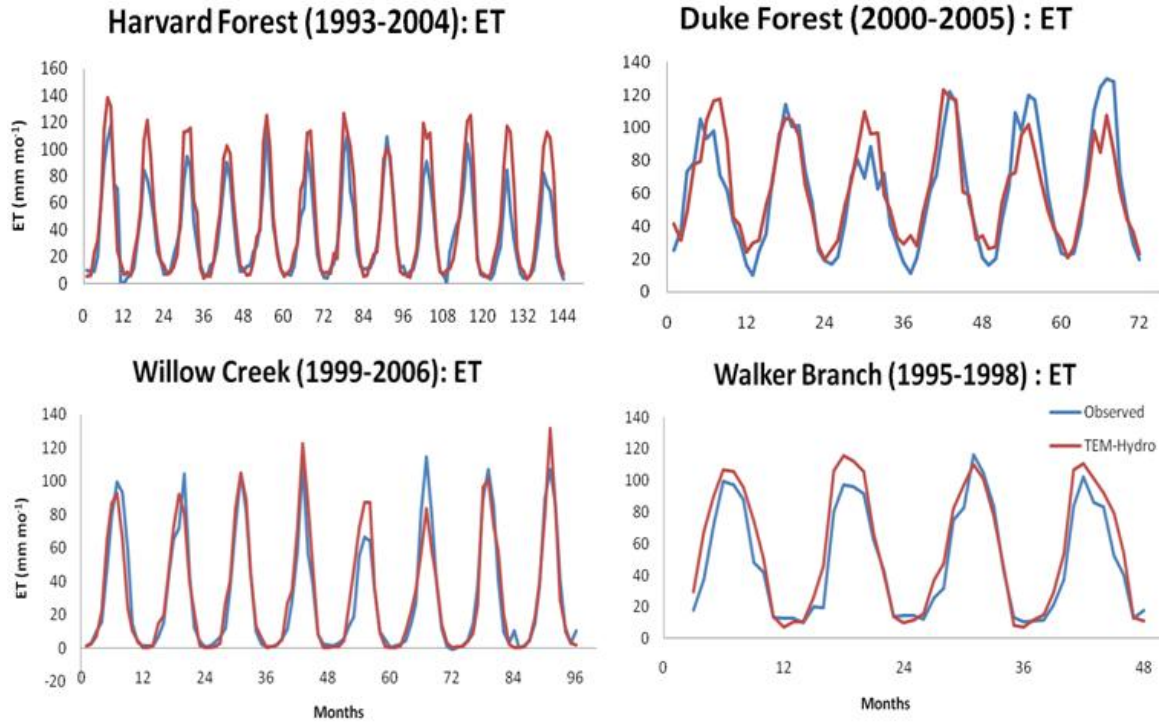
Figure 4. Comparison of monthly modeled vs EC ET at four eddy covariance sites in eastern temperate forest. EC ET are obtained from latent heat fluxes available for each site, while modeled ET are obtained from 100 year simulation using CRU and EC climate data.

Table 4. Comparison of annual modeled vs EC ET at four different sites.*

Site ID	Eddy Covariance	Model	% difference	RMSE
HVD	455	564	19	17
DUK	738	755	2	16
WLK	573	661	13	12
WIL	370	386	4	11

* units are in mm yr^{-1}

3.2. Net Ecosystem Productivity (NEP)

TEM-Hydro show that the modeled NEPs agree well with EC measurements at Harvard

and Duke Forest, while under-estimates the NEP at Walker Branch, and Willow Creek.

TEM-Hydro underestimates the EC NEP by 240 and 520 mm yr^{-1} at Willow Creek and

Walker Branch respectively (Fig 5; Table 5). Comparison of NEP and NCE at Walker

Branch show that NCE is more than the NEP by 4 g C m^{-2} yr^{-1}. Comparisons of NEP to

biometric measurements show strong agreement with Walker Branch and Willow Creek.

The root mean square error (RMSE) indicates that TEM-Hydro captures monthly

variability ($\pm$45 g C m^{-2} yr^{-1}) well for all sites except Walker Branch. Comparison of

simulated LAI for the month of July matched well with observed LAI for that particular

year (Fig. 6). Previous studies have shown that differences between biometric and EC

NEP are due to different periods of data collection, and uncertainties associated with the

two measurements are discussed below.
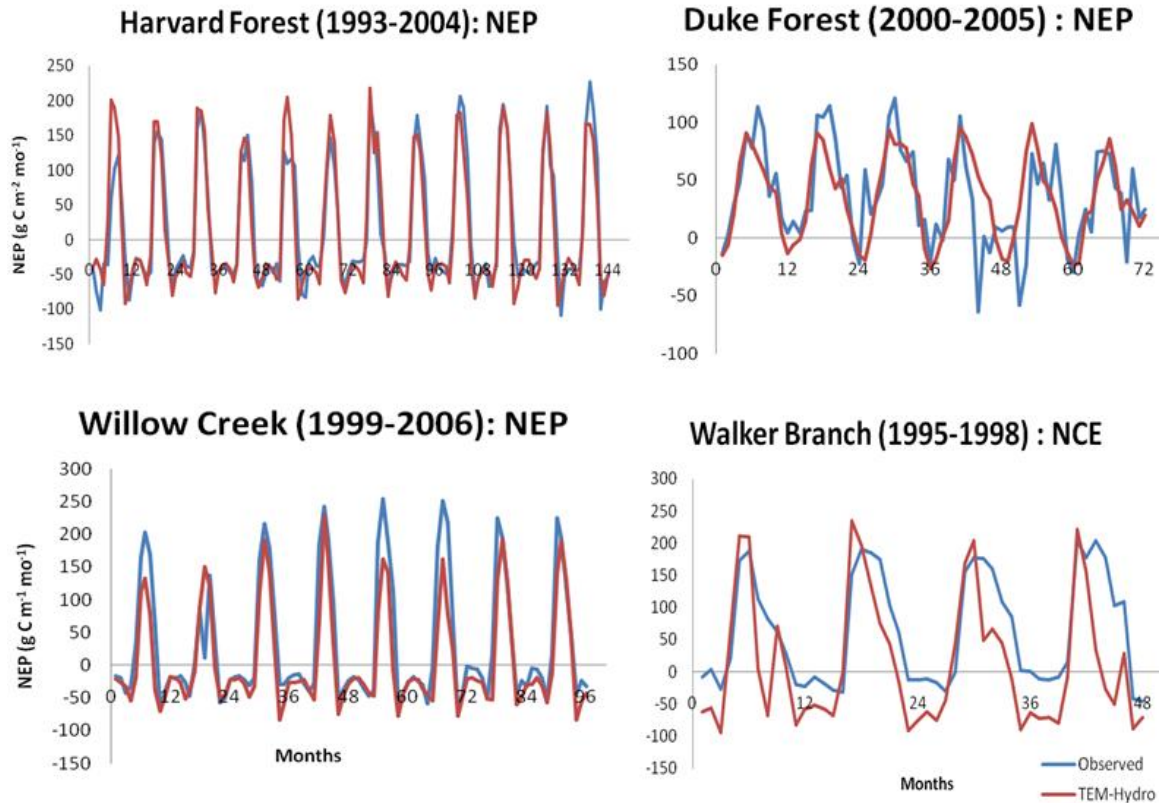
Figure 5. Comparison of Modeled vs EC NEP at four eddy covariance sites in the eastern temperate forest. EC NEP are obtained as a net change in CO_2 fluxes within atmospheric boundaries, while modeled NEP are obtained as the difference between GPP and R_a and R_h. In case of Walker Branch, I compared EC NEP with the modeled NCE.

Table 5. Comparison of annual modeled (disturbed and undisturbed), EC NEP and Biometric NEP at four different sites.*

Site ID	Eddy Covariance	Model Disturbed	% diff.	RMSE	Biometric	Model Undisturbed	References
HVD	170	160	5	31	160	35	Barford et al. 2001
DUK	430	420	2	33	599	0	Hamilton et al. 2002
WLK	750 (NCE)	230	69	200	250	0 (NCE)	Curtis et al. 2002
WIL	380	140	63	45	106	33	Curtis et al. 2002

* Units are in g C m^{-2} yr^{-1}

3.3. Land-Use History

3.3.1. Effects of Disturbance and Re-growth History

Fastest regrowth (source-to-sink) following disturbance occurs at Duke and Willow Creek, which recover from clear-cut and agricultural abandonment, respectively (Fig 7, 8; Table 6). Although Duke Forest is a higher source of carbon compared to Willow Creek, recovery time after disturbance is similar in both cases. However, Harvard and Walker Branch take the longest time to recover following disturbance. Because Harvard forest recovers from a hurricane, large inputs of woody debris into the soil enhance decomposition, which lengthens the recovery period. Similarly, exposure of soils for a longer period of time in the case of Walker Branch leads to increased decomposition and lengthens the recovery time. While Willow Creek and Duke Forest have the same type of disturbance, Willow Creek is a lower net source of carbon compared to Duke Forest immediately following disturbance due to significant differences in the mean annual temperature.
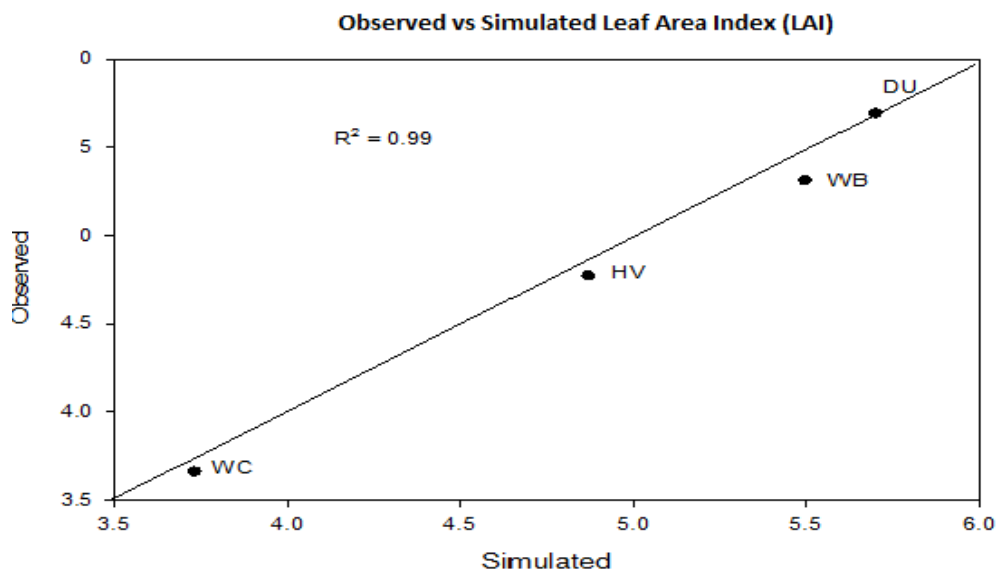
Figure 6. Comparison of modeled vs. observed LAI for each site. Observed values are obtained from literature and are based on actual field measurements.

Table 6. Forest recovery and net carbon source following disturbance.*

Site ID	Disturbance	Type	NEP/NCE following disturbance	Years to recover
HVD	1938	Hurricane	-1700	12 years
DUK	1982	Logging	-1200	8 years
WIL	1933	Logging	-600	8 years
WLK	1901	Agriculture	-1700	19 years

* Units are in g C m^{-2} yr^{-1}

Rates of litter fall carbon (ltrc), Gross Primary Productivity (GPP), and autotrophic respiration (Ra) went down immediately following disturbance while heterotrophic respiration (Rh) peaked at all sites (Fig 9; Appendix II). Rapid addition of organic material to the soil enhanced decomposition rates, allowing higher Rh. Harvard forest has a large amount of woody debris added to the soil following disturbance enhancing the decomposition rates and leading to increased recovery time. While Willow Creek and Duke Forest have the same rate of litter fall and woody debris input to the soil, Willow Creek has less decomposition than Duke due to significantly lower mean annual temperature. In the case of Walker Branch, less organic matter input following agricultural abandonment decreases the decomposition rates allowing faster rates of recovery.
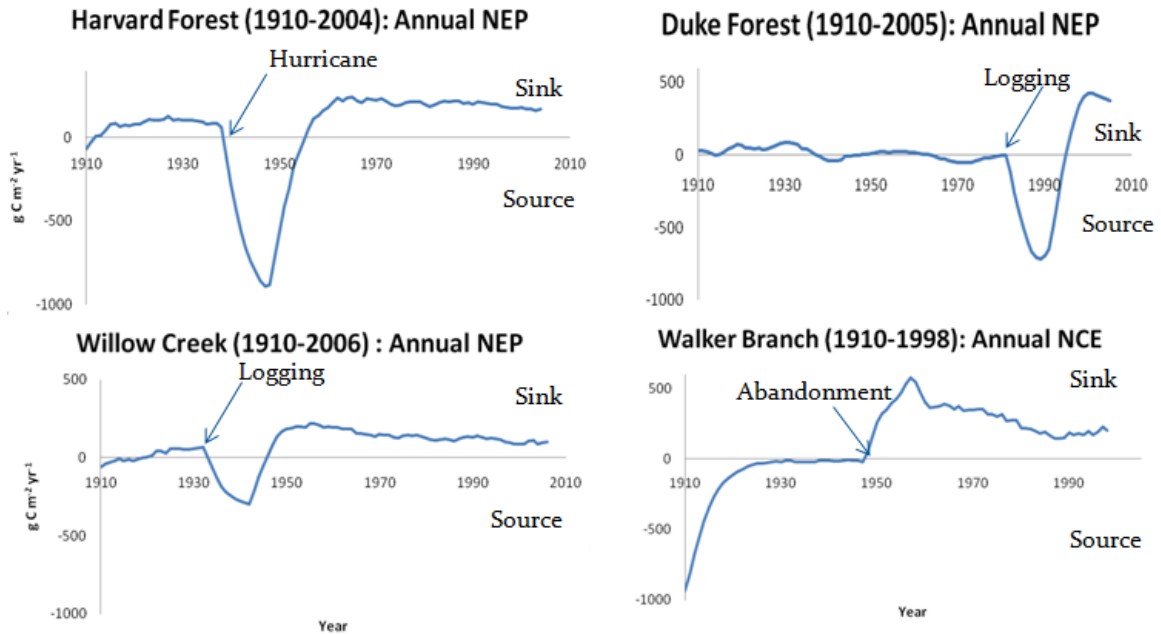
Figure 7. Time series of change in Net Ecosystem Productivity with disturbance. All sites show a net source of carbon after disturbance that continues with time followed by a longer period of net carbon sink. Positive NEP is a sink while negative NEP is a source of carbon to the atmosphere.

3.3.2. Carbon Sequestration

The modeled NEP values at a given time are highly dependent on the time since disturbance, and the recovery rates following disturbance. For all sites, TEM-Hydro shows a net carbon source immediately after disturbance, which declines with time, followed by a longer period of carbon sink. All sites become a carbon sink immediately after stand replacement and the sink decreases with time. The largest sink occurs at recently disturbed Duke Forest (Fig 7; Fig 8). Cumulative NEP with disturbed and undisturbed vegetation (Fig 7; Fig 8; Table 5) shows that disturbed vegetation is a greater sink of carbon compared to undisturbed vegetation. As the growing forest sequesters more carbon than the mature forest, my results show that recently disturbed sites have a higher rate of carbon accumulation compared to undisturbed sites.

3.3.3. Temperature Effects on Forest Regrowth

While the NEP recovery period for Duke Forest and Willow Creek is similar (8 years),

Harvard Forest and Walker Branch take 12 and 19 years respectively to recover to a

positive NEP after disturbance. Effects of temperature on the pace of recovery show that

the warmer site (Duke Forest) and the cooler site (Willow Creek) take the same period of

time (8 years) to recover (Fig. 10; Table 6). Forest regrowth primarily depends on the

type of disturbance with important secondary effects of temperature.

3.4. Effects of Nitrogen Limitation on Recovery

For all sites, TEM-Hydro shows reduced nitrogen uptake immediately after disturbance

followed by a longer period of enhanced nitrogen uptake. Nitrogen uptake recovered

within 5-7 years for all sites except Walker Branch. Simulations with and without

elevated CO_2 show that elevated CO_2 enhanced nitrogen uptake for all sites except

Willow Creek (Fig.11; Appendix III). Calculation of nitrogen use efficiency (NUE),

measured as an amount of biomass added per unit of nitrogen taken, reveal that NUE is

higher at Willow Creek than the other sites under elevated CO_2.
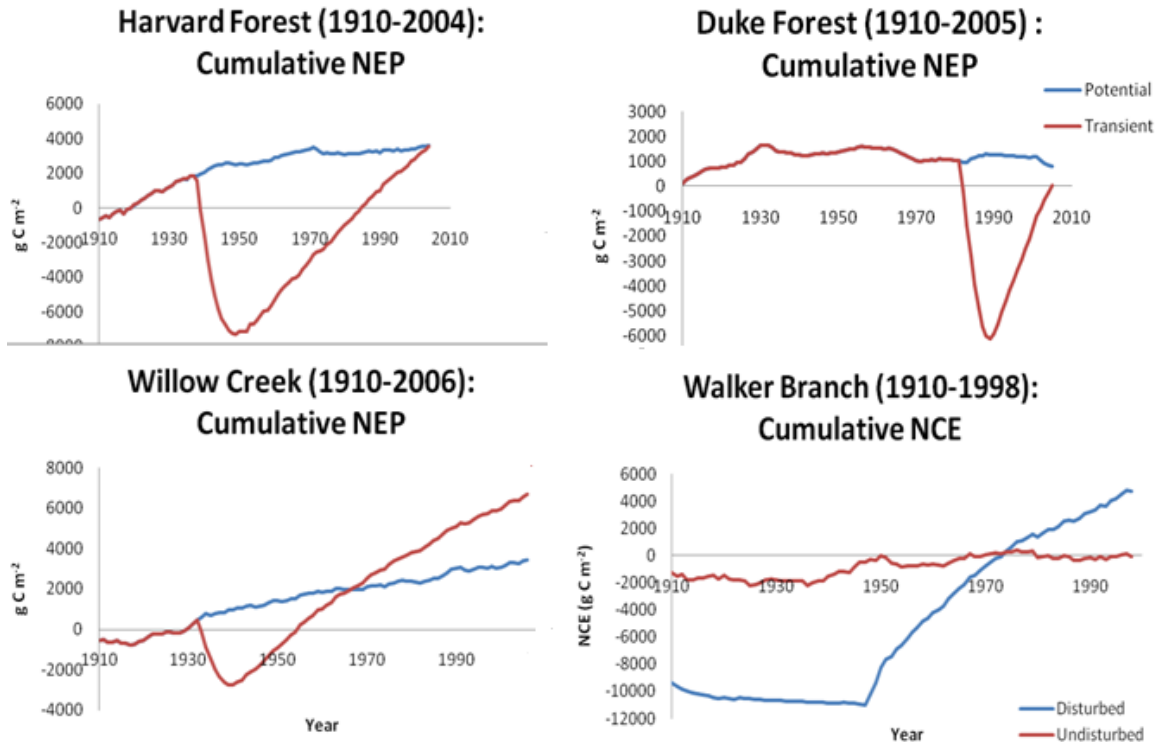
Figure 8. Cumulative NEP with undisturbed and disturbed simulation. Disturbed simulation shows that growing forests are a greater sink of carbon (Willow Creek and Walker Branch). While the sink of carbon at Harvard Forest is similar with and without disturbance, Duke Forest is a lower sink with disturbance.

4. Discussion

4.1. Comparison of Modeled and Eddy Covariance ET

Several modeling studies have found that there are energy imbalance issues associated with EC measurements at different sites (Luo et al. 2003). Wilson et al. (2002) have explored the energy imbalance at several eddy flux sites and observed that the sum of latent and sensible heat flux is less than the sum of net radiation, resulting in significant change in heat storage by 10-30%. This discrepancy in flux measurement is likely due to sampling errors, instrument bias, neglected energy sinks, and advection (Massman and Lee. 2002; Wilson et al. 2002). Because energy is typically out of balance at EC sites by

about 20% (Wilson et al. 2002), increasing ET by a factor of 1.20 eliminates the average

annual bias for Harvard Forests and Walker Branch.
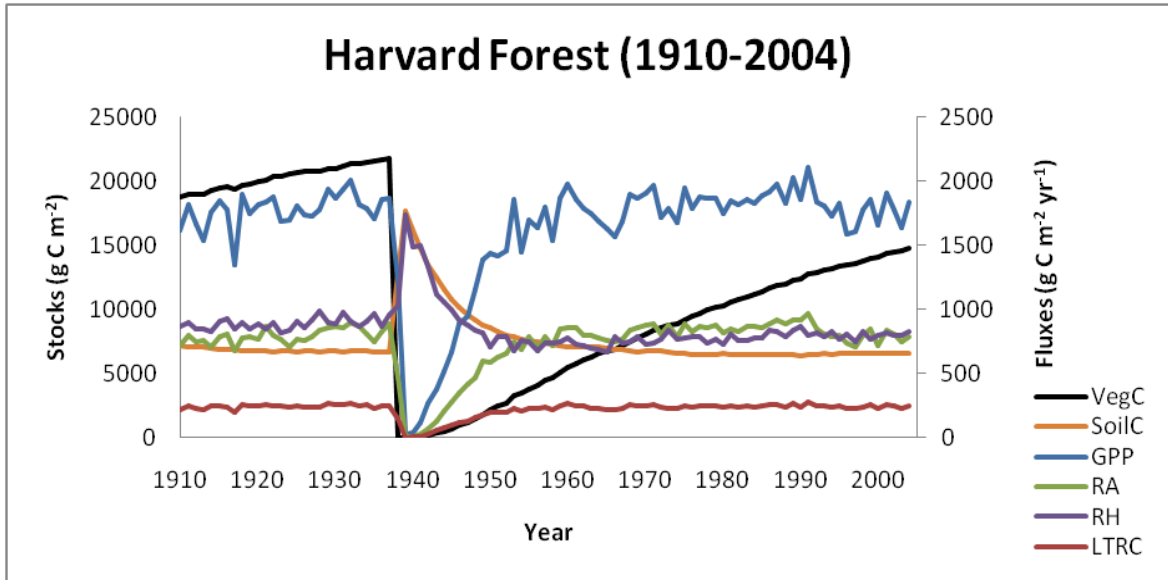
Figure 9. Time series of changes in carbon stocks and fluxes at Harvard Forest. The vegetation carbon at Harvard Forest is still 80% mature (Barford et al. 2001). The change in carbon stocks and fluxes at Duke Forest, Willow Creek, and Walker Branch are given in Appendix II.

4.2. Comparison of modeled NEP with EC and Biometric NEP

Several models also under-estimate the NEP in mid-summer, especially at Harvard Forest

and Walker Branch (Thornton et al, 2002; Hanson et al, 2004; Kucharik et al, 2006). At

Harvard Forest, TEM-Hydro slightly under-estimates the uptake of carbon during

summer, which is compensated by less release of carbon during winter in most cases.

However, our largest biases are the NEPs at Walker Branch and Willow Creek where

TEM-Hydro under-estimate the EC NEP by 69% and 63% respectively (Fig 5; Table 5).

This significant difference between the modeled and EC NEP is likely due to

underestimation of night time and winter respiration at Walker Branch (Hanson et al,

2004). Although Walker Branch and Harvard Forest have similar stand ages and climate,

and comparable carbon stocks (Schaefer et al, 2006), EC estimates show that Walker

Branch has a significantly higher carbon sink. Several studies at Walker Branch

Watershed have shown that EC measurements significantly underestimate the NEP at

night and during the winter (Baldocchi and Meyers, 1998; Baldocchi et al, 2000b;

Schaefer et al, 2006). The night time bias results from fairly sloping terrain where stable

night time condition allows low turbulence (Massman and Lee, 2002) and causes the air

to sink downhill, which is undetected by the tower sensor kept at a certain height above

the canopy.
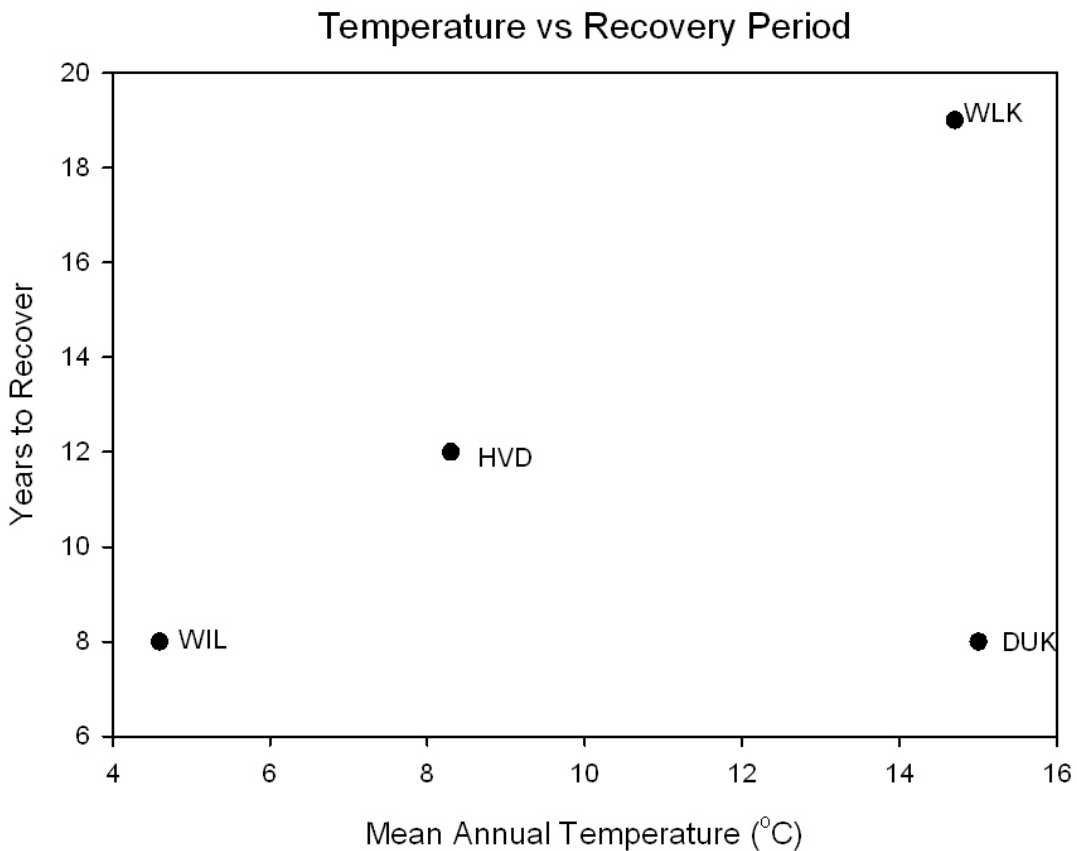
Figure 10. Comparison of Temperature and pace of recovery for all sites. The pace of recovery is slower in warmer sites due to increased heterotrophic respiration and increased organic matter input to the soil immediately following disturbance.

The modeled NEP at Walker Branch and Willow Creek are much closer to the biometric

values than the EC NEP. While the biometric and EC NEP at Harvard Forest matches

well with each other, the biometric NEP at Walker Branch and Willow Creek are less than the EC NEP by 500 and 114 g C m^{-2} yr^{-1} respectively. Similarly, biometric NEP at Duke Forest is higher than EC NEP by 169 g C m^{-2} yr^{-1}.
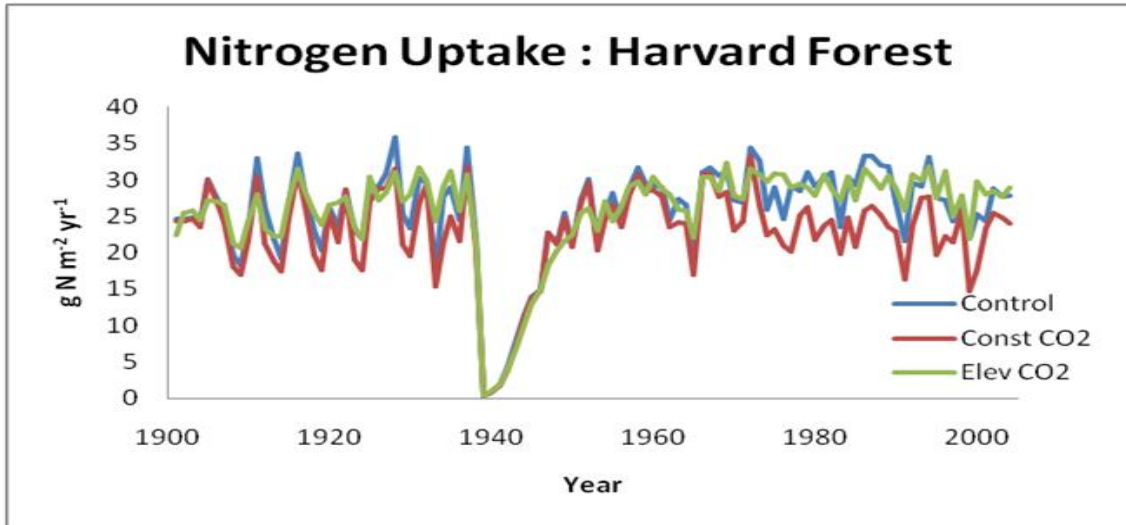
Figure 11. Time series of plant nitrogen uptake at Harvard Forest. Nitrogen uptake decreases following disturbance but recovers quickly within 5-7 years for all sites. While elevated CO_2 allocates more carbon to roots allowing increased nitrogen uptake at Harvard Forest, Duke Forest, and Walker Branch, it decreases nitrogen uptake at Willow Creek. The plant nitrogen uptake at Duke Forest, Willow Creek, and Walker Branch are given in appendix III.

Differences in NEP between biometric and EC measurements at Willow Creek are due to different periods of data collection and uncertainties associated with the two methods (Curtis et al. 2002). Cook et al. (2004), in his study over Northern Wisconsin, found that Willow Creek NEP obtained from biometric measurement was 44% less than the EC measurements. While Curtis et al. (2002), in his study of 4 North American deciduous forests, observed that biometric measurements differ from EC estimates by 35-325 g C m^{-2} yr^{-1}, Barford et al. (2001) found good agreement with a 10 year comparison of the EC and biometric measurements in her study carried out at Harvard Forest. However, the individual year comparison was poorly resolved due to lagged response of detritus input and environmental stress. The discrepancies associated with biometric and EC estimates

show no systematic pattern among sites resulting in over or underestimation of NEP. For instance, biometric measurements at Duke Forests are larger than EC NEP while Walker Branch biometric estimates are less.

4.3.Forests as a Carbon Sink

Studies have shown that growing forests are a greater sink of carbon compared to the mature forests (Goward et al, 2008; Gough et al, 2008; Amiro et al, 2010). In this study, we found that the ecosystem goes from a net source to a net sink following disturbance, after which annual carbon fluxes rise to a maximum, declining slowly with age. Thornton et al. (2002) have shown similar pattern of carbon fluxes in their modeling study carried out over several evergreen forests. The source-sink relationship explicitly depends on the amount of woody biomass added to the 1, 10, and 100 year product pool. For instance, at Harvard Forest, the largest source following disturbance is likely due to addition of large amount of living biomass to soil pools, while in case of Duke, Willow Creek, and Walker Branch, large amounts of living biomass are transferred to the 1, 10, and 100 year product pool. Chambers et al. (2007) found that 320 million large trees, corresponding to 0.09-0.11 peta grams of carbon, were transferred from live to dead pools as a result of Hurricane Katrina. Goward et al (2008) pointed out that it might take several decades for the pools to respire completely, after which the ecosystem starts to behave as a net carbon sink. Although Duke Forest and Willow Creek both are clear-cut, they exhibit differential rates of recovery. Immediately following disturbance, Willow Creek is a smaller carbon source than Duke Forest because Duke has a mean annual temperature four times higher than Willow Creek, allowing for higher rates of decomposition, which lengthens the recovery time at Duke Forest. Gough et al. (2008), in his study at the University of

Michigan Biological Station (UMBS), found that rising mean annual temperature in the growing season could reduce the existing forests mean annual carbon storage by 28% in 25 years. Several studies have pointed out the importance of climate on carbon storage and productivity of the forests (Franklin et al. 1991; He et al. 1999; Dale et al. 2000; Thornton et al. 2002).

4.4. Importance of Disturbance History

The recovery following disturbance primarily depends on the type of disturbance. For instance, hurricanes, agricultural abandonment, and clear cutting have different rates of organic matter input into the soil which might affect the net ecosystem fluxes. Amiro et al. (2010), in their recent studies in North America, found that the change in carbon flux after clear cut is relatively short term, with the greatest decrease in the year of disturbance, while such effects are long-lasting in the case of hurricanes, where availability of woody debris causes higher decomposition and increases the length of recovery. My studies at Harvard Forest show longer recovery time (12 years) than Duke Forest and Willow Creek. Walker Branch, which regenerates from agricultural abandonment, recovered well following the year after agricultural abandonment due to significantly less organic matter and higher nutrient content in the soil (Davidson and Ackermen 1993; Koernel et al. 1997). Harrison et al. (1995), using radiocarbon measurement, found that the turnover of carbon in an agricultural abandoned site was two times faster compared to the undisturbed soil. While forest soils may continue to reflect characteristics of ancient forest soils within 100 years after abandonment (Compton and Boone 2000; Flinn et al. 2005), Houghton et al. (1983) show that temperate forest soils recover to 90% within 50 years. Studies suggest that changes in vegetation biomass after

agricultural abandonment may be due to changes in soils or topography rather than land use history (Singleton et al. 2001).

4.5. Disturbance and Elevated CO_2 Effect on Nitrogen Uptake

Temperate forests are thought to be nitrogen limited. Studies have shown decreased nitrogen uptake for 2 to several years following disturbance (Marks 1974; Boring et al. 1981) and increased nitrogen mineralization (Matson and Vitousek 1981; Matson and Boone 1984). Nitrogen uptake decreases following disturbance for all sites and recovers quickly within 5-7 years. Compton and Boone (2000), in their studies of New England forests, have shown that accelerated nitrogen mineralization makes more nitrogen available for plant use, which might lead to increased nitrogen uptake. While increased nitrogen mineralization after disturbance reduces plant nitrogen demand (Thornton et al. 2002), nitrogen mineralization and nitrogen uptake are unpredictable prior to disturbance (Vitousek and Melillo 1979).

Elevated CO_2 affects the nitrogen cycling of the terrestrial ecosystem with significant changes in net nitrogen mineralization, nitrogen uptake, and leaching. Under elevated CO_2, plant nitrogen uptake have been found to increase due to increases in fine root production, allowing trees to take in more available nitrogen from the soil pool (Holmes et al. 2003; Liberloo et al. 2006). Increases in plant nitrogen uptake under elevated CO_2 at Harvard, Duke, and Walker Branch is primarily due to increased net nitrogen mineralization and fine root production (Parrent et al. 2006; Phillips 2007). However, elevated CO_2 causes less nitrogen uptake at Willow Creek due to decreased nitrogen mineralization, making it more nitrogen use efficient than the other sites. Finzi et al.

(2006) have shown that rapid rates of nitrogen immobilization decrease nitrogen mineralization, resulting in less nitrogen uptake under elevated CO_2.

It is important to use the correct land use history to simulate the carbon fluxes at particular sites (Foster et al, 2003). Many modeling studies don't take into account the disturbance history partly due to unavailability of detailed disturbance records from events such as hurricanes, fire, logging, and wind (Gough et al, 2008). However, Hurtt et al. (2006) have produced gridded data sets with detailed disturbance record for the past three centuries. In the Eastern U.S., terrestrial ecosystems have experienced widespread deforestation that occurred through the early 20th century (Birdsey et al. 2006). Gough et al. (2008) have shown that forest stands that have been clear cut and burned twice store less carbon than those disturbed once due to decreased site productivity. This study shows that disturbed recovering terrestrial ecosystems are a greater sink of carbon compared to fully mature forests, when past disturbance is taken into account (Fig 7; Fig 8; Table 4).

5. Conclusions

In this study, we use the TEM-Hydro model to determine how disturbances such as hurricanes, logging, and agricultural abandonment affect the net carbon sequestration over specific eddy covariance sites in the U.S. eastern temperate forests for different climate zones. While these disturbances, along with local climate, have different effects on the carbon and nitrogen dynamics of the vegetation and soil, the net effect of disturbance is to decrease the rate of carbon sequestration immediately following stand replacement, followed by a longer period of carbon sink. As these regrowing forests

approach maturity, the influence of past land use on carbon sequestration diminishes and other factors become more important. The model output suggests that recovery rates depend on the nature of disturbance, with important secondary effects of temperature.

A full understanding of the dynamics of carbon sequestration requires knowledge of prior land use and human activity as nearly all ecosystems have been subjected to change by humans (Foster et al. 2003; Chen et al. 2004; Pregitzer and Euskirchen 2004; Magnani et al. 2007). Since temperate forests are considered to be a significant sink of carbon, it is crucial to take into account the disturbance history of the site in order to simulate the accurate carbon and nitrogen stocks and fluxes. Most modeling studies carry out simulations with potential vegetation, which may underestimate the amount of carbon stored by terrestrial ecosystem. Carbon storage in terrestrial ecosystems may continue to increase as a result of CO_2 fertilization until saturation levels are reached, if no other resources limit forest growth (Norby et al. 2005).

Nitrogen deposition may have significant effects over the global carbon storage during the 21st century. The magnitude of nitrogen fertilization in the eastern US is debatable due to uncertainties in estimating the distribution of added nitrogen among wood, non-woody biomass, soil, and leachate (DeVries et al, 2006; Jenkinson et al, 1999; Nadelhoffer et al, 1999; Sievering, 1999). While TEM-Hydro does not account for nitrogen deposition from the atmosphere I found that all sites show increased nitrogen mineralization and decreased nitrogen uptake immediately after disturbance followed by enhanced nitrogen uptake. Elevated CO_2 increases carbon allocation to roots in case of Harvard Forest, Duke Forest, and Waker Branch, allowing enhanced nitrogen uptake as

long as other factors are not limiting. Plants may respond to decreased nitrogen uptake by becoming more nitrogen efficient, as happens at Willow Creek.

In this paper, I use EC data from US eastern temperate forest sites to improve our understanding of hydrology, phenology, and carbon-nitrogen dynamics in the temperate forests. I have explored how carbon and water fluxes from EC sites can be used to calibrate and validate biogeochemical models over a wide range of environmental conditions in the US eastern temperate forests. Future work on adding a nitrogen deposition and multi-layer soil decomposition pool is important to explore the effects of nitrogen deposition and soil respiration on carbon sequestration.

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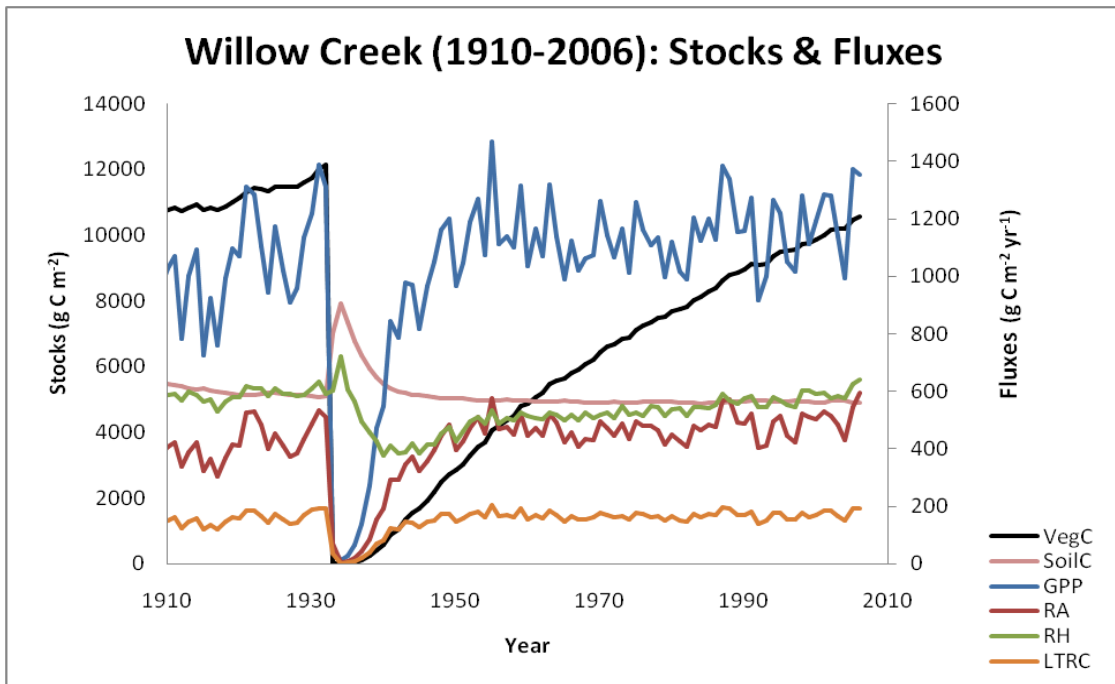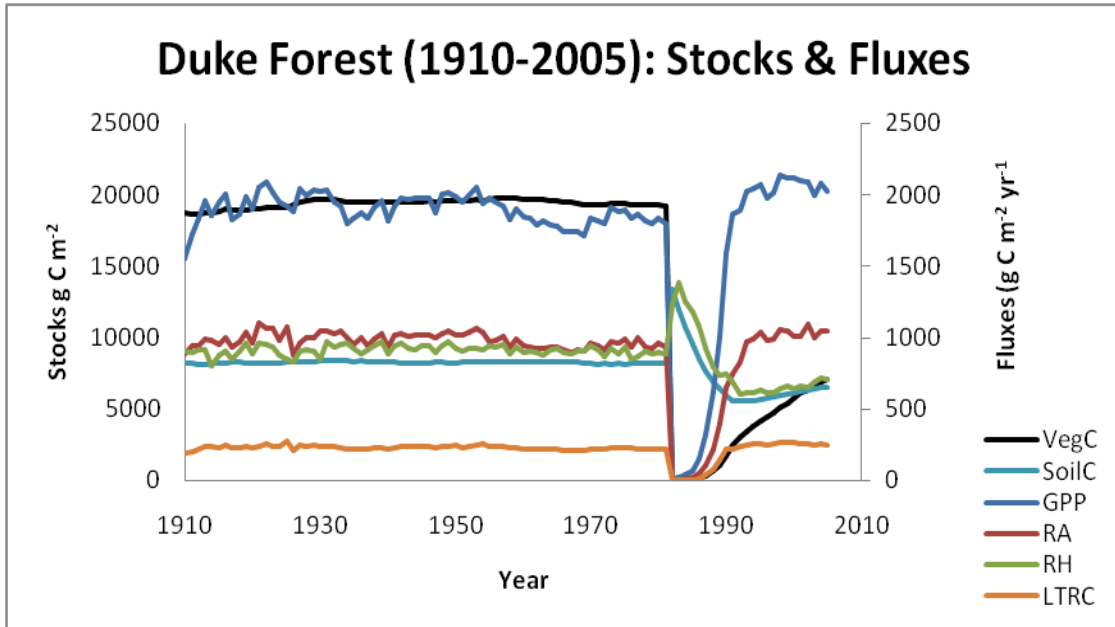 Experiments". *Ecological Applications* 13: 1508-1514.

Appendix I

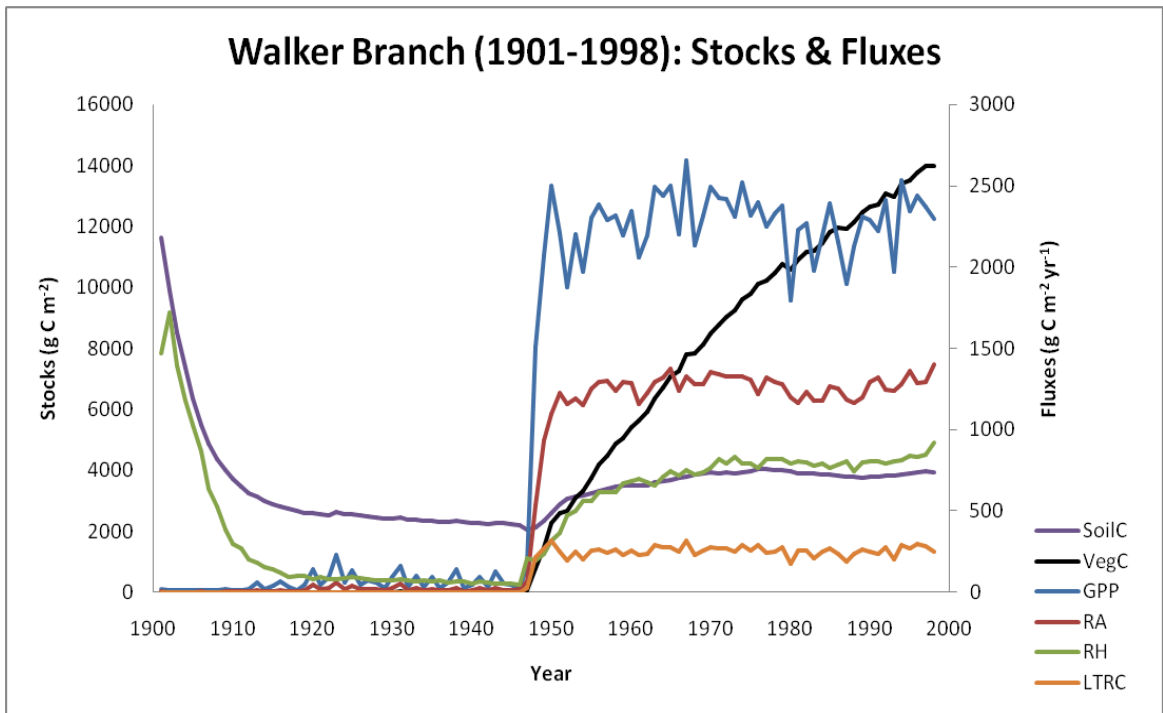### Harvard Forest (Temperate Coniferous)

Variable	Value	Units	Source
VEGC	10800	$gC\,m^{-2}$	based on McClaugherty et al. (1982), Pastor et al. (1984), and K.J. Nadelhoffer (unpublished data, 1991)
SOILC	8290	$gC\,m^{-2}$	based on Gaudinski et al. (2000) – all carbon above bottom of BW1 horizon
SOILN	414.5	$gN\,m^{-2}$	assume soil C:N ratio of 20
AVALN	1.9	$gN\,m^{-2}$	based on Vitousek et al. (1982)
NPP	600	$gC\,m^{-2}\,yr^{-1}$	based on McClaugherty et al. (1982), Pastor et al. (1984), and K.J. Nadelhoffer (unpublished data, 1991)
GPP	1130	$gC\,m^{-2}\,yr^{-1}$	based on Waring et al. (1998)
NPPSAT	750	$gC\,m^{-2}\,yr^{-1}$	assume N saturation effect is 25%
NUPTAKE	8.9	$gN\,m^{-2}\,yr^{-1}$	based on Figure 2 of Aber et al. (1983) – assume N up = N min.
τ(leaf)	2	yr	Kucharik et al. (2000)
τ(stem) – sapwood	10	yr	estimated**
τ(root)	1	yr	Kucharik et al. (2000)
CNleaf	47.5	$gC\,gN^{-1}$	Magill et al. (1997) – estimated from figure 1
CNstem	500	$gC\,gN^{-1}$	estimated**
CNroot	57.7	$gC\,gN^{-1}$	McClaugherty et al. (1982)
CNleafltr	48.8	$gC\,gN^{-1}$	calculated to balance N cycle
pleafc	0.42		same as for NPP
pstemc	0.25		same as for NPP
prootc	0.33		same as for NPP
fstemlive	0.07		Friend et al. (1997)
yrEET	569	mm	Internet website: http://intranet.lternet.edu/archives/documents/Publications/climdes/siteclim.toc.html

Harvard Forest (Temperate Deciduous)

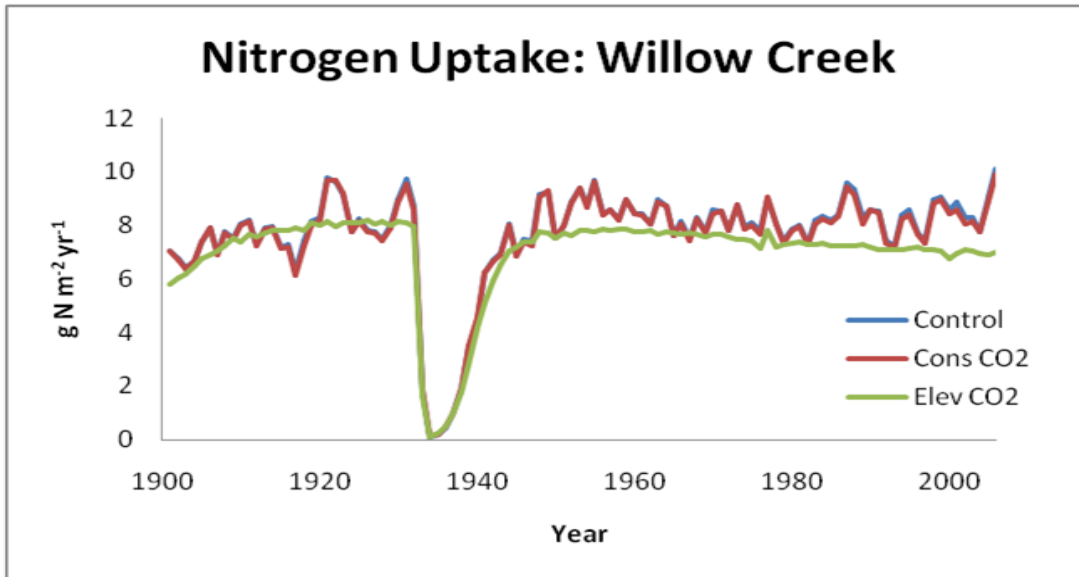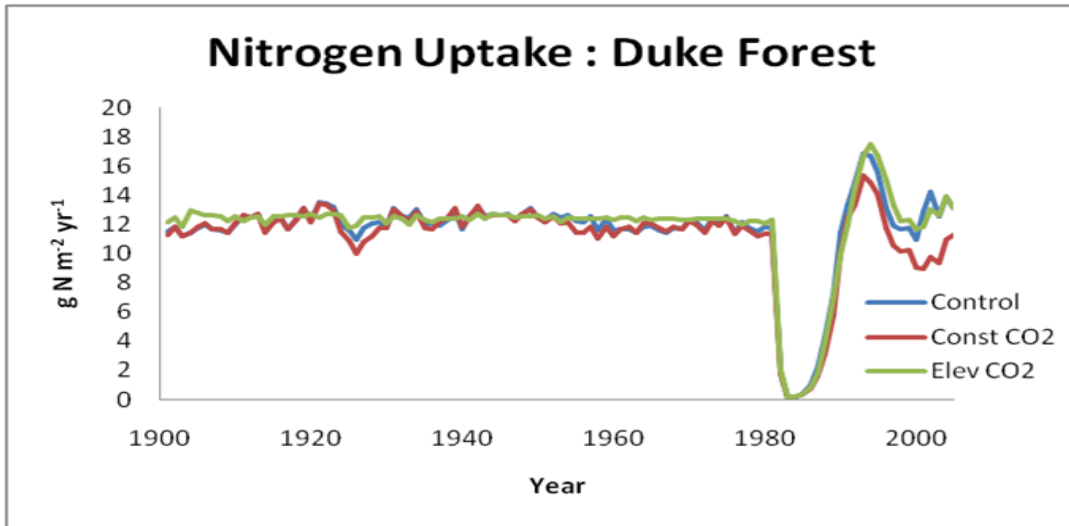| Variable	Value	Units	Source
VEGC	17440	$gC\,m^{-2}$	based on McClaugherty et al. (1982), Pastor et al. (1984), and K.J. Nadelhoffer (unpublished data, 1991)
SOILC	8290	$gC\,m^{-2}$	based on Gaudinski et al. (2000) – all carbon above bottom of BW1 horizon
SOILN	414.5	$gN\,m^{-2}$	assume soil C:N ratio of 20
AVALN	2.2	$gN\,m^{-2}$	based on Vitousek et al. (1982)
NPP	730	$gC\,m^{-2}\,yr^{-1}$	based on McClaugherty et al. (1982), Pastor et al. (1984), and K.J. Nadelhoffer (unpublished data, 1991)
GPP	1380	$gC\,m^{-2}\,yr^{-1}$	based on Waring et al. (1998)
NPPSAT	912.5	$gC\,m^{-2}\,yr^{-1}$	assume N saturation effect is 25%
NUPTAKE	10.3	$gN\,m^{-2}\,yr^{-1}$	based on Figure 2 of Aber et al. (1983) – assume N up = N min.
τ(leaf)	1	yr	Kucharik et al. (2000)
τ(stem) – sapwood	10	yr	estimated**
τ(root)	1	yr	Kucharik et al. (2000)
CNleaf	23.8	$gC\,gN^{-1}$	Magill et al. (1997) – estimated from figure 1
CNstem	300	$gC\,gN^{-1}$	estimated**
CNroot	44.6	$gC\,gN^{-1}$	McClaugherty et al. (1982)
CNleafltr	57.3	$gC\,gN^{-1}$	calculated to balance N cycle
pleafc	0.29		same as for NPP
pstemc	0.36		same as for NPP
prootc	0.35		same as for NPP
fstemlive	0.17		Friend et al. (1997)
yrEET	569	mm	Lternet website: http://intranet.lternet.edu/archives/documents/Publications/climdes/siteclim.toc.html

Appendix II

Duke Forest (1910-2005): Stocks & Fluxes

Willow Creek (1910-2006): Stocks & Fluxes

Walker Branch (1901-1998): Stocks & Fluxes

Appendix III

Nitrogen Uptake : Duke Forest

Nitrogen Uptake: Willow Creek

Nitrogen Uptake : Walker Branch
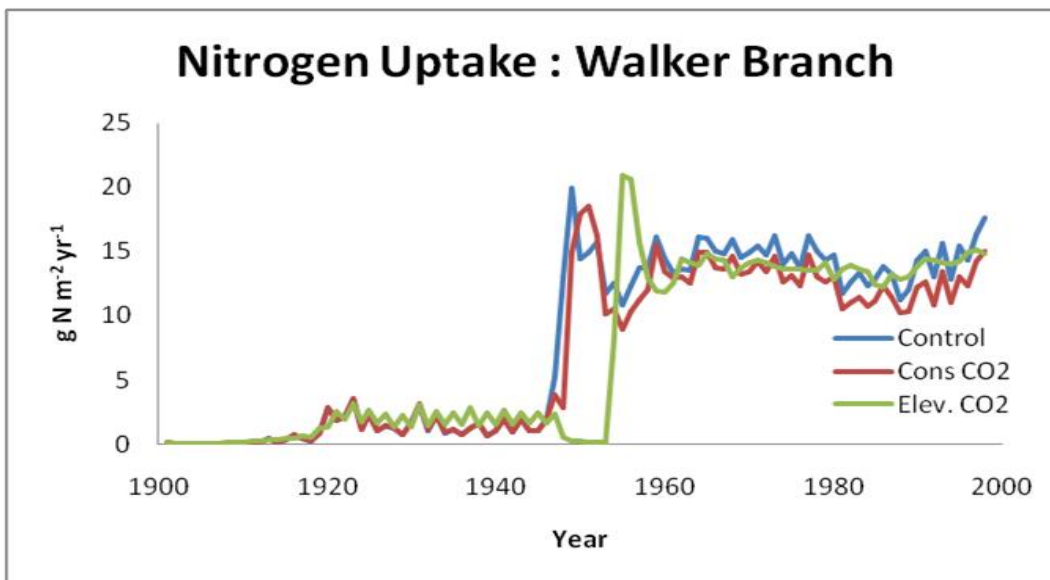
<p style="text-align:center">**Curriculum Vitae**</p>

Shree Ram Sharma Dangal

shreeram.iof@gmail.com

shreerams@lehigh.edu

Qualifications

Academic   **M.S. in Earth and Environmental Sciences**

2nd Year student (Expected Graduation: 2011 May)

Lehigh University, Bethlehem, PA-18015

Bachelor of Science in Forestry (B.Sc Forestry)

Passed in 2008 (80.93% with honors)

Institute of Forestry, Hetauda Campus, Hetauda

Tribhuvan University, Nepal

Awards and Honors

- ❖ Graduate Research Fellowship, Department of Earth and Environmental Science, Lehigh University, Bethlehem, PA

- ❖ Mahendra Vidya Bhusan Award, Tribhuvan University, Nepal for attaining first position in the faculty of forest science.

- ❖ Certificate of appreciation, Free Student Union, Institute of Forestry, Hetauda

- ❖ Best Student award, Forester's association, Kathmandu, Nepal.

Professional Experience

❖ **Researcher cum Student** at Institute of Forestry, Tribhuvan University. (2006/2007 A.D.)

❖ **Extentionist** at Environment for Life (EnFoL) (2003/2004 A.D.)

Professional Membership

❖ Member of "**American Goephysical Union"**, Washington DC, United States

❖ Member of "**Nepal Forestor's Association**", Babarmahal, Kathmandu, Nepal.

❖ Life Member of "**Forestor's Initiation for Bio-diversity Conservation**", Makwanpur, Nepal

❖ Member of "**Group Initiation for Forest Technology**", Makwanpur, Nepal.

Personal details and Contacts

ADDRESS : - JORPATI VDC, KATHMANDU, NEPAL

BIRTH PLACE : - RAGHOPUR VDC-1, SIRAHA

DATE OF BIRTH : - APRIL 22, 1982 (A.D)

SEX : - MALE

LANGUAGES PROFICENCY : - NEPALI, ENGLISH AND HINDI