HYDROLOGY AND MANAGEMENT OF FORESTED WETLANDS

Proceedings of the International Conference

April 8-12, 2006 • New Bern, North Carolina

ASABE

Weyerhaeuser

FOREST SERVICE U S DEPARTMENT OF AGRICULTURE

Ge Sun
4-10-06

Hydrology and Management of Forested Wetlands

Proceedings of the
International Conference
8-12 April, 2006
New Bern Riverfront Convention Center
New Bern, North Carolina

Published by

American Society of Agricultural and
Biological Engineers (ASABE)
2950 Niles Road, St. Joseph Michigan 49085-9659 USA
www.asabe.org

Library of Congress Card Number (LCCN) 2006922954

International Standard Book Number (ISBN) 1-892769-53-0

ASABE Publication 701P0406

54

53-0

ıeers is not
neetings or
ndividual to
a whole.

Sponsors and Endorsing Organizations

Sponsored By

American Society of
Agricultural and Biological Engineers

Weyerhaeuser

Endorsing Organizations

American Society of Agronomy
American Water Resources Association
Crop Science Society of America
Duke University Wetland Center
International Peat Society
International Union of Forest Research Organizations (IUFRO) Forest Hydrology Working Group
North Carolina State University
Soil Science Society of America
USDA-Natural Resources Conservation Service

Planning Committee

Dr. Devendra Amatya, Forest Service – Co-Chair
Dr. Jami Nettles, Weyerhaeuser Company – Co-Chair
Dr. Wayne Skaggs, North Carolina State University
Dr. Peter Farnum, Weyerhaeuser Company
Dr. John Parsons, North Carolina State University
Dr. Tom Williams, Clemson University
Dr. Curtis Richardson, Duke University
Dr. Robert Evans, North Carolina State University
Dr. Ge Sun, Forest Service
Dr. Roy Sidle, DPRI Japan
Dr. Vicki Tatum, NCASI, Inc.
Dr. George Chescheir, North Carolina State University
Dr. Jim Gregory, North Carolina State University
Ms. Sharon McKnight, ASABE

This international c
management of for
discussions with D
Weyerhaeuser Cor
Charleston, South
planners, land mar
discuss relevant is
20 years of collab
site in North Caro

The conference p
topics including v
and water quality
effects, and sustai
renowned schola
current understan

We would like to
Southern Resear
endorsed this co
who contributed
whom it would r
session, speaker
associated comn
been working h

A special word
colleagues at N
has added so m

It was a privile
hope this confe
regarding the s

Devendra M A
Conference Co
Center for For
USDA Forest

Jami Nettles
Conference C
Southern Hyd
Weyerhaeuser

PREFACE

This international conference is a first-of-its kind specialty conference focused on hydrology and management of forested wetlands. The idea of this conference was conceived in May 2003 in discussions with Dr. Wayne Skaggs of North Carolina State University and Dr. Peter Farnum of Weyerhaeuser Company at the USDA Forest Service Center for Forested Wetlands Research in Charleston, South Carolina. This conference brings together scientists, engineers, researchers, planners, land managers, and decision makers to exchange the latest research findings and discuss relevant issues concerning forested wetlands. It also provides an opportunity to celebrate 20 years of collaborative forest hydrology and management research at Weyerhaeuser's Carteret site in North Carolina.

The conference participants have an opportunity to learn from presentations on a broad range of topics including wetland hydrologic processes, biogeochemical cycling and transport, hydrology and water quality, restoration and BMPS, monitoring and modeling, land use, climate change effects, and sustainable management. Many of the sessions have been assembled by world renowned scholars, and these 59 oral and 36 poster presentations will add significantly to our current understanding and management of this important ecosystem.

We would like to acknowledge ASABE, Weyerhaeuser Company, and the USDA Forest Service Southern Research Station for cosponsoring the conference, and also all other agencies who endorsed this conference. Most importantly, we would like to sincerely thank all those authors who contributed their important works for this wetlands conference and all participants without whom it would not have been a success. Thanks are also due to all invited guests of the plenary session, speakers, session moderators, invited panelists, members of the conference planning and associated committees, volunteers, and the ASABE and Weyerhaeuser Company staff who have been working hard for the success of this conference.

A special word of acknowledgement goes to Dr. Wayne Skaggs, Dr. Wendell Gilliam, and their colleagues at North Carolina State University for their great vision and research direction that has added so much to the field of forested wetlands.

It was a privilege to serve as chairmen of this unique international specialty conference. We hope this conference can be a basis for planning future similar conferences focused on issues regarding the science and management of forested wetlands.

Devendra M Amatya
Conference Co-Chair
Center for Forested Wetlands Research
USDA Forest Service, Charleston, SC

Jami Nettles
Conference Co-Chair
Southern Hydrology Research
Weyerhaeuser Company, Columbus MS

's included a number of very rapid and large
tion during the first decade of operation.

›ility to map the water level results back to the
›us validation of the model. It reproduced a
he ability to map a flood modeled for any
ely independent event. In this case, flooding
l be used for validation.

a very large TIN. TIN creation also limited the
y shaped polygons in flooded areas. Such
ns more difficult, and certainly less elegant. It is
we consider the entire 550 km^2 floodplain. A
e LIDAR. For floodplain modeling, it is
ssible water levels. In the southeastern US that is
en corresponds to high water levels.

d by the South Carolina Public Service Authority
complete with topographic breaklines and
Inc. I would like to thank L. Wayne Inabinette,
collection of cross section data.

RENCES

etstone. 1985. Hydrology and its effects on
np National Monument, South Carolina. Water-
Columbia, SC. , U.S.Geological Survey

relationships of the Congaree Swamp National
son University, Department of Forest and Natural

stem. Available at
'software.htm. Accessed May 20, 2005

eological Survey Water-Supply Paper 2294
ame.txt#Region03. Accessed Sept 25, 2005

Carolina. Available at
arge/. Accessed May 10, 2005

SIMULATING THE BIOGEOCHEMICAL CYCLES IN CYPRESS WETLAND-PINE UPLAND ECOSYSTEMS AT A LANDSCAPE SCALE WITH THE WETLAND-DNDC MODEL

G. Sun[1], C. Li[2], C. C. Trettin[3], J. Lu[4], and S.G. McNulty[1]

ABSTRACT

A modeling framework (Wetland-DNDC) that describes forested wetland ecosystem processes has been developed and validated with data from North America and Europe. The model simulates forest photosynthesis, respiration, carbon allocation, and litter production, soil organic matter (SOM) turnover, trace gas emissions, and N leaching. Inputs required by Wetland-DNDC include daily meteorological data, forest type and age, soil properties (e.g., texture, initial SOM content, bulk density and pH), and forest management practices (e.g., harvest, thinning, fire, reforestation, drainage, wetland restoration etc.). For wetland applications, observed or modeled water table depth data are required to drive the soil redox potential dynamics. Wetland-DNDC runs at a daily time step, and produces daily and annual results of forest growth, net ecosystem C exchange, fluxes of CO_2, CH_4, N_2O, NO, N_2, and NH_3 emissions, and N leaching from the rooting zone. This study extended the original field-scale model to simulate the carbon, nitrogen, and water dynamics at the landscape scale by linking the biogeochemical processes to groundwater table dynamics predicted by the spatially explicit MIKE SHE hydrological model. Model testing and validation was performed with both hydrological data and carbon flux data from a 40 ha cypress wetland – slash pine flatwoods watershed (40 ha) in north central Florida. We found that pine plantations sequestered 167 tons C/year and cypress wetlands are weak carbon sources (i.e. 8 tons C/year) during averaged climatic conditions. However, a drought could turn the flatwoods system from a strong carbon sink to a carbon source. Pine uplands were sources of N_2O emission at the landscape scale (41 kg N_2O /year), and wetlands are sources of CH_4 emission (i.e. 2.5 tons CH_4/year). Wetlands reduced large amount of nitrites by denitrification, but nitrogen leaching into surface water is also common.

KEYWORDS. Wetlands, Hydrology, Biogeochemical Cycling, Modeling

[1] Southern Global Change Program, Southern Research Station, USDA Forest Service, 920 Main Campus Dr., Suite 300, Venture II, Raleigh, NC 27606, USA. Email: Ge_Sun@ncsu.edu; Phone: (919)5159498.

[2] Complex Systems Research Center, Institute for the Study of Earth, Ocean and Space, University of New Hampshire, Durham, New Hampshire 03824, USA.

[3] Center for Forested Wetlands Research, Southern Research Station, USDA Forest Service, Charleston, South Carolina 29414, USA.

[4] Department of Forestry and Environmental Resources, North Carolina State University, Raleigh, NC 27606, USA.

INTRODUCTION

About half of wetland areas of 20.5 million ha in the United States are forested (Dahl, 2000). Forested wetlands have been widely valued beyond their roles in providing clean water, wildlife habitat, and timber. Globally, wetlands cover about 5% of the land surfaces (Eswarn et al., 1995), but contain 15-22% of total terrestrial carbon and contribute 15-20% of total emission of methane, a powerful green house gas (Matthews and Fung, 1987). Wetlands are perceived as carbon, sulfur, and nitrogen sinks. Forested wetlands have relatively high net ecosystem primary productivity and store disproportionally more carbon than other landuses (Trettin and Jurgensen, 2003). As a unique type of ecosystem dominated by water, wetland biogeochemical processes are extremely dynamic and complex, and inherently vary both in time and space at a landscape scale. For example, a small change in water table depth due to either land topography or climate variations can result in completely different redox conditions and alter the rates of soil organic carbon decomposition, plant respiration and photosynthesis, CH_4 production and consumption, and N transformation and transport. Field experiments to examine the interactions of carbon, nitrogen, water, and climate and the fluxes are often expensive, and thus data are often incomplete for wetland ecosystems. A limited number of sites in the carbon and water flux network were established for wetlands (Clark et al., 1999). Multi-factorial experiments are often conducted in a controlled laboratory environment. It is largely unknown how future climate change, landuse change, and forest management will affect the delicate wetland biogeochemical cycling and associated ecological values at a landscape scale.

Limited studies on forest-atmosphere carbon exchange in wetlands in the southern U.S. suggested that cypress wetlands had highly contrasting daytime and nighttime carbon flux patterns when compared to nearby drier pine flatwoods ecosystems (Clark et al., 1999; 2004). On an annual basis, wetlands accumulated less carbon than pine uplands (Clark et al., 1999) mainly due to their lower photosynthesis rates, higher respiration rates and short growing season. Methane emission from pine flatwoods was highly controlled by site hydrology and soil moisture that can be altered by forest management practices (e.g. bedding, tree harvesting) and climate variability. Castro et al., (2000) suspected that the coastal plain region might be a significant CH_4 source under certain climatic and plantation management regimes. They called for an in-depth study of the interactions between climate, soil moisture, and soil microbial dynamics (Castro et al., 2000). Individual carbon flux study such as on soil respiration processes in pine flatwoods was also available (Fang et al., 1998).

Computer simulation models are simplifications of the real world. They provide tools for examining complex ecosystem processes such as the biogeochemical cycling in wetlands. Several advantages of mathematical models are recognized: 1) Models are synthesis tools that integrate data collected for individual processes and functional relations using a systems approach. Such an approach for data synthesis is often helpful for identifying deficiencies in field data measurements and knowledge about the interactions of various processes. 2) Models are useful for testing hypotheses. Our understanding of the internal relationships of ecosystem processes are incomplete although we may have sufficient measurements of 'end products' such as discharge amount and its concentrations at the watershed outlets and state variables such carbon or water storage in soils. Hypotheses can be tested by linking the ecosystem processes using mathematical equations and by validating the model performances with certain measurable 'end products'. 3) Models are prediction tools. Once a model is properly validated against a wide range of measurements, it becomes a powerful tool to test the sensitivity to ecosystem model parameters or input variables to answer 'what if' type of management questions.

Large numbers of biogeochemical models at different scales has emerged in the past two decades due to the advances of information technology and wetland sciences. However, few comprehensive models are available to fully describe forested wetlands ecosystems. A review of 12 widely used carbon models suggested that most of the existing models do not allow for anaerobic conditions, do not explicitly simulate wetland hydrology, and can not track daily biogeochemical dynamics (Trettin et al., 2001). Efforts have been devoted to develop a new integrated modeling framework that simulates wetland carbon, nitrogen, and water cycles at a

finer temporal scale (i.e. daily) for applicati
Zhang et al., 2002; Li et al., 2003; Cui et al.
with site-level data (i.e. forest productivity,
climate zones for both upland and wetland
al., 2002) and Europe (Li et al., 2000; Butte

The objectives of this study were to: 1) link
distributed groundwater table depths simula
system to a watershed with both upland and
of biogeochemical fluxes, and 3) examine h
fluxes in pine flatwoods at multiple spatial s

Wetland-DNDC model

The Wetland-DNDC model was a modified
originally designed for simulating C and N
forest ecosystems (Li et al., 2000) (Fig. 1).
(DeComposition and DeNitrification) model
features of the DNDC family of models, but
describe the groundwater table controls on r
decomposition, CH_4 production and consum
anaerobic conditions (Zhang et al., 2002; Li

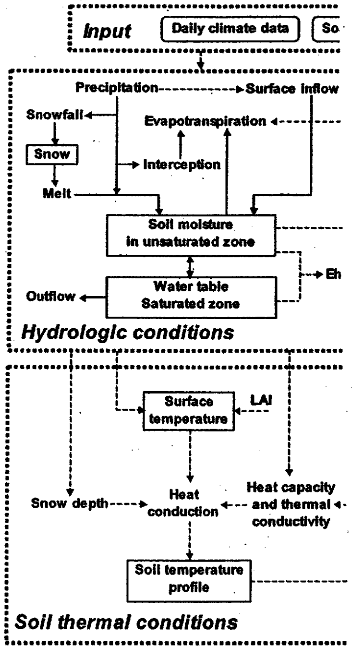

Figure 1. Framework of the Wetland-DNDC
groundwater hydrology, plant growth and product
factors (from Zhang et al., 2002). GPP=Gross P
LAI=L

finer temporal scale (i.e. daily) for application at landscape to regional scale (Trettin et al., 2001; Zhang et al., 2002; Li et al., 2003; Cui et al., 2005). The modeling framework has been tested with site-level data (i.e. forest productivity, carbon eddy flux, CH_4) in temperate and subtropical climate zones for both upland and wetland ecosystems in North America (Li et al., 1992; Zhang et al., 2002) and Europe (Li et al., 2000; Butterbach-Bahl et al., 2004; Kesik et al., 2005).

The objectives of this study were to: 1) link the field-scale Wetland-DNDC model with spatially distributed groundwater table depths simulated by hydrologic model; 2) apply the linked modeling system to a watershed with both upland and wetland components to map the spatial heterogeneity of biogeochemical fluxes, and 3) examine how climate variability affects the biogeochemical fluxes in pine flatwoods at multiple spatial scales.

METHODS

Wetland-DNDC model

The Wetland-DNDC model was a modified version of the PnET-N-DNDC model that was originally designed for simulating C and N dynamics including trace gas emissions in upland forest ecosystems (Li et al., 2000) (Fig. 1). The PnET-N-DC model was a variant of the DNDC (DeComposition and DeNitrification) model family. The Wetland-DNDC model inherited many features of the DNDC family of models, but significant improvements have been made to better describe the groundwater table controls on redox potential, soil temperature, carbon fixation and decomposition, CH_4 production and consumption, and other biogeochemical processes under anaerobic conditions (Zhang et al., 2002; Li et al., 2003; Cui et al., 2005).

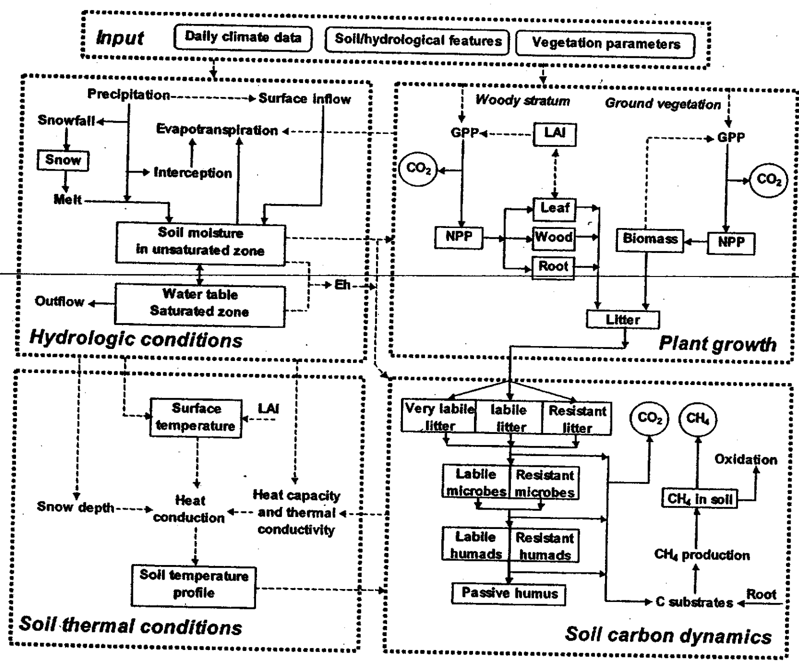

Figure 1. Framework of the Wetland-DNDC modeling system showing the intimate interactions of groundwater hydrology, plant growth and production, soil biogeochemical cycling, and other environmental factors (from Zhang et al., 2002). GPP=Gross Primary Productivity; NPP = Net Primary Productivity; LAI=Leaf Area Index.

The Wetland-DNDC model consists of four major components including: wetland hydrology, soil thermal conditions, forest overstory and understory including mosses and herbaceous, soil carbon and nitrogen dynamics (Zhang et al., 2002). All four of these components interact closely at a daily time interval. The outputs from the model include almost all carbon and nitrogen pools and fluxes in a forested ecosystem. Examples are net ecosystem primary productivity (NPP), net ecosystem exchange of CO_2, soil and plant carbon storage, soil and plant respiration, CH_4 emission, N_2O emission, NO_3 and NH_4 concentration in soils and leaching from the rooting zone.

Wetland hydroperiod is a key variable that drives the entire biogeochemical processes. The Wetland-DNDC model has the options of accepting external inputs or estimating hydroperiod by an empirical submodel for this variable (Zhang et al., 2002). In this study, we employed a physically based hydrologic model MIKE SHE (DHI, 2004) to provide spatially distributed water table depths. The MIKE SHE model will be described later.

The Wetland-DNDC model simulates growth and productivity of both overstory and ground vegetation. Tree growth and carbon allocations were modeled by the algorithms described in the PnET model (Aber and Federer, 1992). Growth, litter production, and respiration of mosses and herbaceous plants under the forest canopy were modeled by the SPAM model (Frolking et al., 1996).

Soil thermal conditions for different soil layers are modeled within the Wetland-DNDC model using a vertical one-dimensional heat conduction equation. Soil moisture content, organic matter content, snow pack, and leaf area index all have influences on the heat transport and soil temperature distributions. Soil carbon pools and fluxes were closely related to redox potential. Redox potential is calculated as a function of oxygen concentration in the soil layers. An 'anerobic balloon' concept was introduced to track the reduction-oxidation reactions in the anaerobic and aerobic microsites in the soil. Based on the size of the 'balloon', or proportion of the soil under an anaerobic state, Wetland-DNDC allocates substrates (e.g. DOC, NO_3^-, NH_4^+) and estimates productions, consumptions, and emissions of N_2O, NO, N_2, CH_4. Details of the complex algorithms describing the biogeochemical interactions are found in Li et al., (1992, 2000, 2003), Zhang et al. (2002), and Cui et al. (2005).

MIKE SHE Hydrologic Model

As the first generation of spatially distributed hydrologic model, the MIKE SHE model simulates the full hydrologic cycle of a watershed across space and time, including spatial distribution of groundwater table depth, soil moisture content, and evapotranspiration (Abbot et al., 1986; DHI, 2004). The model simulates both surface and groundwater flows and their interactions, so the model is especially appropriate for wetland conditions. The infiltration processes are modeled using the Richard's equation or a simple wetland soil water balance equation. Saturated water flow in the subsurface is simulated by a 3-D groundwater flow model. The modeling package is user-friendly with an interface to Geographic Information Systems (GIS) (DHI, 2004). A major advantage of this model is its window-based program and can directly use GIS database as model inputs for watershed topography, geology, soils, vegetation distributions, and climate variables. We have tested this model at selected forested watersheds across a physiographic gradient in the southern U.S. (Jianbiao Lu, personal communication).

Linking the Distributed Hydrology Model (MIKE SHE) with the Wetland-DNDC Model

We adopted a 'loosely coupled' approach in linking wetland hydrology and the biogeochemical processes. The main reason is that both the distributed hydrologic model and the biogeochemical model are extremely complex. A fully interactive integration is ideal, but it is not practical at this stage. This 'loosely coupled' approach entails two steps: 1) simulate the spatial distribution (30 m grid) daily groundwater table dynamics with MIKE SHE using the same soil and vegetation parameters in Wetland-DNDC. The output files of water table depth were used as inputs to the wetland-DNDC model; 2) run the Wetland-DNDC model for each of the grid cells delineated by the MIKE SHE model. Outputs of daily biogeochemical variables were presented in the same spatial resolution as the hydrology model.

Study Site

The study site selected for model testing was a flatwoods landscape that consists of cypress swamps and slash pine stands. The site was located 15 km northeast of Gainesville, Alachua County in north central Florida, USA. Plio-Pleistocene terrace deposits and the Hawthorne Formation dominate the geology. The flatwoods landscape had a small topographic relief ranging from 0 to 1.6%. Impermeable blue-green clays (> 4 m thick) below the sandy soil layers (2 - 3 m thick) separate the shallow ground water from the underlying secondary aquifer consisting of various materials. Approximately 30% of the research site (about 40 ha) was in cypress swamps dominated by pond cypress (*Taxodium ascendens* Brongn.), with wetland sizes ranging from a few square meters to more than 5 ha. The remaining 'upland' areas (~30 ha) were in a 29-year old mature slash pine (*Pinus elliottii* Engelm.) plantation. The average annual temperature in the region was 21°C, with a mean monthly low of 14°C in January and high of 27°C in July. Average annual rainfall was about 1330 mm, with dry periods during the spring and the fall. The study period covered a wet year in 1992 and a dry year of 1993 with 1995 and 1996 being normal. The relative topographic elevations were surveyed manually (Bliss and Comerford, 2002). The actual elevation of the study site was about 47 m above mean sea level.

In the early 1990s, extensive studies were conducted at the research site to examine how forest harvesting affected groundwater hydrology, ecosystem evapotranspiration, soil chemistry, plant regeneration, and wildlife habitats as part of the forested wetland research initiatives (Sun et al., 2000; Bliss and Comerford, 2002). Long-term (1991-1996) spatial groundwater table depth data were collected bi-weekly using over 140 1.5-m shallow wells (Bliss and Comerford, 2002). Three representative wetland systems and associated uplands were instrumented extensively for developing water balances and validating process-based hydrologic models (Sun et al., 2000).

RESULTS

Model validation

Both the MIKE SHE model and the Wetland-DNDC model were validated with field data measured at the research site as described above on hydrology and published reports on carbon from similar nearby pine flatwoods ecosystems (Clark et al., 1999; Clark et al., 2004; Castro et al., 2000). The MIKE SHE model was calibrated with data from 1992 and 1993 and validated with data in 1994-1996 at selected points and across the landscape by comparing simulated and measured groundwater table depths. In general, the model captured the seasonal fluctuation dynamics of groundwater table and matched groundwater table depth at most of the upland wells (Fig. 2.). The Nash-Sutcliffe coefficients (Nash and Sutcliffe, 1970) and correlation coefficient ranged from -1.23 to 0.69, and from 0.73 to 0.91, respectively, during the 3-year model validation period (1994-1996). The model tended to underestimate wetland water level when flooded (Fig 2.), probably due to the inadequate representation of land topography of this flat landscape although a manual 100*100 m^2 grid elevation survey was made prior to the study.

Net Ecosystem Exchange (NEE) defined as Gross Primary Productivity-Ecosystem Respiration is a measure to determine whether an ecosystem is a carbon sink or a carbon source. In general, simulated monthly NEE values compared well to measured by the eddy covariance flux study by Clark et al. (1999) (Fig. 3). The slash pine ecosystems had much higher NEE than the cypress ecosystem. The former was a carbon sink (positive NEE) year round, but the cypress swamp

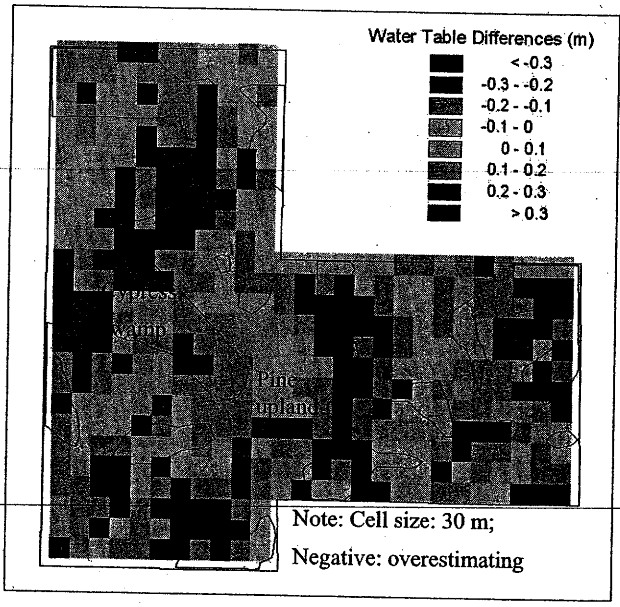

Figure 2. Differences between MIKE SHE simulated and measured water table level on October 29, 1992.

became a carbon source (negative NEE) during the fall, winter, and early spring when it was leafless and soil carbon decomposition was active. The model performed better for the pine uplands than for the wetlands, but under-predicted carbon gains were found for the winter months. The model could track the transition between a 'sink' (positive NEE) and a 'source' in the cypress wetlands. However, the model overestimated NEE in the summer months (June and July), but underestimated NEE in other seasons. On an annual basis, the slash pine forest (upland) was a strong sink of atmospheric carbon with a measured NEE of 7.4 t C/ha (modeled 6.72 t C/ha) while the cypress swamp (wetland) was a weaker sink with measured NEE at 0.84 t C/ha (modeled 0.65 t C/ha).

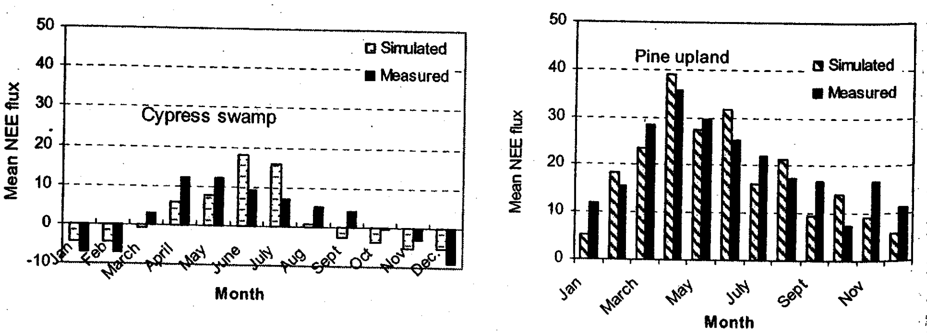

Figure 3. Comparing daily averaged NEE (kg/ha/day) by month between simulated and measured by the eddy covariance.

Model Application at the Landscape Scale

Spatial Distribution of Carbon flux

After the model was validated individually for the paired ecosystems of a cypress swamp and a pine upland stand, we applied the Wetland-DNDC simulation system to the pine flatwoods landscape. The landscape has a total area of 39-ha consisting 30 ha slash pine upland and 17 cypress swamps with a total area of about 9 ha (Fig. 2). The daily spatial distribution of groundwater table depths during 1992, a wet year, 1993 a dry year, and 1996, a normal year was first simulated by the MIKE SHE model at a 30 m by 30 m spatial resolution. Due to the spatial variability of hydrology and ecosystem characteristics, NEE distribution showed a large gradient at the landscape scale (Table 1; Fig 3). The entire watershed sequestered about 160 tons carbon, mostly in the upland area in a year with average precipitation (i.e. 1996). The total carbon emission as CH_4 was about 2.5 tons, mostly from cypress swamps. It is apparent that climate variability had large effects on both groundwater table fluctuations and carbon fluxes at the landscape scale (Table 1). A wet year would result in a large amount of CH_4 emission and a drought episode could turn a landscape that is normally a carbon sink to a carbon source. This phenomenon is largely controlled by a dramatic rise in decomposition and carbon emission rates in the wetland portion of the landscape during dry periods.

Table 1. Summary of simulated annual Net Ecosystem Exchange at the flatwoods research site.

Climate characteristics	Precipitation (mm)	Slash pine upland (t C year^{-1})	Cypress wetland (t C year^{-1})	Annual total (t C year^{-1})	Carbon Balance at : landscape
1992 (wet)	1553	157	–47	110	Sink
1993 (dry)	1104	77	–125	–48	Source
1996 (Normal)	1290	167	–8	159	Sink

Spatially, annual NEE ranged from almost neutral for the cypress wetland cells to as high as 8.0 ton C/ha/yr for pine uplands. It is important to note that the groundwater table depth had large impact on NEE distribution and CH_4 emission. This is true within the wetland or upland forest itself that has uniform stand characteristics (except topography) across the study area. An example of spatial distribution of simulated annual NEE and CH_4 emission for the normal climate year (1996) was presented in Fig. 3.

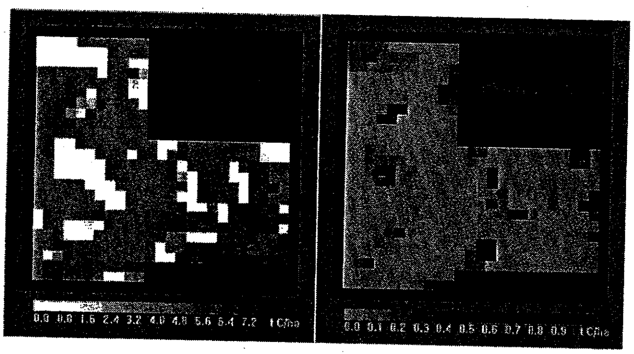

Figure 3. Simulated spatial distribution (30 m resolution) of net ecosystem exchange (left panel) and CH4 (right panel) emission at the landscape scale.

Spatial Distribution of N Flux

Similar to carbon fluxes, nitrogen emission in the form of trace gas N_2O was highly affected by the spatial distribution of groundwater table depth and vegetation characteristics. Cypress swamp were the major source of N_2O during the drought year (Table 2). Wetlands were also sources of N_2 emission. About a total of 356 kg nitrogen gas (N_2) was released to the atmosphere from the 9-ha wetlands in 1996 due to denitrification in wetland soils. The simulation results also suggested N leaching is mostly common in wetland soils and little N was lost below the rooting zone in the upland pine stands (Table 2).

Table 2. Summary of simulated annual N_2O emission and N leaching from the pine flatwoods site

Climate Characteristics	N_2O (Kg N year^{-1})			N leaching (Kg N year^{-1})		
	Slash pine	Cypress swamp	Total	Slash pine	Cypress swamp	Total
1992 (wet)	14	3	17	1	130	132
1993 (dry)	24	62	86	0	51	51
1996 (normal)	24	17	41	0	43	43

CONCLUSION

A modeling framework, Wetland-DNDC, was developed and tested with limited observation data (e.g. carbon) at the field and landscape scales. This modeling study demonstrated the important controls of wetland hydrology on the chemical fluxes at multiple spatial scales. Depending on climatic conditions (e.g. precipitation), the pine flatwoods ecosystems can be an either carbon sink or source. Modeling results had important implications regarding the roles of wetlands in contributing to carbon sequestrations and greenhouse gas emissions under global climate and landuse changes. We developed a research tool to guide future studies on how disturbances affect wetland biogeochemical balances.

The modeling system is also a management tool to assess potential management effects on wetland ecosystems (Li et al., 2003). Future studies are needed to validate the internal relationships and interactions of carbon and nitrogen in plants and soils under variable hydrologic conditions. Field data on CH_4 and N_2O emissions across multiple geographic and management gradients and scales are needed to improve the existing model. A tighter model coupling of groundwater hydrology and the biogeochemical cycling, and plant growth and productivity will enhance the feedback functions of the model. Finally, watershed-scale and regional scale data will be helpful for examining how the model responds to the spatial heterogeneity of climate, groundwater table depth, soil moisture, nutrient gradient, and plant community.

Acknowledgements

This study was supported by the Southern Global Change Program, USDA Forest Service, Raleigh, NC.

REFERENCES

1. Abbott, M.B., Bathurst, J.C., Cunge, J.A., O'Connell, P.E., and Rasmussen, J. 1986. An introduction to the European Hydrological System-Systeme Hydrologique Europeen, "SHE", 1. History and philosophy of a physically-based, distributed modeling system. *J. Hydrol* 87, 45-59

2. Aber, J.D. and C.A. Federer. 1992. A generalized, lumped-parameter model of photosynthesis, evaporation and net primary production in temperate and boreal forest ecosystems, *Oecologia, 92,* 463-474.

3. Bliss, (in a Fl
4. Buttert regiona process
5. Castro, on soil *Resear*
6. Clark, of slasl
7. Clark, control *Ecolog*
8. Cui, J., carbon 167.
9. Dahl, T U.S. D
10. DHI, 2
11. Eswara P. 27-4 CRC P
12. Fang, C variatic
13. Frolkin Crill, J, tempor 2: 343-
14. Kesik, L. Hor Simpso N_2O an
15. Li, C., of N2O 4369-4
16. Li, C., sequest *Manag*
17. Li, C., driven
18. Matthe distribu 1:61-86
19. Nash, J A discu
20. Sun, G. cypress

3. Bliss, C.M. and N.B. Comerford. 2002. Forest harvesting influence on water table dynamics in a Florida flatwoods landscape. *Soil Science Society of America Journal* 66(4): 1344–1349.

4. Butterbach-Bahl, K., M. Kesik, P. Miehle, H. Papen, and C. Li. 2004. Quantifying the regional source strength of N-trace gases across agricultural and forest ecosystems with process based models. *Plant and Soil* 260:311-329.

5. Castro, M. S., H. L. Gholz, K. L. Clark, and P. A. Steudler. 2000. Effects of forest harvesting on soil methane fluxes in Florida slash pine plantations, *Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere*, 30:10. 1534-1542.

6. Clark, K. L., H. L. Gholz, and M. S. Castro. 2004. Carbon dynamics along a chronosequence of slash pine plantations in north Florida, *Ecological Applications*, 14:4. 1154-1171.

7. Clark, K. L.;H. L. Gholz;J. B. Moncrieff;F. Cropley;H. W. Loescher. 1999. Environmental controls over net exchanges of carbon dioxide from contrasting Florida ecosystems, *Ecological Applications*, 9:3. 936.

8. Cui, J., C. Li, G. Sun, and C.C. Trettin. 2005. Linkage of MIKE SHE to Wetland-DNDC for carbon budgeting and anaerobic biogeochemistry simulation. *Biogeochemistry*, 72(2), 147-167.

9. Dahl, T.E. 2000. Status and Trends of Wetlands in the Conterminous United States 1986-1997. U.S. Department of Interior, Fish and Wildlife Service, Washinton, D.C.

10. DHI, 2004. *MIKE SHE User's Manual. Version 2004. DHI Water & Environment.*

11. Eswaran, H., E. Van den Berg, Reich, P., and J. Kimble. 1995. Global soil carbon resources. P. 27-43 In: R. Lal, J. Kimble, E. Levine, and B.A. Stewart (eds) Soils and Global Change. CRC Press, Boca Raton, FL.

12. Fang, C., J. B. Moncrieff, H.L. Gholz, and K.L. Clark. 1998. Soil CO2 efflux and its spatial variation in a Florida slash pine plantation, *Plant and Soil*, 205:2. 135.

13. Frolking, S., M. Goulden, S. Wofsy, S-M. Fan, D. Sutton, J. Munger, A. Bazzaz, B. Daube, P. Crill, J. Aber, L. Band, X. Wang, K. Savage, T. Moore, and R. Harriss. 1996. Modeling temporal variability in the carbon balance of a spruce/moss boreal forest. *Global Change Biol.* 2: 343-366.

14. Kesik, M., P. Ambus, R. Baritz, N. Brüggemann, K. Butterbach-Bahl, M. Damm, J. Duyzer, L. Horváth, R. Kiese, B. Kitzler, A. Leip C. Li, M. Pihlatie, K. Pilegaard, G. Seufert, D. Simpson, U. Skiba, G. Smiatek, T. Vesala, S. Zechmeister-Boltenstern, 2005. Inventories of N_2O and NO emissions from European forest soils (submitted to Biogeosciences).

15. Li, C., J. Aber, F. Stange, K. Butterbach-Bahl, and H. Papen, 2000. A process-oriented model of N2O and NO emissions from forest soils: 1, Model development, *J. Geophys. Res., 105,* 4369-4384.

16. Li, C., J. Cui, G. Sun, and C. Trettin. 2003. Modeling impacts of management on carbon sequestration and trace gas emissions in forested wetland ecosystems. *Environmental Management* 3:S176-S186.

17. Li, C., S. Frolking, and T.A. Frolking. 1992. A model of nitrous oxide evolution from soil driven by rainfall events: 1. model structure and sensitivity, *J. Geophys. Res., 97,* 9759 -9776.

18. Matthews, E., and I. Fung. 1987. Methane emission from natural wetlands: global distribution, area and environmental characteristics of sources. *Global Biogeochem. Cycles* 1:61-86.

19. Nash, J.E. and J.V. Sutcliffe. 1970. River flow forecasting through conceptual models. Part1 - A discussion of principles. *Journal of Hydrology* 10:282-290.

20. Sun, G., H. Riekerk, L.V. Kornak. 2000. Groundwater table rise after forest harvesting on cypress-pine flatwoods in Florida. *Wetlands* 20(1):101-112.

21. Trettin, C.C. and M.F. Jurgensen. 2003. Carbon cycling in wetland forest soils. Pg. 311-331, In: J. Kimble, R. Birdsie, R. Lal. *Carbon Sequestration in US Forests*. Lewis Publisher. Boca Raton, FL

22. Trettin, C.C., B. Song, M.F. Jurgensen, and C. Li. 2001. Existing soil carbon models do not apply to forested wetlands. Gen. Tech. Rep. SRS–46. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 10 p.

23. Zhang, Y., C. Li, Carl C. Trettin, H.Li, and G.Sun. 2002. An integrated model of soil, hydrology and vegetation for carbon dynamics in wetland ecosystems. *Global Biogeochemical Cycles* 16(4)1061.

SUSTAINABL
TIDAL B

In this paper, chron
Southwest coastal a
saline water and tida
drainage congestion
measurement and m
couple of years af
prominent. Rivers a
out of surface runo
environmental haza
rotational tidal basi
mitigation of longst
in nature. Redefiniti

Hydraulic modeling
and to assess its hy
rate. Modeling stud
management of tida
even for shorter p
volume. Lifetime of
maintenance it can
about 1.0 m sedimen

KEYWORDS: Draina
products, Reduction
management, Tidal

The Southwest regi
Bay of Bengal and
rivers, creeks, and l
flood water through
flood plain and be
resulting damage to
feasibility study wa
the Coastal Embank
and economic evalu

[1] Associate Specialist,
Referee, IWA-UK, E
Bangladesh, At pres
mnresj04@gmail.com