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FIELD EVALUATIONS OF A FORESTRY VERSION OF DRAINMOD-NII MODEL

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ABSTRACT This study evaluated the performance of the newly developed forestry version of DRAINMOD-NII model using a long term (21-year) data set collected from an artificially drained loblolly pine (*Pinus taeda L.*) plantation in eastern North Carolina, U.S.A. The model simulates the main hydrological and biogeochemical processes in drained forested lands. The model was calibrated using observed data during 1988-1997 and validated during 1998-2008. Predicted subsurface drainage, water table fluctuation, annual net primary production, leaf area index, and nitrate export were compared with measured values. Goodness-of-fit statistics include Nash-Sutcliffe coefficient (NSE), degree of agreement (d) and mean absolute error (MAE). Both annual and monthly drainage predictions were in very good agreement with measured values (NSE = 0.95, d = 0.95, and MAE = 53 mm yr^{-1} for yearly predictions and NSE = 0.91, d = 0.96 and MAE = 8.8 mm mo^{-1} for monthly predictions). Predicted daily water table depths closely followed observed values with goodness-of-fit statistics: NSE = 0.90, d = 0.96 and MAE = 0.10m. Predicted mean annual NPP was 18.7 t DM ha^{-1}, which was very close to estimated value of 18.6 t DM ha^{-1}. The goodness-of-fit statistics of the annual NPP predictions were: NSE =0.66, d = 0.78, and MAE =1.46 t $ha^{-1}yr^{-1}$. The model well predicted both the magnitude and dynamics of LAI. Predicted mean annual nitrate loss was 2.59±1.64kg ha^{-1}, which was very close to observed value of 2.64±1.50kg ha^{-1}. The goodness-of-fit statistics for predicted annual nitrate loss were: NSE = 0.88, MAE = 0.46kg ha^{-1} yr^{-1} and d = 0.93. The goodness-of-fit statistics for monthly nitrate export were: NSE = 0.76, MAE = 0.09 kg ha^{-1} $mo^{-1}$and d = 0.81, all of which indicated a good performance of the model in predicting monthly nitrate export. These overall accurate predictions clearly demonstrate the capabilities of the forestry version of DRAINMOD-N II as a model for simulating the hydrology, biogeochemistry, and forest growth for drained forested lands.

Keywords DRAINDMOD-NII, drainage, nitrogen dynamics, forest ecosystem modeling

INTRODUCTION A forestry version of DRAINMOD-NII model has been developed to predict water, carbon and nitrogen dynamics in artificially drained forested lands (Tian *et al*., 2009). The model links a forest growth module to the DRAINMOD hydrology model (Skaggs, 1978) and the DRAINMOD-NII carbon and nitrogen model (Youssef *et al*., 2005). The newly developed model needs to be tested before it can be applied to predict long term impacts of forest management practices on the hydrology and biogeochemical cycling in drained forested lands.

The objective of this paper was to evaluate the performance of the newly developed forestry version of DRAINMOD-NII model using a long term (21-year) data set collected from an artificially drained loblolly pine plantation in eastern North Carolina, U.S.A.

MATERIALS AND METHODS

Study site and data collection. The loblolly pine plantation is on a 24 ha watershed located in the Atlantic Lower Coastal Plain of North Carolina, U.S. (34^o 48' N, 76^o 42' W). The site is relatively flat (less than 0.1% slope) and has hydric soil (Deloss fine sandy loam, Thermic Typic Umbraquult). The watershed is drained by four 1.2 to 1.5 m deep parallel lateral ditches spaced 100 m apart. The loblolly pine trees were planted in 1974 at a density of 2100 trees ha^{-1}. The site underwent a pre-commercial thinning in 1981 (thinned to 988 trees ha^{-1}) and commercial thinning (thinned to 370 trees ha^{-1}) in late 1988 when the pine was about 14 years old and followed by a nitrogen fertilization (195 kg Urea-N ha^{-1}) applied in 1989. Since 1988, hydrological data including subsurface drainage and water table depth midway between the drains have been continuously collected. Climatological data including air temperature, relative humidity, wind speed and direction, solar and net radiation were measured on a half-hourly basis by an on-site weather station. Leaf area index (LAI) dynamics were continuously monitored using LI-COR LAI 2000 Plant Canopy Analyzer from 1991 to 2004. Other tree stage variables such as diameter at breast height (DBH) and height were also monitored each year. The annual increments in DBH were used to estimate annual net primary production using an empirical equation given by Hu and Wang (2008). Drainage water quality samples (both automatic water samples and manual grab samples) were collected at the outlet of the small watershed. The reader is referred to McCarthy *et al*. (1991) and Amatya *et al*. (1998, 2001) for a detailed description of the study site and experimental procedure.

Model description. A forestry version of DRAINMOD-NII has been developed to simulate carbon and nitrogen dynamics in drained forested lands under different climatic conditions and forest management practices (Tian *et al*., 2009). The new model simulates the main hydrological and biogeochemical processes in drained forested ecosystems. The forest growth component estimates net primary production (NPP) using radiation use efficiency methods and allocates fixed carbon using species dependent allometric relationships. It simulates the growth of mixed or uneven-aged stands by accounting for resource (water, nutrient, and light) competition among different species. It takes into account the effects of forest management practices such as thinning, pruning, harvesting and regenerating, fertilization, and prescribed burning on carbon and nitrogen cycling. It predicts stand variables such as LAI, DBH, and tree height. The module estimates nitrogen uptake based on nitrogen concentration of plant components and their biomass increment in each time step. Carbon loss through foliage litterfall is estimated as a function of leaf longevity, while fine root turnover is quantified based on fine root lifespan. Predicted litterfall and root turnover are inputs to the organic matter (OM) component of DRAINMOD-NII model, which updates OM pools on the forest floor and in the soil profile. Predicted LAI is a critical input for estimating hydrological processes such as rainfall interception and potential evapotranspiration (PET). Detailed description of the hydrological model of DRAINMOD is given by Skaggs (1978), McCarthy (1990), and Amatya et al. (2001). Readers are referred to Youssef (2003) and Youssef *et al*. (2005) for a detailed description of DRAINMOD-NII model.

Model calibration and validation. The model was first calibrated using measured hydrological and drainage water quality data during 1988- 1997, and then validated using observed data during 1998- 2008. Predicted drainage, water table depth and nitrogen export were compared to observed values. Nash-Sutcliffe coefficients (NSE), degree of agreements (d), and mean absolute error (MAE) were used as goodness-of-fit statistics to quantify the performance of the forestry version of DRAINMOD-NII. Hydrological parameters were mainly adapted from Amatya *et al*. (2001). Hydraulic conductivities and soil associated inputs were adjusted during the calibration of the hydrologic model DRAINMOD. Rate coefficients for C and N transformations were obtained from Youssef *et al*. (2006). Organic matter decomposition rates were adjusted during the calibration of the DRAINMOD-N II model.

RESULTS AND DISCUSSION

Hydrological predictions. Amatya *et al*. (2001) previously modeled hydrological processes for this site during 1988 to 1997 using DRAINLOB, a forestry version of the DRAINMOD hydrology model (McCarthy, 1990). The research of Amatya *et al*. (2001)demonstrated that DRAINMOD is capable of simulating the hydrological processes for drained forests. As part of developing the forestry version of DRAINMOD-N II model, we have modified the algorithms of the DRAINMOD hydrology that estimate rainfall interception and PET (Tian *et al*. 2009). Because of these modifications, we have included the hydrologic model in the evaluation process. The availability of longer term data set than the one used by Amatya et al., (2001) should provide a more robust calibration and validation of the hydrologic model DRAINMOD and consequently lead to more accurate predictions of the hydrological processes, which are extremely critical for accurate prediction of nitrogen export from the site.

Subsurface drainage predictions Predicted yearly and monthly drainage rates were compared to measured values over the study period. In general, predicted annual drainage rates were in very good agreement with measured values (Figure 1). Predicted and

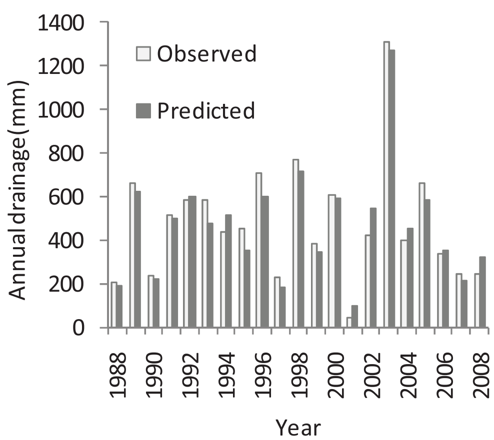

Figure 1. Comparison between predicted and observed annual drainage. Calibration period from1988 to 1997 and validation period from 1998 to 2008 was validated. d=0.95, MAE=53mm yr^{-1}, NSE=0.95, n=21

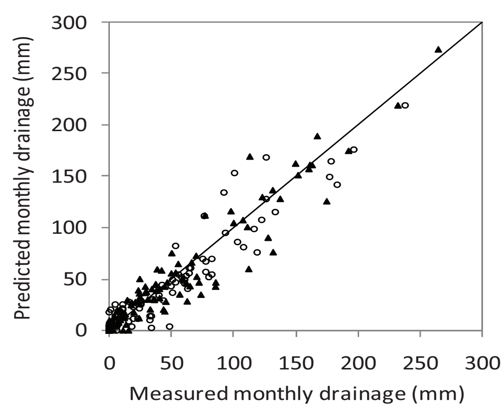

Figure 2. Comparison between predicted and observed monthly drainage; Circles represent calibration years, while solid triangles denote validation years. d=0.96, MAE=8.8mm, NSE=0.91, n=242.

measured mean annual drainage over the study period were 465.5mm and 478.5 mm, respectively. The normalized percent errors in predicting annual drainage were less than 10% in 13 of the 21 simulated years. Excluding 2001, which was extremely dry with only 45 mm measured drainage, the mean percent error in predicting annual drainage was 11.7% with a standard deviation of 8.7%. The MAE in predicting annual drainage was 53mm yr^{-1}, which is significantly lower than the standard deviation of measured annual drainage (271mm yr^{-1}), indicating that the model's predictions are acceptable (Moriasi *et al*., 2007). The goodness-of-fit statistics for annual drainage predictions over the study period were: d= 0.96, NSE= 0.95 and MAE=53mm, all of which indicate that the model performed well in predicting annual drainage rates for the simulated site.

Table 1, Goodness-of-fit statistics of model predictions for monthly drainage and daily water table depth during calibration and validation periods

Period	Monthly drainage			Daily Water table depth		
	NSE	d	MAE(mm mo^{-1})	NSE	d	MAE(m)
Calibration	0.90(0.10)	0.92(0.05)	8.27(0.23)	0.90(0.07)	0.95(0.04)	0.10(0.03)
Validation	0.84(0.23)	0.89(0.06)	9.28(0.29)	0.89(0.08)	0.94(0.04)	0.10(0.03)
Overall	0.88(0.29)	0.90(0.06)	0.64(0.27)	0.89(0.07)	0.94(0.04)	0.10(0.03)

Predicted monthly drainage volumes were also in very good agreement with observed values (Figure 2). The goodness-of-fit statistics of monthly drainage predictions were: NSE = 0.91, MAE = 8.8 mm mo^{-1} and d = 0.96. According to guidelines given by Moriasi *et al*. (2007), monthly drainage predictions were very good (NSE>0.75) in 18 of 21 years, acceptable (0.5<NSE<0.75) in 2 years and unsatisfactory (NSE=0.1) in only 1 year (2001). Table 1 summarizes goodness-of-fit statistics of monthly drainage predictions for both calibration and validation periods. Statistical analysis shows no significant differences between d values of calibration and validation periods (p=0.54, *df* =14). MAEs of monthly predictions during calibration period were slightly lower than those during validation period, but not statistically significant (p=0.42, *df* =14). NSEs of monthly drainage predictions during calibration period were higher than those during validation period and the difference was marginally significant (p=0.09, *df* =14).

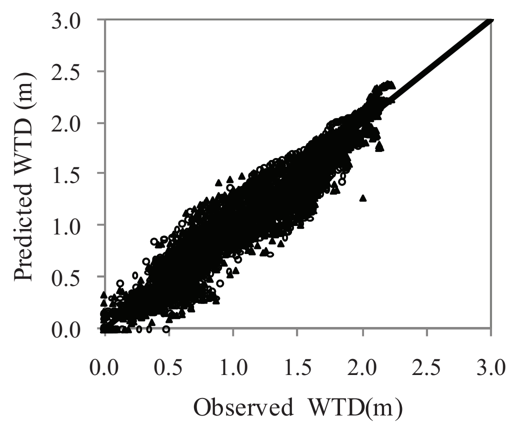

Figure 3. Scatter plot of predicted and observed daily water table depth (WTD). Circles represent calibration years and solid triangles denote validation years. d=0.96, MAE=0.10m, NSE=0.90, n=6805.

Water table depth predictions

Predicted daily water table depth closely followed observed values (Figure 3) with goodness-of-fit statistics: NSE = 0.90, d = 0.96 and MAE = 0.10m. According to the criteria given by Moriasi *et al*. (2007), daily water table depth predictions were excellent in 17 of 21 simulated years and satisfactory during remaining years. Goodness-of-fit statistics for daily water table depth predictions are summarized in Table1. Statistical analysis shows no significant differences between all goodness-of-fit statistics for (p>0.5, *df*=14) predicting daily water table depth during calibration and validation period.

Water balance analysis. Based on model predictions and field observations, water balance components of the artificially drained loblolly pine plantation ae presented in Table 2. Over the study period from 1988 to 2008, observed mean annual rainfall was 1525±291mm. Model predictions indicated that about 184±43 mm precipitation was intercepted by forest canopy, which accounted for about 12% of total precipitation. McCarthy et al. (1990) measured rainfall interception for the site during 1990 and 1991 and concluded that forest canopy intercepted about 15% of total rainfall. Predicted total ET including rainfall interception was 1057±73mm, which represented approximately 69.3% of total precipitation.

Table 2. Annual water balance components of the drained loblolly pine plantation
All units are in mm.

Precipitation	Rainfall interception	ET	Drainage	
			Observed	Predicted
1525.3 (291.3)	183.8(42.6)	1057.4 (72.6)	478.5 (270.0)	465.4(252.0)

The results of the hydrologic simulations indicate that the forestry version of DRAINMOD-NII model is capable of predicting subsurface drainage and water table fluctuation dynamics in artificially drained forests. These hydrological predictions also indicate that the newly built-in algorithms for estimating PET and rainfall interception improved the performance of the original DRAINMOD hydrology module (Skaggs, 1999). Accurate predictions of drainage volume and water table fluctuation also provided the basis for a successful and robust testing of carbon and nitrogen component of the model .

Carbon dynamics in the forest ecosystem

NPP predictions. Comparisons between predicted and estimated annual NPP are presented in Figure 4. Predicted mean annual NPP was 18.72 t DM ha^{-1}, which was very close to estimated value of 18.6 t DM ha^{-1}. The goodness-of-fit statistics of the annual NPP predictions were: NSE =0.66, d = 0.78, and MAE =1.46 t $ha^{-1}yr^{-1}$. These results are acceptable according to Hanson et al. (2004) who considered model predictions as poor for NSE values much less than 0.5. In addition, percent errors of yearly NPP predictions in 15 of 21 simulated years were less than 10%, which indicates that predicted annual NPPs were comparable to estimated annual NPP in most simulated years. Discrepancies between predicted and estimated annual NPPs for the other five years were possibly caused by the assumed constant carbon allocation fraction (30% in this study) to belowground biomass when estimating annual NPP from measured DBH values. This assumption may not be true in reality as carbon allocation to root biomass changes in response to temporal variations in climatic and soil nutrient conditions.

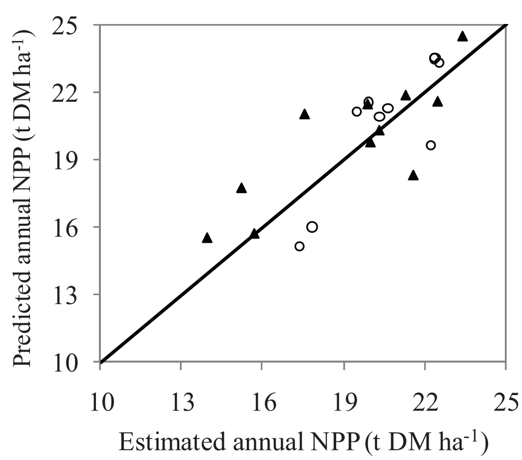

Figure 4. Comparison between predicted and estimated annual net primary production (NPP). Circle represents calibrated period, while solid triangle denotes validation years. d=0.78, MAE=1.46 t ha-1yr-1, NSE=0.66, n=21.

LAI predictions. In general, the model was able to predict both the magnitude and dynamics of LAI (Figure 5). The model predicted intra-annual fluctuations of LAI as it usually peaked during late fall and bottomed in early spring of the year, which closely matched observed seasonal variations in LAI. Although the model consistently underestimated LAI peaks of all years except 1997 and 1999, its predictions of lowest LAI closely matched observed values (Figure 5). To some extent, model predictions captured inter-annual LAI dynamics. The model responded reasonably well to dry conditions during 1993 (Apr. to Oct. Precipitation=320mm) and 2001 (Total precipitation=850mm).

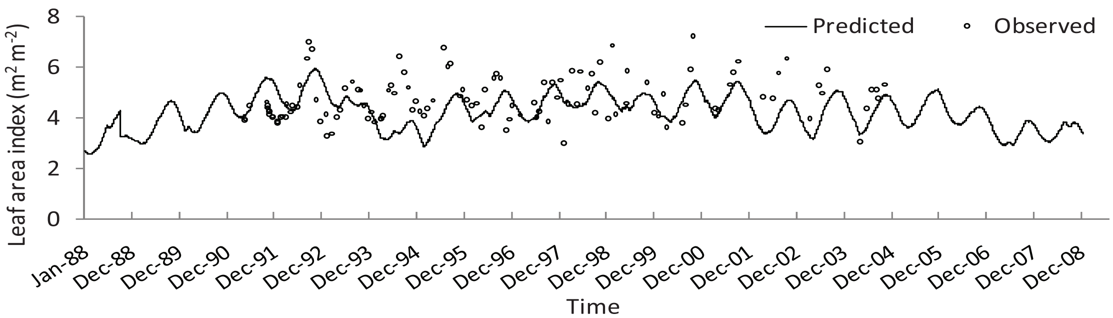

Figure 5. Comparison between predicted and observed annual mean leaf area index (LAI).

The model underpredicted LAIs for the years that followed dry years such as 1994, 1995 and 2002, which means the model overestimated the length of drought influence on LAI dynamics. These results demonstrate that the model is capable of predicting dynamics of leaf production and senescence as it is influenced by local environmental conditions.

Organic carbon pools. Predicted organic carbon (OC) pools in the forest floor and the soil profile of each month over the study period are shown in Figure 6. OC pool in forest floor ranged from 4330 kg ha^{-1} in the summer of 1991to 10575 kg ha^{-1} in the spring of 2002, with a mean value of 6856 kg ha^{-1} (SD=1245 kg ha^{-1}, n=252).

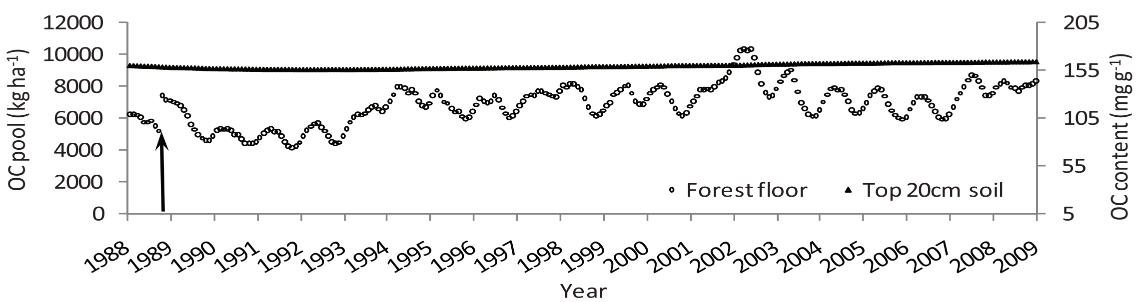

Figure 6. Temporal dynamics of organic carbon (OC) pool size in forest floor and top 20 cm soil. The arrow indicates the thinning that occurred in early October, 1988.

Predicted OC pool in the forest floor was comparable to those observed 5000-10000 kg ha^{-1} in Duke Forest (Lichter *et al*., 2005), as well as to those observed by Zerpa, (2005) who measured OC accumulation processes of several loblolly pine plantations located in Alabama. OC content in forest floor fluctuated both intra and inter annually based on model predictions. For each year, the OC content usually peaked in late spring and followed by lowest OC content in late summer. In addition to plant physiology controlling litterfall processes, climate condition was another critical factor influencing OC dynamics (Figure 6). For instance, dry period during growing seasons in 1993 and 2001 led to OC pool in forest floor increased significantly during these periods. In contrast to obvious OC fluctuations in forest floor, predicted OC content in the soil profile was relatively stable for both inner- and inter-annually (Figure 6). Predicted OC contents in top 20 cm soil ranged from162 to 156 mg g^{-1} soil with a mean value of 159±2.7 mg g^{-1} soil. Predicted soil OC dynamics in the drained loblolly pine plantation were consistent with Johnson *et al*. (2003) who reported that no statistically significant changes in soil OC content were found over 18 years in a loblolly pine plantation without significant disturbances.

Nitrogen predictions

Nitrate export predictions. Since both observed and predicted ammonium losses through subsurface drainage were very small (< 0.1 kg ha^{-1} yr^{-1} on average), data about ammonium leaching data are not presented herein. Months with no water quantity measurements were excluded when comparing predicted and observed nitrate export.

Predicted annual nitrate loading via subsurface drainage closely followed observed annual nitrate export dynamics (Figure 7). Predicted mean annual nitrate loss was 2.6±1.6kg ha^{-1}, which was very close to observed value of 2.64±1.50kg ha^{-1}. The goodness-of-fit statistics for predicted annual nitrate loss were: NSE = 0.88, MAE = 0.5kg ha^{-1} yr^{-1} and d = 0.93. MAE was much smaller than the standard deviation (1.6kg ha^{-1} yr^{-1}), indicating results were acceptable (Moriasi *et al*., 2007). Percent errors of annual nitrate export predictions were less than 10% in 6 years and less than 20% in 12 of the 21 simulated years. The relatively large percent errors that occurred in the other 9 years were caused by the relatively low nitrate loss from the forested site. For example, the model overpredicted annual nitrate export by 0.5 kg ha^{-1} in 1994, which was

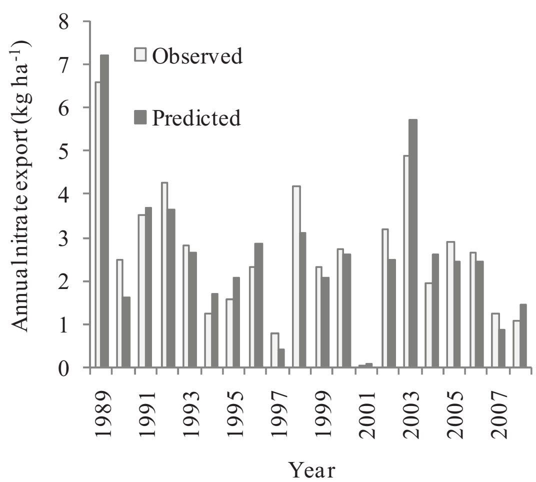

Figure 7. Comparison between predicted and observed annual nitrate export (Calibration period from1988 to 1997 and validation period from 1998 to2008). d=0.91, MAE=0.46 kg ha-1 yr-1, NSE=0.88, n=21.

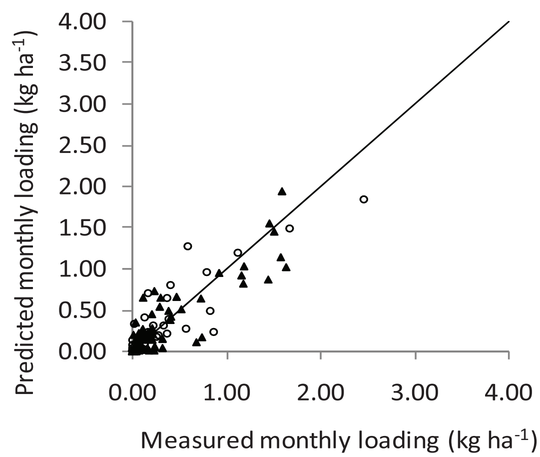

Figure 8. Comparison between predicted and observed monthly nitrate export. Circles represent calibration period, and solid triangles denote validation years. d=0.81, MAE=0.09 kg ha-1mo-1, NSE=0.76, n=174.

equivalent to 36% of the measured nitrate export during this year. The largest percent error (120%) occurring in 2001 corresponds to poor prediction of annual drainage during this extremely dry year. In 2001, predicted and observed drainage volumes were 110 and 45mm, respectively, and predicted and observed nitrate export were 0.09 kg ha^{-1} and 0.05 kg ha^{-1}, respectively.

Predicted monthly rates of nitrate export were also in good agreement with observed monthly nitrate losses through subsurface drainage (Figure 8). Predicted and observed mean monthly nitrate loading were 0.2±0.4kg ha^{-1} and 0.19±0.36kg ha^{-1}, respectively. The goodness-of-fit statistics for monthly nitrate export were: NSE = 0.76, MAE = 0.09 kg ha^{-1} $mo^{-1}$and d = 0.81, all of which indicated a good performance of the model in predicting monthly nitrate export. Discrepancies between predicted and observed nitrate export can be attributed to either inaccurate hydrological predictions or imprecise quantification of nitrogen transformations (Youssef, *et al*. 2006).

Simulated nitrogen transformations. Accurate quantification of physical, chemical, and biological processes that regulate nitrogen fate and transport in drained forest ecosystems is essential for predicting nitrogen export from these drained forests to downstream surface waters. Three sources of mineral nitrogen are considered in the forestry version of DRAINMOD-NII model: mineralization of soil organic nitrogen, wet deposition and nitrogen fertilizer application. In the study site, predicted mean annual wet nitrogen deposition was 9.0±1.1 kg ha^{-1} which was very close to observed 10 kg ha^{-1} yr^{-1} based on measurements made in a nearby site (one of the sites of the National Atmospheric Deposition Program, National Trends Network) located in Carteret county, North Carolina USA. .

Table 3 summarizes predicted rates of nitrogen transformations over the study period. All mean values and standard deviations were calculated without year 1989 when fertilization occurred. Predicted mean annual net mineralization was 74.0±11.3 kg ha^{-1}, which was the principal nitrogen source providing around 90% of mineral nitrogen (Except 1989 because of fertilization). Predicted mean annual nitrogen uptake was 76.2±11.2 kg ha^{-1} (Table 3). The inter-annual variations in nitrogen uptake were mainly attributed to annual NPP fluctuations controlled by climatic conditions,nutrients availability, and management practices such as thinning and fertilization that occurred in 1988 and 1989, respectively. Predicted annual nitrogen uptake ranged from as low as 56.3 kg ha^{-1} in 1993 due to the extremely dry growing season to as high as 186kg ha^{-1} in 1989 after thinning and fertilization. According to model predictions, a quarter of the high nitrogen uptake in 1989 was attributed to temporary growth of understory species because of the low canopy closure after thinning. Predicted annual nitrogen uptake rates of loblolly pine were comparable to results of Albaugh *et al* (2008) and Ducey and Allen (2001).

Table 3. Predicted mean annual rate and corresponding standard deviation of nitrogen transformation processes from 1988 to 2003

	Net mineralization	Nitrification	Denitrification	Plant uptake	Nitrogen leaching
	--------------------------------------Kg $ha^{-1}yr^{-1}$--				
Mean	74.0 (11.3)	41.1(7.6)	1.9 (1.7)	76.2 (11.2)	2.6 (1.6)

Note: All mean values and standard deviations were calculated excluded data of 1989 because of fertilization application.

Annual rates of nitrate export were closely related to annual nitrification rates as indicated by a correlation coefficient of 0.83. In this study, predicted annual nitrification rate ranged from 16.2kg ha^{-1} in 2001 to 123.2 in 1989. The predicted mean annual nitrification rate was 41.1kg $ha^{-1}yr^{-1}$ with a standard deviation of 7.6 kg $ha^{-1}yr^{-1}$ (Table 3). Our predictions were comparable to rates reported by Stark and Hart (1997) for undisturbed mature coniferous forests.

Unlike agricultural fields where denitrification process is an important pathway for nitrogen loss (Youssef, *et al*., 2006), denitrification rate was relatively small in forested lands (Barton *et al*., 1999). Predicted annual denitrification rate varied from 0.7 kg ha^{-1} in 2001 to 5.9 kg ha^{-1} in 1989 with a mean of 1.9 and a standard deviation of 1.7 kg ha^{-1}. The predictions were reasonable according to a review by Barton *et al*., (1999) who concluded that denitrification rates in forest ecosystems were usually as low as 0 to 2.0 kg ha^{-1}. Our predictions were also consistent with field measurements given by Robertson *et al*. (1987) who reported annual denitrification rates in the range of 0.6 kg ha^{-1} to 5.2 kg ha^{-1} for a clear cut loblolly pine plantation in the Southeastern US. Predicted annual denitrification rates were closely related to nitrate pool size and soil water conditions. For instance, the highest denitrification rate of 5.9 kg ha^{-1} was predicted in 1989 when the highest nitrification rate of 123.3 kg ha^{-1} was predicted following the application of the urea fertilizer; The lowest denitrification rate occurred in 2001(852mm rainfall compared with mean annual precipitation of 1525 mm over the whole study period). This analysis indicates the model's ability to capture the close relationship between denitrification and substrate availability and soil water conditions.

CONCLUSIONS The newly developed forestry version of DRAINMOD-NII was evaluated using a long term experimental data set from an artificially drained Loblolly pine plantation in eastern North Carolina. The model simulated hydrological and biogeochemical processes for the drained forested land over a 21 year period. The model was calibrated using the data collected during 1988-1997 and validated using the 1998-2008 data. Predicted yearly and monthly drainage, as well as daily water table fluctuations were accurately predicted. Annual NPP and daily LAI dynamics predictions were also comparable to field measurements. Predicted temporal changes in the OC pools on forest floor and in soil profile during the simulation period were reasonable compared to published literature. Both predicted annual and monthly nitrate export were in good agreement with observed nitrate losses via subsurface drainage. Predicted internal nitrogen transformations such as net mineralization, nitrification, and denitrification were also reasonable compared to published literature. This study demonstrates the capabilities of the forestry version of DRAINMOD-N II as a model for simulating the hydrology, biogeochemistry, and forest growth for drained forested lands. Further research is needed to evaluate the performance of the model under intensive forest management practices such as thinning, fertilization, harvesting, bedding and regeneration.

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