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ENVIRONMENTAL MODELS, MODULES, AND DATASETS

DRAINMOD-FOREST: Integrated Modeling of Hydrology, Soil Carbon and Nitrogen Dynamics, and Plant Growth for Drained Forests

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We present a hybrid and stand-level forest ecosystem model, DRAINMOD-FOREST, for simulating the hydrology, carbon (C) and nitrogen (N) dynamics, and tree growth for drained forest lands under common silvicultural practices. The model was developed by linking DRAINMOD, the hydrological model, and DRAINMOD-N II, the soil C and N dynamics model, to a forest growth model, which was adapted mainly from the 3-PG model. The forest growth model estimates net primary production, C allocation, and litterfall using physiology-based methods regulated by air temperature, water deficit, stand age, and soil N conditions. The performance of the newly developed DRAINMOD-FOREST model was evaluated using a long-term (21-yr) data set collected from an artificially drained loblolly pine (*Pinus taeda* L.) plantation in eastern North Carolina, USA. Results indicated that the DRAINMOD-FOREST accurately predicted annual, monthly, and daily drainage, as indicated by Nash–Sutcliffe coefficients of 0.93, 0.87, and 0.75, respectively. The model also predicted annual net primary productivity and dynamics of leaf area index reasonably well. Predicted temporal changes in the organic matter pool on the forest floor and in forest soil were reasonable compared to published literature. Both predicted annual and monthly nitrate export were in good agreement with field measurements, as indicated by Nash–Sutcliffe coefficients above 0.89 and 0.79 for annual and monthly predictions, respectively. This application of DRAINMOD-FOREST demonstrated its capability for predicting hydrology and C and N dynamics in drained forests under limited silvicultural practices.

Large areas of managed forests in the southeastern United States are located on naturally poorly drained soils in coastal regions. To improve trafficability and increase forest productivity in this area, artificial drainage has commonly been used along the Atlantic Coastal Plain (Amatya and Skaggs, 2001). Additionally, these forests are usually intensively managed with common silvicultural practices such as site preparation and bedding, fertilization, pruning, thinning, and harvesting. Artificial drainage and these silvicultural practices fundamentally alter forest hydrological and biogeochemical processes, which could lead to detrimental environmental impacts (Amatya et al., 1996; Beltran et al., 2010). The hydrologic and water quality impacts of these human activities on forests can ideally be investigated using plot- and field-scale experiments. However, conducting long-term field measurements is prohibitively expensive. Alternatively, computer models can be used to simulate the hydrology and biogeochemistry of managed forests and predict the long-term impacts of silvicultural and water management practices on water quantity and quality, C and N dynamics, and forest productivity. Such models, when successfully validated, can be valuable tools for developing and assessing sustainable silvicultural management practices.

Numerous models, including NuCM (Liu et al., 1991), G'DAY (Comins and McMurtrie, 1993), 3-PG (Landsberg and Waring, 1997), PnET-CN (Aber et al., 1997), CenW (Kirschbaum, 1999), DNDC (Li et al., 2000), Biome-BGC (Thornton et al., 2002), and CABALA (Battaglia et al., 2004), have been developed and applied to simulate hydrological, biogeochemical processes, and forest growth in forest ecosystems. These models have significantly improved our understanding of the complex, highly dynamic, and interactive physical, chemical, and biological processes that regulate water, C, and N cycling in forest ecosystems. However, current models are seldom "well balanced" in representing the water, C, and N cycles (Tiktak and van Grinsven, 1995; Waring and Running, 2007). For instance, G'DAY (Comins and McMurtrie, 1993), PnET-CN (Aber et al., 1997), and Biome-BGC (Thornton et al., 2002) simulate forest

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Abbreviations: ADR, advection–dispersion–reaction; DBH, diameter at breast height; DM, dry matter; ET, evapotranspiration; GPP, gross primary production; LAI, leaf area index; MAE, mean absolute error; NPE, normalized percent error; NPP, net primary production; NSE, Nash–Sutcliffe coefficient; OC, organic carbon; PET, potential evapotranspiration; SOC, soil organic carbon.

growth and/or biogeochemical processes at a considerable level of detail, while adopting less rigorous approaches to simulate forest hydrology. Chen and Driscoll (2005) demonstrated that incorporating a more detailed hydrologic cycle into the Biome-BGC model improved predictions of seasonal effluent nitrate concentrations. The inconsistency in the relative rigor of representing the water, C, and N cycling is expected to limit the ability of many of these models to predict the hydrology and biogeochemistry of forest ecosystems in response to changes in climate, land use, and/or management practices (Wallman et al., 2005; Waring and Running, 2007).

Despite the large area and proximity to nutrient-sensitive surface waters of drained lowland forests (Amatya et al., 1998), seldom have mechanistic models been developed and applied specifically to predict water, C, and N dynamics in artificially drained forest ecosystems under intensive silvicultural practices. DRAINMOD (Skaggs, 1978, 1999) and DRAINMOD-N II (Youssef, 2003; Youssef et al., 2005) models were originally developed for simulating hydrological processes and soil C and N cycling in artificially drained agricultural lands. An earlier forestry version of DRAINMOD (DRAINLOB) was developed and used to simulate the hydrological processes of drained forest lands (McCarthy et al., 1992; Amatya and Skaggs, 2001). Diggs (2004) used the DRAINMOD-N II model to simulate C and N dynamics in three artificially drained forests. To conduct the simulation with the agro-ecosystem version of DRAINMOD-N II, Diggs estimated the litterfall and N uptake outside the model using the forest growth model, PnET-CN (Aber et al., 1997). These previous applications demonstrated applicability of the DRAINMOD and the DRAINMOD-N II models in forest ecosystems, while suggesting several drawbacks. The application of the former forestry version of the DRAINMOD model (McCarthy et al., 1992; Amatya and Skaggs, 2001) was limited because it requires inputs of the usually unavailable leaf area index (LAI). Additionally, the rainfall interception algorithm adapted by DRAINLOB has been proven to overestimate rainfall interception for sparse forest canopies (Gash et al., 1995; Valente et al., 1997). The simulation study of Diggs (2004) did not fully represent the interactions and feedbacks among hydrological, biogeochemical, and plant growth processes. Most importantly, previous studies lacked representation of plant growth processes and their interactions with common silvicultural practices. Therefore, developing a comprehensive and fully integrated forestry version of DRAINMOD (called DRAINMOD-FOREST hereafter) is necessary to extend the applicability of the DRAINMOD suite of models from agricultural to forest lands.

The DRAINMOD-FOREST model is developed as a research tool to simulate the hydrology, biogeochemistry, and productivity of naturally poorly drained forests as affected by climatic conditions and silvicultural practices (Tian et al., 2009; Tian, 2011). The model can potentially be used to predict forest ecosystem responses to projected climate changes, including temperature increase and change in the magnitude and pattern of precipitation. It can also be used to predict the long-term hydrological and biogeochemical impacts of potential biofuel-related land-use changes in lowland forests, which are currently proposed as a source of biomass production for the biofuel industry. Predictions from DRAINMOD-FOREST will provide valuable information for both forest managers and policymakers to develop science-based management strategies and decisions. This paper presents the newly developed DRAINMOD-FOREST model and reports a preliminary field testing of the model for simulating hydrology, soil C and N cycling, and tree growth for an artificially drained loblolly pine (*Pinus taeda* L.) plantation in eastern North Carolina. This first application and field testing of the DRAINMOD-FOREST model was used to demonstrate the basic functions of the model and validate the integration of the three component models of DRAINMOD-FOREST. Tian et al. (2012) reported another field testing of the model, using data from two intensively managed forest ecosystems.

Description of the DRAINMOD-FOREST MODEL

The DRAINMOD-FOREST model was developed as a stand-level forest ecosystem model for simulating hydrological, biogeochemical processes, and plant growth in drained lowland forests (Fig. 1). The model was developed by linking DRAINMOD, the hydrological model, and DRAINMOD-N II, the C and N dynamics model, to a physiologically based forest productivity model that was mainly adapted from the 3-PG model. The three component models, DRAINMOD, DRAINMOD-N II, and the forest growth model, are integrated with key internal feedbacks reflecting interactions among soil water, soil C and N, and vegetation. The LAI, plant height, and canopy fraction predicted by the forest growth model are used by the DRAINMOD model to predict potential evapotranspiration (PET). The DRAINMOD-predicted hydrological variables, including soil water conditions and drainage, are used by the DRAINDMOD-N II model to simulate decomposition of organic matter, the reactive transport of soil N, and mineral N leaching losses. Predicted evapotranspiration (ET) and PET by the DRAINMOD model are used for representing water stress when simulating canopy photosynthesis and C allocation under water deficit conditions. Litterfall and root turnover simulated by the plant model are sources of organic matter for the soil C and N cycles simulated by the DRAINMOD-N II model, which predicts soil nutrient status for simulating plant growth (Fig. 1). While the DRAINMOD-FOREST model mechanistically integrates water, C, and N cycling, it is not a fully mechanistic model but rather a hybrid model because both process-based and empirical modeling approaches were adopted in various components of the model. The next section briefly introduces the well-documented DRAINMOD and DRAINDMOD-N II models and provides a relatively detailed description of the newly integrated forest growth model. Key equations of the DRAINMOD-FOREST model are listed in Appendix A.

The Hydrologic Model, DRAINMOD

The DRAINMOD (Skaggs, 1978, 1999) model, with some modifications, was used to simulate hydrological processes in drained forest ecosystems, including ET, rainfall interception, surface runoff, infiltration, subsurface drainage, deep seepage, water table fluctuation, and soil water status (Fig. 1). The DRAINMOD model was originally developed to predict the effects of drainage and associated water management practices on water table depths, the soil water condition, flow regime, and crop yields in artificially drained high-water-table agricultural lands (e.g., Luo et al., 2010; Thorp et al., 2010). It conducts a water balance on an hourly and daily basis at the soil surface (Eq. [A-1]) and in the soil column midway between two parallel drains (Eq. [A-2]). The model predicts infiltration using the Green–Ampt equation. Subsurface drainage is calculated using Hooghoudt's equation for water table drawdown and Kirkham's equations for ponded surface conditions. Surface runoff is estimated as the difference between rates of precipitation and infiltration, once site-specific surface depressional storage is filled (Skaggs, 1999). The soil water distribution in unsaturated zone is quantified using soil water characteristic curves under the assumption of a hydrostatic condition. In the original DRAINMOD, daily PET can be internally computed using the temperature-based Thornthwaite method or estimated outside the model by any method of the user's choice and read in by the model as input data. The new model internally calculates daily PET using the Penman–Monteith method (Eq. [A-3]) (Monteith, 1965) with canopy conductance estimated as a function of climatologically regulated stomatal conductance (Jarvis, 1976) and LAI that is predicted by the forest growth model (Eq. [A-4] and [A-5]). A modified version of the Gash model (Gash et al., 1995), applicable for sparse canopy, is used to estimate rainfall interception (Eq. [A-6]).

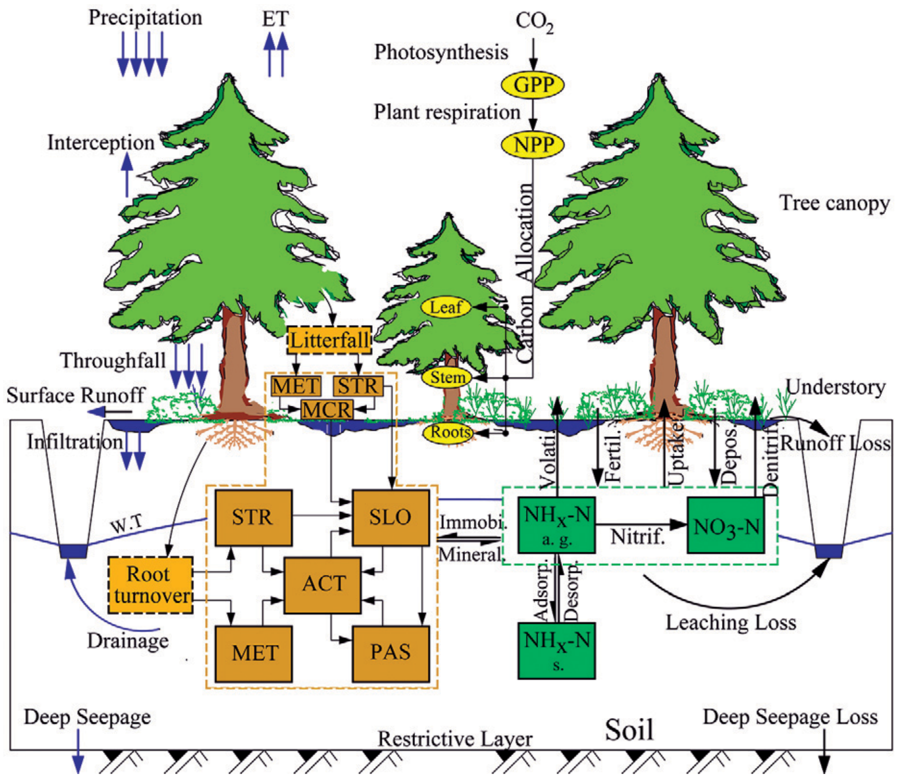

Fig. 1. Water, carbon, and nitrogen cycles in a typical drained forest ecosystem as simulated by DRAINMOD-FOREST. Processes: GPP = gross primary production, NPP = net primary production. Soil organic matter pools: ACT = active pool, MCR = microbial pool, MET = metabolic pool, PAS = passive pool, SLO = slow pool, STR = structural pool. Nitrogen cycling: Adsorp. = adsorption, Denitrif. = denitrification, Depos. = air deposition, Desorp. = desorption, Fertil. = fertilization, Immobi. = immobilization, Mineral. = mineralization, Nitrif. = nitrification, Volati. = volatilization. a.g., aqueous and gas phase; ET, evapotranspiration; s., solid phase; W.T, water table.

The Soil Carbon and Nitrogen Model, DRAINMOD-N II

The DRAINMOD-N II model (Youssef, 2003; Youssef et al., 2005) is a field-scale, process-based model that simulates soil C and N cycling in drained agricultural fields with different soil types, climatic conditions, and farming practices. The soil C and N cycles simulated in the DRAINMOD-N II model are shown in Fig. 1. Environmental factors that affect biochemical processes of soil C and N include temperature, pH, and soil water content. Three nitrogen forms—nitrate-nitrogen, ammoniacal-nitrogen, and organic nitrogen—are simulated by the DRAINMOD-N II. The model simulates a detailed N cycle, including atmospheric deposition, application of mineral N fertilizers and organic N sources, plant uptake, N mineralization/immobilization, nitrification, denitrification, ammonia volatilization, and N losses via surface runoff, lateral subsurface drainage, and vertical deep seepage (Fig. 1). Mineral N reactive transport is simulated using a finite differential solution to a multiphase form of the one-dimensional advection–dispersion–reaction (ADR) equation (Eq. [A-7]). The simulated N transformations are included in a source–sink term of the ADR equation. The nitrification and denitrification processes are simulated using a Michaelis–Menten function. Soil C dynamics are simulated using a soil C submodel adapted from the CENTURY model (Parton et al., 1993). The soil C submodel divides organic matter into three soil pools (active, slow, and passive), two above- and belowground residue pools (metabolic and structural), and a surface microbial pool (Fig. 1). Each organic matter pool is characterized by the organic C content, potential rate of decomposition, and C-to-N ratio (Youssef et al., 2005). The litterfall and root turnover predicted by the forest growth model are used to update organic matter pools represented in the DRAINMOD-N II model. The decomposition of each organic matter pool is simulated using first-order rate kinetics. The DRAINMOD-N II model has been tested for a wide range of soils and climatological conditions in the United States (Youssef et al., 2006; David et al., 2009; Thorp et al., 2010; Luo et al., 2010) and in Europe (Salazar et al., 2009).

The Forest Growth Model

The forest growth component simulates tree growth following three main steps: (i) calculation of gross primary production (GPP), (ii) calculation of net primary production (NPP), and (iii) carbon allocation (Fig. 1). A more detailed flow chart of processes simulated in the forest growth model is shown in Fig. 2. It is worth noting that the model was developed with the assumptions of evenly distributed trees and spatially homogeneous climatic variables. Similar to the 3-PG model (Landsberg and Waring, 1997; Sands, 2004), the radiation use efficiency method is used to simulate GPP (Eq. [A-8]). Intercepted radiation is simulated using the Beer–Lambert law as a function of LAI and canopy fraction. The canopy fraction is a function of tree stocking rate and empirical estimated canopy radius.

As indicated in Eq. [A-8], estimated GPP is further constrained by water deficit (Eq. [A-9]), temperature (Eq.

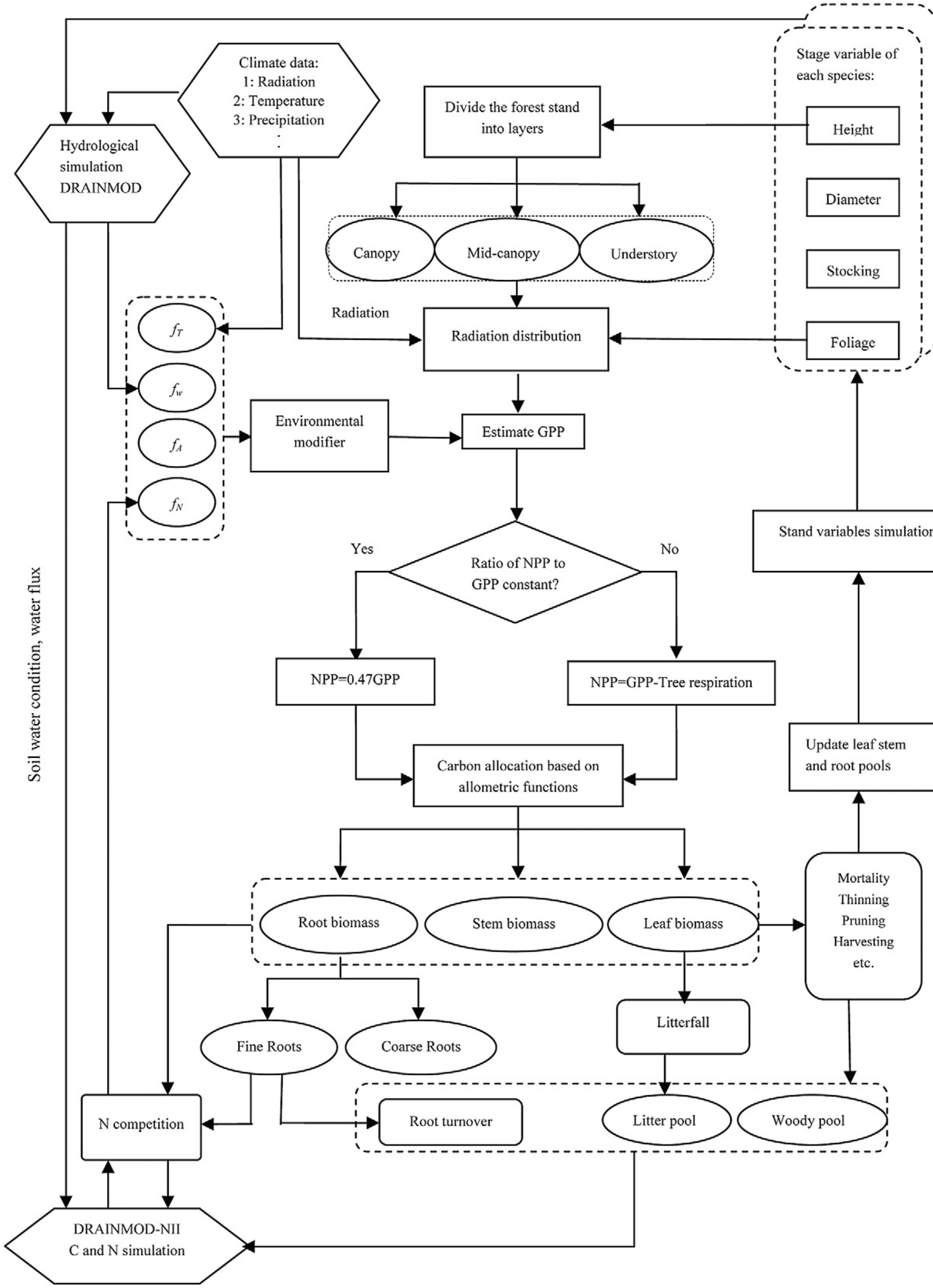

Fig. 2. Schematic diagram of DRAINMOD-FOREST showing the detail of simulation processes of gross primary production (GPP), net primary production (NPP), and carbon allocation, as well as the interactions among DRAINMOD, DRAINMOD-N II, and the forest growth model. f_T = air temperature modifier, f_w = water stress modifier, f_A = stand age modifier, f_N = nutrients modifier.

[A-10]), stand age (Eq. [A-11]), and soil nitrogen availability (Eq. [A-12]). Value of each stress modifier ranges from 0 to 1, with 0 meaning total inhibition of photosynthesis and 1 meaning no environmental stresses limiting the rate of the photosynthesis process. For the nutrients modifier, only effects of the soil N availability on C assimilation and allocation are included in the model because N is usually the main limiting nutrient in forest ecosystems (McLauchlan et al., 2007). The nutrients modifier (Eq. [A-12]) is defined as the ratio of available soil N within the root zone and the potential N uptake for each plant species (Peng et al., 2002; Paul and Polglase, 2004; Xenakis et al., 2008). This new definition made this critical factor dynamic, and internally estimated by the model using a process-based approach. Following the approach used in the FORECAST model (Kimmins et al., 1999), N availability for individual plant species is simulated as a function of total available soil N pool and the relative occupancy of the soil by fine roots of each plant species in each soil layer (Eq. [A-13]). The daily potential N uptake is estimated as a function of N content of plant tissues and the potential biomass increments of different plant components without N stress (Eq. [A-14]).

The NPP of trees can either be estimated as a constant fraction (Eq. [A-15]) of GPP or determined as the difference between GPP and plant respiration (Eq. [A-16]). The model simulates growth of deciduous trees during the growing season, defined using degree-days method. A small LAI value (e.g., 0.05 m^2 m^{-2}) is assigned to deciduous species at the beginning of the growing season to avoid the explicit simulation of the nonstructural carbohydrate used for sprouting at the start of each growing season (Bond and Midgley, 2001). The NPP of the two understory groups considered in the model (shade-tolerant and shade-intolerant species) is estimated empirically in terms of light availability and a user-defined maximum productivity (Keane et al., 1996).

Carbon balance (Eq. [A-17], [A-18], [A-19], and [A-20]) of live biomass is controlled by carbon allocation, litterfall, root turnover, tree mortality, and human disturbances. Carbon allocation to three biomass pools—foliage, stem, and root (Fig. 1 and 2)—are simulated using allometric relationships adapted from the 3-PG model (Landsberg and Waring, 1997). The allometric relationships (Eq. [A-21], [A-22], and [A-23]) are tree species-dependent and regulated by resource (soil water and N) availability (Eq. [A-24] and [A-25]) and tree size (Eq. [A-26], [A-27], and [A-25]). Carbon allocation to fine roots (Eq. [A-17]) is assumed to be a constant fraction of total C allocated to roots (Nadelhoffer and Raich, 1992). The forest model estimates LAI as a simple function of leaf biomass and specific leaf area. The height of each tree species is estimated at each time step using the widely used height–diameter relationship (Landsberg and Waring, 1997). The tree diameter is estimated as an empirical function of stem biomass (Landsberg and Waring, 1997).

Foliage litterfall for evergreen trees is quantified as a function of leaf longevity. For deciduous tree species, the litterfall rate is assumed to be zero during the growing season while following a user-defined function beyond the growing season. Since ratio of fine root biomass to total root biomass is relatively constant through time (West et al., 2004), root turnover is estimated using a user-specified constant rate. Tree mortality is simulated using the method of 3-PG (Landsberg and Waring, 1997), which is density dependent and determined by the self-thinning rule (−3/2 rule) to ensure that the mean single tree stem biomass will not exceed the maximum single stem biomass.

The DRAINMOD-FOREST simulates the effects of commonly used silvicultural practices on hydrological and biogeochemical processes in the forest ecosystem (Fig. 2). Thinning, pruning, and harvesting remove certain live biomass based on user-assigned management intensity. The amount of foliage, woody litter, and dead root biomass produced during these practices are estimated using user-specified "remaining" fractions and added to surface and belowground litter pools of the soil C and N model DRAINMOD-N II. The effects of site preparation on mixing surface litter and enhancing the decomposition of organic carbon (OC) within the topsoil are simulated using the tillage and residue management component of the DRAINMOD-N II model. Fertilizer application is simulated using the fertilizer component of DRAINMOD-N II. Drainage water management practices are simulated using the hydrologic model DRAINMOD.

Field Testing of the DRAINMOD-FOREST MODEL

Study Site and Data Collection

The loblolly pine plantation, a 24-ha watershed, is located in the Atlantic Lower Coastal Plain of North Carolina (34°48′ N, 76°42′ W). The site is relatively flat (<0.1% slope) and has hydric soil (Deloss fine sandy loam; fine-loamy, mixed, semiactive, thermic Typic Umbraquult). The watershed is drained by four 1.2-m-deep parallel lateral ditches spaced 100 m apart (Fig. 3). 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 followed by N fertilizer application (195 kg urea-N ha^{-1}) in 1989. Thereafter, the site had not been disturbed for 20 yr until it was clear-cut in 2009. Refer to McCarthy et al. (1991) and Amatya et al. (1996) for a detailed description of the study site.

The field experiment was initiated in 1986 and hydrologic data collection began in 1988 when the loblolly pine trees were 15 yr old. Rainfall was measured with a tipping bucket rain gauge connected to a data logger on the western side of the watershed (Fig. 3). Air temperature, relative humidity, wind speed and direction, and solar and net radiation were measured. Before mid-1997, weather data were collected from a weather station 800 m away from the study site. Between 1997 and 2005, weather data were collected using an on-site station. Following damage in 2005 by Hurricane Ophelia, weather data were obtained from a station 3.2 km from the study site. On-site weather data collection was resumed in August 2008.

Drainage water outflow was measured using a 120° V-notch weir, mounted on a water level control structure, installed at the outlet of the collector ditch. The bottom of the V-notch weir was placed about 1.2 m below the average ground surface. Automatic stage recorders were installed upstream and downstream of the weir. The downstream recorder was placed to detect weir submergence. The data from the recorder were used for calculating flow during infrequent periods of submergence. Groundwater table elevations were measured using two wells equipped with automatic water level recorders, located at two experimental plots midway between the inner field ditches of the watershed (Fig. 3).

Drainage water quality was intensively monitored during 1989 to 1994. During that period, automatic ISCO-2700 samplers were used to collect drainage water samples every 2 h during each storm event. Four consecutive samples were mixed together to make one composite sample of an 8-h period (three water quality samples per day). Starting from 1994, flow-proportional

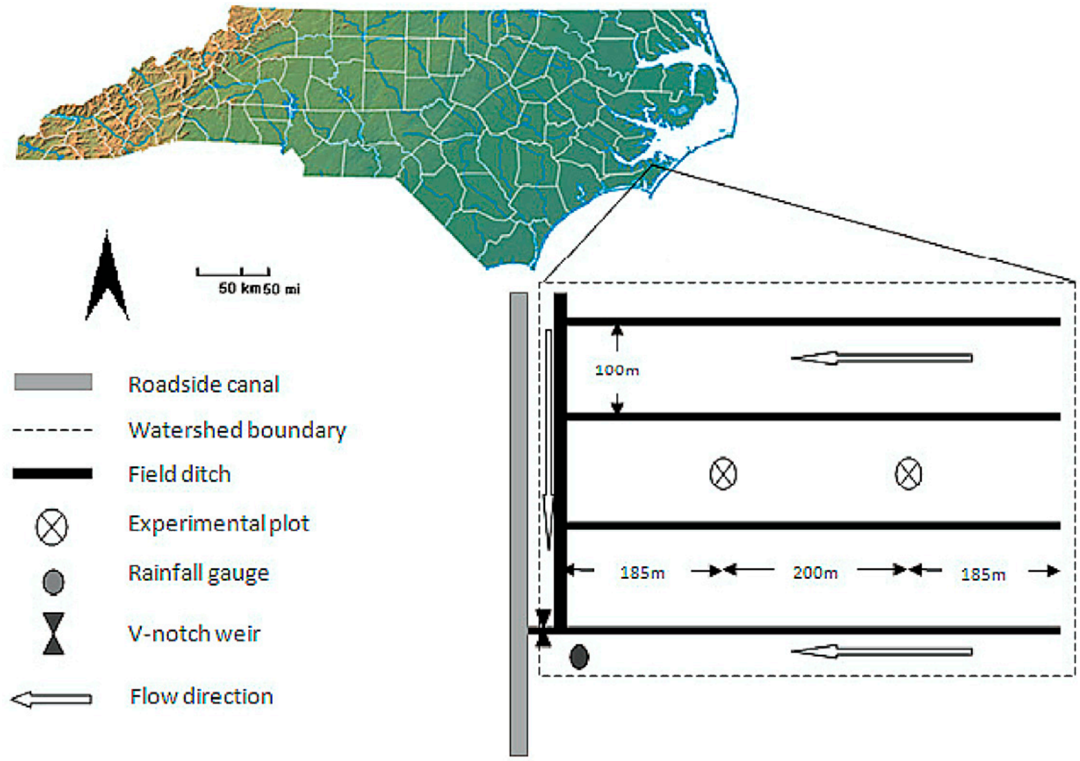

Fig. 3. Location (eastern North Carolina) and schematic diagram of the study site (after Amatya and Skaggs, 2001).

composite sampling was used to collect water samples every 2 wk. Additionally, grab samples were collected weekly or every 2 wk during flow events for the whole study period. Water samples were analyzed for nitrate and nitrite, ammonium and dissolved organic N, sediments, and phosphorus. Detailed procedures of event sampling and lab analyses are documented by Amatya et al. (1998, 2003). Nitrate loads were calculated as the product of measured drainage flux and measured nitrate concentration.

The LAI (projected leaf surface area per unit ground surface area) dynamics were continuously monitored. The LAI dynamics from 1988 to early 1991 were estimated from litterfall collected at the study site on a monthly basis (Amatya et al., 1996). From late 1991 to 2004, LAI was obtained from field measurements conducted using a LI-COR LAI 2000 Plant Canopy Analyzer (Sampson et al., 2011). Data measured by the LI-COR analyzer were converted to projected LAI by multiplying a conversion factor of 1.436 according to the regression relationship developed by Sampson et al. (2011). The tree diameter at breast height (DBH) was measured annually since 1989. An allometric biomass regression equation (Ter-Mikaelian and Korzukhin, 1997; Hu and Wang, 2008) was used to estimate the annual increment in tree biomass in terms of measured DBH values:

$$M = a \times \mathrm{DBH}^{b} \qquad [1]$$

where M is the aboveground biomass of a single tree (kg), DBH (cm) is the diameter at breast height measured at 1.37 m above ground level, and a and b are regression parameters. The values of parameters a and b for loblolly pine are assumed to be 0.0662 and 2.5417, respectively (Hu and Wang, 2008). Belowground biomass was estimated as a constant fraction (30%) of aboveground biomass (King et al., 1999). Annual increments in total biomass (aboveground plus belowground) are calculated as the difference between the total biomass at the end of the current year and the total biomass at the end of the previous year.

Model Initialization

Table 1 summarizes model inputs characterizing initial conditions for the hydrologic, soil C and N, and forest growth module of the DRAINMOD-FOREST model. The first day of model simulation was 1 Jan. 1988. Initial water table depth and snow depth were determined based on field measurements. The initial OC content of the surface and belowground litter pools were obtained through model calibration. The surface litter pool represents foliage and woody litter on the forest floor. The belowground litter pool represents dead roots and any previously incorporated woody litter within the top 20-cm soil layer. The litter pools were assumed to have 45% C and 23% lignin (Zerpa, 2005). Initial soil organic C (SOC) was determined based on field measurements conducted in 2007 (unpublished data). Measured SOC content in 2007 was considered a good approximation of the initial SOC content because changes in the organic matter content of forest soils usually occur over long periods of time (from several decades to centuries) (Johnson et al., 2003). The initial partitioning of SOC into active, slow, and passive pools was adjusted before model calibration to achieve quasi-equilibrium among the three SOC pools. An iterative procedure, requiring multiple runs (usually fewer than five) of the model using the measured 20-yr climate record, was followed to obtain the initial partitioning of SOC.

In this study, the initial partitioning used for the first iteration was based on values used by Diggs (2004), who previously tested the DRAINMOD-N II model for similar geophysical conditions. The iterative model runs continued until the initial and final SOC partitioning converged, indicating a quasi-equilibrium among the SOC pools was attained. The initial percentages of active, slow, and passive SOC pools were comparable to values used by Kelly et al. (1997), who conducted a long-term simulation of SOC dynamics for a forest soil using the Century model. Initial mineral N concentrations in soil water were estimated based on measured mean concentrations of nitrate and ammonium in the receiving drainage ditch during spring 1989. Consistent with the findings of Thorp et al. (2010), model predictions are insensitive to initial concentrations of mineral N. The initial plant stage variables, including initial biomass of foliage, stem, and roots, were estimated using field-measured DBH values and biomass allocation fractions given by King et al. (1999). The initial tree density was 1000 trees ha^{-1} according to field measurements.

Model Calibration and Validation

Rigorous calibration and validation procedures are crucial for effective field-testing of computer models simulating the hydrology and biogeochemistry of forest lands. In this study, data collected from 1988 to 1997 (10 yr) were used to calibrate the DRAINMOD-FOREST model, and the data collected from 1998 to 2008 (11 yr) were used for model validation. Year 2003 was excluded from the analysis because of the large errors in measured drain flow caused by long durations of weir submergence that occurred during that year. Calibrating this comprehensive forest ecosystem model is a multiobjective task involving the calibration of the hydrological model, followed by calibrating the soil C and N model, and then calibrating the forest growth model.

The calibration of DRAINMOD was performed by comparing predicted daily, monthly, and yearly drainage and daily water table depth to measured values. The DRAINMOD-N II model was calibrated by comparing measured and predicted monthly and yearly nitrate losses via drainage water measured at the outlet of the small watershed. The plant growth model was calibrated by comparing predicted LAI and NPP to measured LAI and estimated NPP, respectively. Since the component models are fully integrated and interacting with each other, changing the parameters of one model could substantially change the predictions of the other two models. For instance, calibrating plant growth may change predicted LAI, which will subsequently affect hydrologic predictions including ET, drainage, and water table fluctuation. The changed LAI predictions will also alter photosynthesis processes and nitrogen uptake, which influence N dynamics. Due to this interaction and feedback among the three component models, a stepwise calibration process was repeated several times to obtain best achievable goodness of fit between model predictions and field observations. The statistical measures (Table 2) used for evaluating model performance include the Nash–Sutcliffe coefficient, mean absolute error, and normalized percent error (Legates and McCabe, 1999). To compare model performance during the calibration and validation periods, a two-tailed Student's *t* test was used to test the hypothesis that the values of the goodness-of-fit statistics during the calibration period are different (better), compared with those during the validation period.

Model Parameterization

The DRAINMOD-FOREST model requires three types of inputs: hydrologic, soil C and N, and vegetation. The model requires about 17 hydrologic parameters, including drainage system parameters, soil hydraulic properties, and plant parameters needed for PET and rainfall interception simulations, and seven soil temperature–related parameters (Table 3). Drainage system parameters, including drain depth and spacing, were set as the physical dimensions of the on-site drainage system (Fig. 3). The depth to restrictive layer was determined according to site measurements (McCarthy et al., 1991). The studied plantation site was bedded, and surface runoff had been negligible in most cases (McCarthy et al., 1991). Soil-related properties were mostly adapted from Amatya and Skaggs (2001), who modeled the hydrology of the same site during 1988 to 1997 using an earlier forestry version of DRAINMOD hydrology model. Unlike the uniform and constant saturated hydraulic conductivity of 3.9 m d^{-1} used by Amatya and Skaggs (2001), the soil depth–dependent effective saturated hydraulic conductivities were obtained through model calibration. These calibrated soil hydraulic conductivities (Table 3) are higher than

Table 1. Model inputs characterizing initial conditions for the study site.

Initial condition	Value
Hydrologic	
Water table depth (cm)	85
Snow depth (cm)	0
Litter pool	
Litter pool on forest floor (t DM† ha^{-1})	23
Litter pool in top soil (t DM ha^{-1})	9
C:N‡ of initial litter on forest floor	120
C:N of initial litter in forest soil	60
Soil organic carbon	
SOC§ content in top 20 cm of soil (mg g^{-1})	157
Partition of SOC to active pool (%)	2.5
Partition of SOC to slow pool (%)	62.5
Partition of SOC to passive pool (%)	35.0
Mineral nitrogen	
Nitrate concentration in topsoil (mg L^{-1})	1.02
Ammonium concentration in topsoil (mg L^{-1})	0.14
Plant	
Density (trees ha^{-1})	1000
Leaf biomass (t DM ha^{-1})	5.6
Stem biomass (t DM ha^{-1})	60
Root biomass (t DM ha^{-1})	18.3

† DM, dry matter.

‡ C:N, carbon-to-nitrogen ratio.

§ SOC, soil organic carbon.

Table 2. Performance measures used for comparing model predictions to observations.

Performance measure	Mathematical expression†
Nash–Sutcliffe coefficient (NSE)	$\mathrm{NSE} = 1.0 - \frac{\sum_{i=1}^{N}(M_i - P_i)^2}{\sum_{i=1}^{N}(M_i - \bar{M})^2}$
Mean absolute error (MAE)	$\mathrm{MAE} = \frac{1}{N}\left(\sum_{i=1}^{N}\lvert M_i - P_i\rvert\right)$
Normalized percent error (NPE)	$\mathrm{NPE} = \frac{(\bar{P} - \bar{M})}{\bar{M}} \times 100\%$

† M_i is the *i*th measured value, P_i is the *i*th predicted value, *N* is the number of paired measured–predicted values, and $\bar{M}$ and $\bar{P}$ are mean of measured and predicted values, respectively.

Table 3. Hydrologic input parameters for DRAINMOD model.

Parameter description	Value		
Drainage system design parameters			
Drain spacing (m)	100		
Drain depth (m)	1.2		
Depth to impermeable layer (m)	2.8		
Surface storage (cm)	7.5		
Kirkham's depth (cm)	3.75		
Effective drain radius (cm)	50		
Drainage coefficient (cm d^{-1})	5.0		
Soil hydraulic properties			
Soil layer	**0–50 cm**	**50–100 cm**	**100–300 cm**
Effective hydraulic conductivity (m d^{-1})	65	30	1.6
Drainable porosity	0.1	0.1	0.1
Saturated water content (cm^3 cm^{-3})	0.41	0.43	0.45
Water content at wilting point (cm^3 cm^{-3})	0.18	0.21	0.24
Rainfall interception and stomatal conductance parameters			
Maximum stomatal conductance (mmol m^{-2} s^{-1})	115		
Rate of stomatal closure to vapor pressure deficit (mmol m^{-2} s^{-1} $(kpa)^{-1}$)	24		
Leaf storage capacity (mm)	0.2		
Radiation regulator (MJ m^{-2} d^{-1})	12		
Stem storage capacity (mm)	0.1		
Percentage of rainfall diverted to stem (%)	0.5		
Soil temperature parameters			
Soil thermal conductivity function coefficient A (W m^{-1}°C)	0.47		
Soil thermal conductivity function coefficient B (W m^{-1}°C)	1.57		
Rain/snow dividing temperature (°C)	0		
Air temperature phase lag (hr)	8		
Temperature at the bottom of the soil profile (°C)	15.6		
Snowmelt base temperature (°C)	2		
Degree-day coefficient (mm d^{-1})	5		
Critical ice content (cm^3 cm^{-3})	0.2		

field measurements (McCarthy et al., 1991), but are comparable to values calculated by Skaggs et al. (2006) based on measured drainage rates and water table depths. The relationship between upward flux and water table depth was adapted from McCarthy et al. (1991). Specific canopy storage capacity was set to the same value used by Amatya and Skaggs (2001). Calibrated parameters for simulating PET (Table 3) were comparable to those used by Novick et al. (2009) and Domec et al. (2009). Specifically, the calibrated maximum stomatal conductance was comparable to the highest values measured on the site during 1988 and 1989 (McCarthy et al., 1991). Soil temperature parameters were obtained from Luo et al. (2000) and Youssef et al. (2005). To directly use air temperature (T_{air}) measured in open areas, we incorporated an empirical function ($T_{surf} = T_{air} \times [1 - e^{-k \times LAI}]$) with an attenuation factor (k) and LAI to quantify the relationship between soil surface temperature (T_{surf}) and air temperature (Kang et al., 2000; Paul et al., 2004). The attenuation factor used in this study was 0.4 according to Kang et al. (2000).

About 24 parameters are needed for simulating soil C and N dynamics, including soil physical and chemical properties, N transport and transformation parameters, and parameters related to the decomposition and cycling of soil organic matter (Table 4). Soil physical and chemical properties, including bulk density and soil pH values, were obtained from field measurements conducted in 2007 (unpublished data). Soil texture data were adapted from soil survey data for Deloss fine sandy loam soil series (NRCS, 2010). Most parameters associated with soil C and N transformation processes were adapted from Youssef et al. (2005) and Youssef et al. (2006), who developed the DRAINMOD-N II model and tested it for an agricultural ecosystem in eastern North Carolina. Michaelis–Menten parameters were obtained from model calibration and are comparable to values obtained by Diggs (2004). The calibrated distribution coefficients were higher than those used by Youssef et al. (2006) to simulate N dynamics in a drained agricultural field. The use of higher distribution coefficients was justified because of the higher organic matter content of the forest soil. In contrast to agricultural soils, the availability of soil mineral N has relatively less effect on decomposition of soil organic matter because forest soils generally accumulate relatively small amounts of inorganic N (Prescott, 1995; Kirschbaum and Paul, 2002). Therefore, the calibrated maximum mineral N content at which transformation of SOC pools occurs with minimum C-to-N ratios was adjusted to a lower value than the one used by Youssef et al. (2006). Calibrated decomposition rates of all soil organic matter pools were substantially lower than those used for agricultural fields (Youssef et al., 2006), while they were within the range given by Kirschbaum and Paul (2002) for forest ecosystems.

The newly incorporated forest growth component requires about 27 vegetation parameters for simulating net primary production, C allocation, litterfall, and forest management practices (Table 5). Most of these parameters were obtained or estimated from published literature. The calibrated values of C allocation parameters (Table 5) were in the range of field measurements reported by Gower et al. (1994), King et al. (1999), and Maier et al. (2004). Calibrated parameters for calculating crown diameter were comparable to values given by Bechtold (2003), who summarized empirical parameters for 80 common tree species in the southeastern United States. Temperature modifier parameters regulating loblolly pine growth were adapted from Teskey et al. (1994). Parameters quantifying effects of age on growth of loblolly pine were obtained from Landsberg and Waring (1997). Leaf longevity was adapted from Zhang and Allen (1996) and fine root turnover rate was set the same as estimations of King et al. (2002). Calibrated specific LAI was very close to measurements by DeLucia et al. (2002). The canopy extinction coefficient was adjusted based on measurements conducted by Dalla-Tea and Jokela (1991). The calibrated C use

Table 4. Inputs of the DRAINMOD-N II model.

Parameter description	Value		
Soil parameters			
Soil layer	**0–50 cm**	**50–100 cm**	**100–300 cm**
Clay fraction	0.14	0.25	0.29
Silt fraction	0.18	0.18	0.22
Dry soil bulk density (g cm^{-3})	0.82	1.25	1.62
Distribution coefficient (cm^3 g^{-1})	4.0	3.6	3.5
Soil pH	4.1	4.3	4.7
Nitrogen transport parameters			
Longitudinal dispersivity (cm)		10	
Tortuosity		0.5	
Critical pH		7.5	
Transformation parameters	**Urea hydrolysis**	**Nitrification**	**Denitrification**
Maximum reaction rate (μg g^{-1} soil d^{-1})	120	8.5	1.0
Half saturation constant	50 mg L^{-1}	12.5 μg g^{-1}	30 mg L^{-1}
Optimum temperature (°C)	51.6	30	35
Threshold water-filled pore space	—	—	0.7
Optimum water-filled pore space range	0.5–0.7	0.5–0.6	—
Organic matter decomposition parameters			
Mineral N concentration at which litter enters SOM† pool with minimum C:N‡		2.5 mg L^{-1}	
Optimum temperature (°C)		35	
Optimum water-filled pore space range		0.5–0.6	
Litter pools	**K_{dec}§ (d^{-1})**		**C:N**
Surface structural	0.21×10^{-2}		150
Surface metabolic	0.78×10^{-2}		15
Surface microbes	0.36×10^{-2}		8
Belowground structural	0.27×10^{-2}		150
Belowground metabolic	0.97×10^{-2}		15
SOM pools			
Active	0.45×10^{-2}		12
Slow	1.48×10^{-4}		24
Passive	0.33×10^{-5}		22

† SOM, soil organic matter.

‡ C:N, carbon-to-nitrogen ratio.

§ K_{dec}, maximum decomposition rate.

efficiency was comparable to estimated values for loblolly pine by Maier et al. (2004). Radiation use efficiency was obtained from DeLucia et al. (2002). Nitrogen concentrations of tree tissues were obtained from field measurements of loblolly pine in North Carolina (Albaugh et al., 2008). Although there was usually minimal understory at the study site over the study period because of the dense canopy (Amatya and Skaggs, 2001), instant removal of 50% forest canopy after the commercial thinning in 1989 might lead to temporal regrowth of local understory species. The maximum productivity of understory species at the study site was determined empirically. Nitrogen and lignin content of understory species were set for on-site dominant understory species (Sampson et al., 2011), based on published studies (Taylor et al., 1989; Walbridge, 1991).

Results and Discussion

Hydrological Predictions

Amatya and Skaggs (2001) previously modeled hydrological processes for this site during 1988 to 1997 using DRAINLOB, an earlier forestry version of the DRAINMOD hydrology model (McCarthy and Skaggs, 1991). As part of developing the DRAINMOD-FOREST, we have modified the algorithms estimating rainfall interception and PET in the DRAINLOB hydrology model. The availability of a longer-term data set than the one used by Amatya and Skaggs (2001) provides a more robust calibration and validation of the hydrologic model and consequently leads to more accurate predictions of the hydrological processes, which are extremely critical for accurate prediction of N export from the site.

Drainage Predictions

Predicted yearly and monthly drainage rates were compared to measured values over the study period (Fig. 4 and 5). Statistical measures of model performance are summarized in Table 6. In general, predicted annual drainage rates were in very good agreement with measured values (Fig. 4). Predicted and measured mean annual drainage over the study period were 472.7 and 465.4 mm, respectively. Normalized percent errors (NPEs) indicate that annual drainage was overpredicted in 9 yr and underpredicted in 11 yr. Absolute NPEs of predicted annual drainage were <10% in 12 of the 20 simulated years. The mean of NPE in predicting annual drainage was 5.4% with a standard deviation of 22.4%. The mean absolute error (MAE) in predicting annual drainage was

Table 5. Input parameters for the plant growth model.

Parameter description	Value	
Allometric relationships and partitioning		
Foliage:stem partitioning ratio at diameter = 2 cm	1.1	
Foliage:stem partitioning ratio at diameter = 20 cm	0.72	
Empirical coefficient of the stem mass vs. diameter relationship	0.063	
Empirical exponent of the stem mass vs. diameter relationship	2.23	
Maximum carbon allocation fraction to roots	0.5	
Minimum carbon allocation fraction to roots	0.23	
Temperature modifier		
Minimum temperature for growth (°C)	2	
Optimum temperature for growth (°C)	25	
Maximum temperature for growth (°C)	45	
Age modifier function, f_A		
Maximum stand age (yr)	200	
Empirical exponent of f_A	4	
Relative age at which f_A = 0.5	0.5	
Litterfall and root turnover		
Leaf longevity (months)	20	
Fine root turnover rate (d^{-1})	0.006	
Canopy structure and processes		
Specific leaf area	4.16	
Extinction coefficient for absorption of PAR† by canopy	0.55	
Canopy quantum efficiency (mol mol^{-1} PAR)	0.05	
Nitrogen and lignin contents of plant tissues	**Nitrogen content**	**Lignin content**
Leaf (%)	1.12	23
Stem (%)	0.19	28
Root (%)	0.83	28
Understory species		
Maximum productivity (t ha^{-1})	6.5	
Mean nitrogen content (%)	1.0	

† PAR, photosynthetically active solar radiation.

53.3 mm yr^{-1}, which was substantially lower than the standard deviation of measured annual drainage (271 mm yr^{-1}), indicating that the model's predictions were acceptable. The Nash–Sutcliffe coefficient (NSE) for annual drainage predictions over the whole study period was 0.93, indicating accurate model predictions of annual drainage rates. The accuracy of model predictions of annual drainage was consistent throughout the whole study period as indicated by comparable NSE values during the calibration and validation periods. However, both MAE and NPE showed that the model performed slightly better during the calibration period (Table 6). This was mostly due to the large discrepancies between model predictions and field measurements during the years of 2001, 2002, and 2008 (Fig. 4). The extremely dry conditions of 2001 led to large NPE (88%) in that year, while the corresponding MAE was only 40 mm. During the period from July to December 2002, on-site rainfall data were unavailable and rainfall measured at an adjacent site was used in the simulation. Using methods suggested by Amatya et al. (1996), we conducted a simple water balance using measured rainfall, drainage, and soil water storage (based on water table depths at the beginning and end of 2002) to compute ET by difference. Estimated ET in 2002 was approximately 1300 mm, which was much higher than the mean ET of 1050 mm over the study period. Therefore, we suspect the use of off-site rainfall data during the second half of 2002 led to the overprediction of ET and drainage rates in 2002. In 2008, estimated ET (1169 mm) was higher than the model prediction (1036 mm), leading to a large difference in predicted and measured drainage.

Predicted monthly drainage volumes were also in very good agreement with measured values (Fig. 5). The goodness-of-fit statistics of monthly drainage predictions were NSE = 0.87 and MAE = 10.1 mm mo^{-1}. Monthly drainage predictions were very good (NSE > 0.75) in 18 of 21 yr, acceptable (0.5 < NSE < 0.75) in 2 yr, and unsatisfactory (NSE = 0.1) in only 1 yr (2001). No significant (p > 0.3, df = 18) differences were found for measures of MAE during the calibration and validation periods (Table 6). However, NSEs of monthly drainage predictions during the calibration period were higher than those during the validation period and the difference was marginally significant (p = 0.09, df = 18). This suggests that model predictions of monthly drainage rates were slightly less accurate during the validation period.

Figure 6 illustrates the scatterplots for predicted and measured daily drainage during model calibration and validation periods. Table 7 summarizes statistical measures of model performance for predicting daily drainage. Days with missing rainfall data were excluded from both graphical and statistical comparison. Predicted daily drainage was in good agreement with measured values. The goodness-of-fit indices for daily drainage predictions were NSE = 0.75 and MAE = 0.34 mm d^{-1}. Student's t test shows that NSEs of daily drainage predictions were significantly higher (p = 0.03, df = 18) during model calibration. The MAEs in daily drainage predictions during the calibration period were slightly lower than those during the validation period, but not statistically significant (p = 0.42, df = 18). Despite the relatively high NSE values,

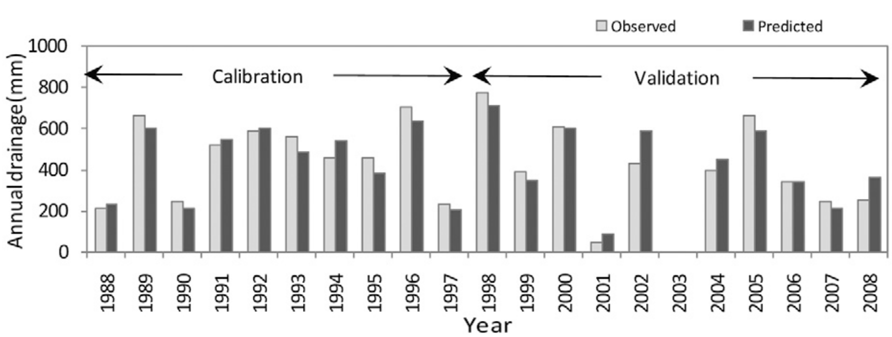

Fig. 4. Comparison between predicted and measured annual drainage during model calibration and validation periods.

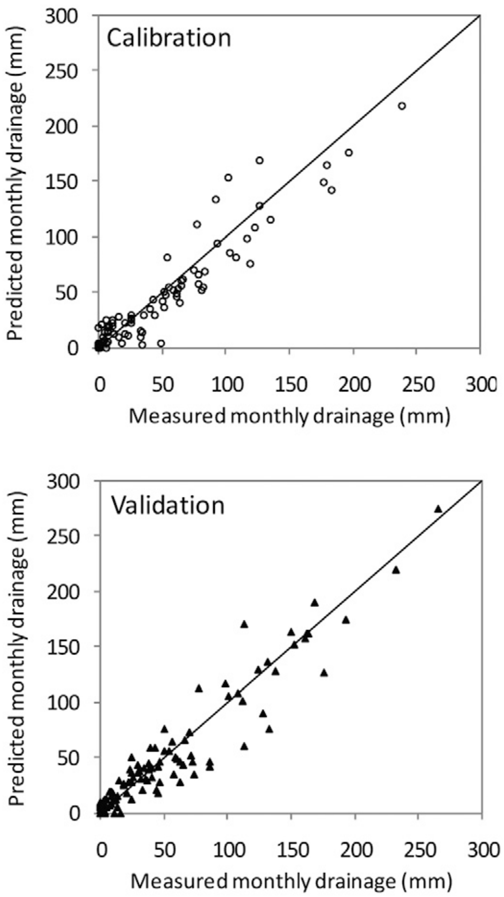

Fig. 5. Comparison between predicted and measured monthly drainage during model calibration and validation periods.

Fig. 6 shows somewhat high discrepancies between predicted and measured daily drainage rates. This might be caused by the inaccurate representation of drainable porosity (Tian et al., 2012), as indicated by the inconsistent model performance of model predictions for daily water table depth and drainage. In addition, the drainage algorithm in DRAINMOD ignores short transition periods of forming the elliptic water table profile following large storm events. This can lead to underestimation of drainage during large rainfall events and can result in a time lag of peak flows (McCarthy and Skaggs, 1991).

Water Table Predictions

Figure 7 compares predicted and measured daily water table depths during the calibration and validation periods. Table 7 summarizes goodness-of-fit statistics of model predictions of daily fluctuation of water table. Both visual comparison and statistical measures show that predicted daily average water table depths were in very good agreement with measured values (Fig. 7). The overall goodness-of-fit statistics were NSE = 0.90 and MAE = 0.10 m (Table 7). Daily water table depth predictions were excellent (NSE > 0.85) in 17 of 21 simulated years and satisfactory during the remaining 4 yr. Student's *t* test showed no significant ($p > 0.5$, df = 18) differences between all goodness-of-fit statistics of predicted daily water table depth during the calibration and validation periods.

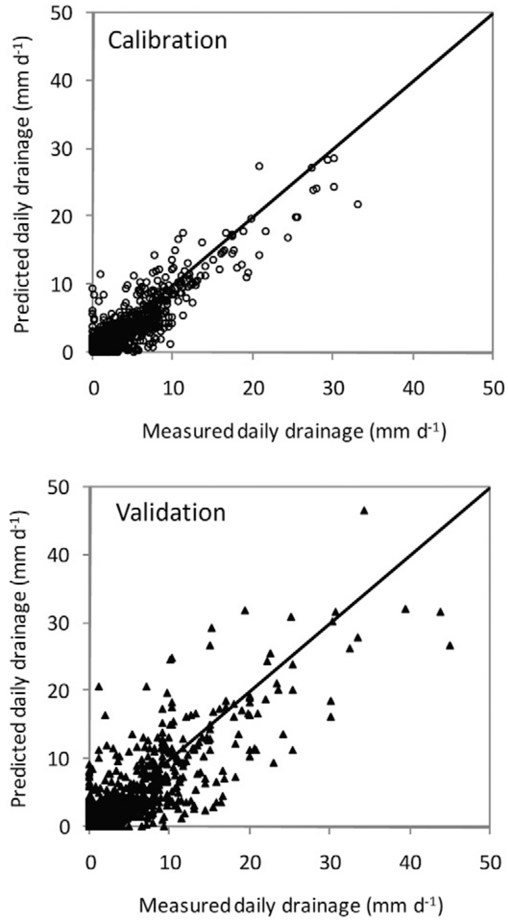

Fig. 6. Comparison between predicted and measured daily drainage during model calibration and validation periods.

The comparisons between model predictions and field measurements indicated that the model did an excellent job of predicting hydrological processes for the managed loblolly pine plantation. The model showed comparable performance to previous applications of the model in agricultural land (e.g., Youssef et al., 2006; Thorp et al., 2010; Luo et al., 2010). Moreover, according to these statistical measures, the DRAINMOD-FOREST model performed slightly better than the DRAINLOB model (Amatya and Skaggs, 2001). For instance, mean NSEs for DRAINLOB-predicted daily water

Table 6. Statistical measures of model predictions for annual and monthly drainage during calibration and validation periods.

Period	Annual drainage			Monthly drainage	
	NSE†	MAE†	NPE†	NSE	MAE
		mm yr^{-1}			mm mo^{-1}
Calibration	0.92	47.14	−4%	0.91	8.66
Validation	0.94	59.38	15%	0.85	11.48
Overall	0.93	53.26	5%	0.87	10.14

† NSE, Nash–Sutcliffe efficiency; MAE, mean absolute errors; NPE, normalized percent errors. The NPEs of predicted monthly drainage were not provided because of zero drainage volume during several months.

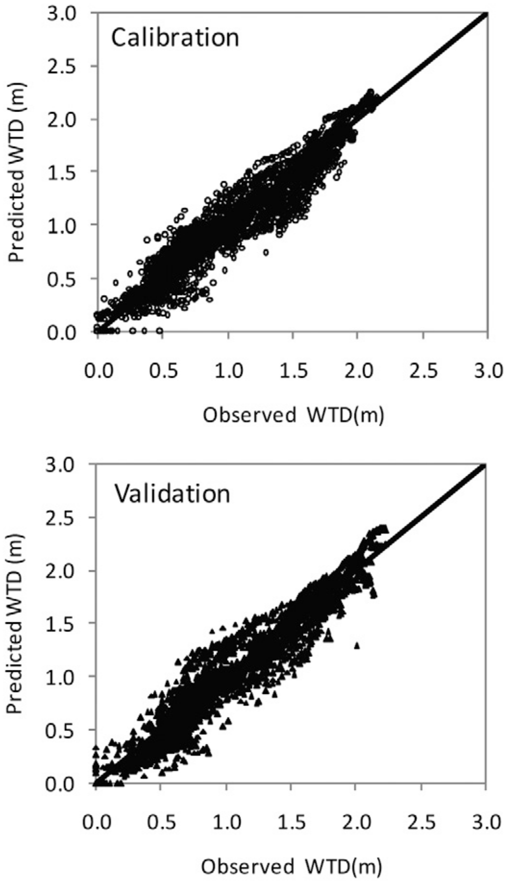

Fig. 7. Scatterplots for predicted and measured daily water table depths (WTD) during model calibration and validation periods.

table depth and drain flow during 1988 to 1997 were 0.78 and 0.71, respectively (Amatya and Skaggs, 2001), both of which were lower than the values obtained in this study (Table 7). The improved model performance in predicting hydrological processes could be largely attributed to the longer data set used for model calibration. The longer time series of data provided a more robust model calibration and validation. The adjusted soil hydraulic conductivity, drainable porosity, and upward flux values might have also improved hydrological predictions, compared to Amatya and Skaggs (2001).

Carbon Dynamics in the Forest Ecosystem

Net Primary Production Predictions

Comparisons between predicted and estimated annual NPP are presented in Fig. 8. Predicted mean annual NPP was 17.4 t dry matter (DM) ha^{-1}, which was very close to the estimated value of 18.3 t DM ha^{-1}. The goodness-of-fit statistics of the annual NPP predictions were NSE = 0.66, MAE = 1.46 t ha^{-1} yr^{-1}, and NPE = −1.8%. These results are acceptable according to Hanson et al. (2004), who considered NSE values <0.5 an indication of poor predictions of NPP. In addition, absolute percent errors of yearly NPP predictions in 15 of 21 simulated years were <10%, which indicated that predicted annual NPPs were comparable to estimated annual NPP in most simulated years. Discrepancies between predicted and estimated annual NPPs partly resulted from inaccurate predictions of the forest growth model. Similar to other forest growth models, there are uncertainties in simulating C assimilation through photosynthesis processes and C allocation to different tree components. Another possible cause that cannot be ignored was the assumed constant C allocation fraction to belowground biomass (30% in this study) when estimating annual NPP from measured DBH values. This assumption might not hold throughout the whole study period, as C allocation to root biomass changes in response to temporal variations in climatic and soil nutrient conditions (King et al., 2002).

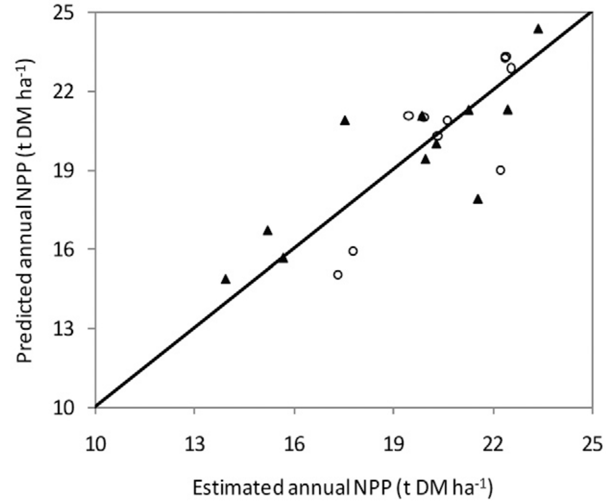

Fig. 8. Comparison between predicted and estimated annual net primary production (NPP). Circles represent model calibration period, while solid triangles denote validation years.

Table 7. Goodness-of-fit statistics for model predictions of daily drainage and water table depth during years of calibration and validation periods. Values in parentheses are standard deviations.

Period	Daily drainage		Daily water table depth	
	NSE†	MAE†	NSE	MAE
		mm d^{-1}		m
Calibration	0.84 (0.04)	0.24 (0.23)	0.90 (0.07)	0.10 (0.03)
Validation	0.73 (0.11)	0.36 (0.36)	0.89 (0.08)	0.10 (0.03)
Overall	0.75 (0.07)	0.34 (0.27)	0.89 (0.07)	0.10 (0.03)

† NSE, Nash–Sutcliffe efficiency; MAE, mean absolute errors.

Leaf Area Index Predictions

In general, the model was able to predict both the magnitude and dynamics of LAI (Fig. 9). The model predictions of intra-annual fluctuations of LAI indicated that it usually peaked during late fall and bottomed in early spring of the year, which closely matched measured seasonal variations in LAI. The model consistently underestimated LAI peaks of all years except for 1997 and 1999. However, the predicted lowest LAI values closely matched the measured in most years (Fig. 9). To some extent, model predictions captured interannual LAI dynamics. The model responded reasonably well to dry conditions during 1993 (April to October precipitation = 320 mm) and 2001 (total precipitation = 850 mm). It is important to note that extreme weather conditions (such as Hurricane Fran in 1996) can damage the forest canopy and lead to sudden decrease in LAI. Predicting effects of such natural disturbances is currently beyond the capability of the model. These results demonstrate that the model is capable of predicting dynamics of leaf production and senescence as controlled by plant

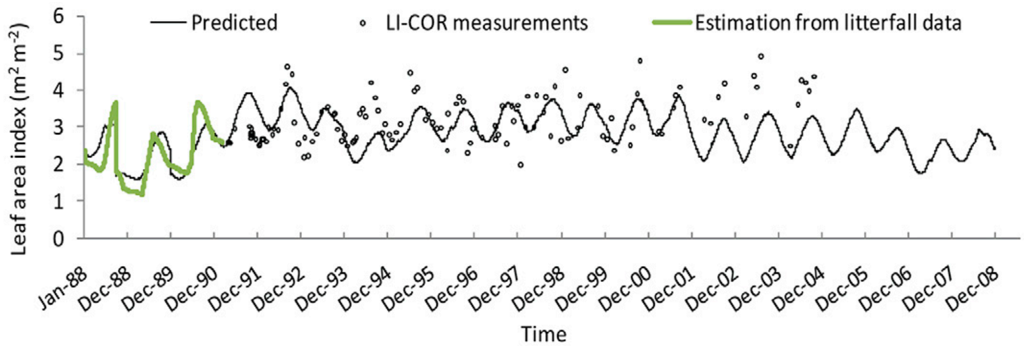

Fig. 9. Comparison between predicted and measured projected leaf area index (LAI); the estimated LAI from litterfall data was interpolated based on monthly field measurements (Amatya et al., 1996).

phenology properties. However, the model consistently predicted a slower recovery of LAI following prolonged dry periods. For instance, the model underpredicted LAI in 1994, 1995, and 2002, following the dry conditions in 1993 and 2001. Similarly, we suspect that the model also underpredicted LAI values in 2008 because of the severe drought during the growing season in 2007. The underprediction of LAI in 1994, 2002, and 2008 further explains the overprediction of annual drainage during these years.

Organic Carbon Pools

Figure 10 shows predicted monthly fluctuation in OC content on the forest floor and in the top 20-cm soil layer during the study period. Predicted OC content on the forest floor ranged from 11.3 t ha^{-1} in the summer of 1992 to 18.3 t ha^{-1} in the spring of 2002, with a mean value of 14.9 t ha^{-1} (SD = 11.2 t ha^{-1}, n = 252). Predicted OC on the forest floor was higher than measured OC of 5 to 10 t ha^{-1} in Duke Forest located in the Piedmont of North Carolina (Lichter et al., 2005), but comparable to results obtained by Zerpa (2005), who measured OC accumulation of several loblolly pine plantations located in the East Gulf Coastal Plain, USA. The predicted storage of OC on the forest floor was also in the range of measured values (10–30 t ha^{-1}) of southeastern loblolly pine stands (Zerpa, 2005; Hass et al., 2010). According to model predictions, OC on the forest floor fluctuated both intra- and interannually. For each year, predicted OC usually peaked in the late spring and reached its lowest content in the late summer (Fig. 10). This seasonal OC dynamics are mainly due to seasonal litterfall dynamics that are regulated by plant physiology and seasonal changes in weather conditions. Silvicultural practices can significantly alter OC pool dynamics on the forest floor. In late 1988, the thinning operation induced a sudden increase in OC storage, followed by a 4-yr period of decrease of OC because of reduced litterfall rate after thinning (Blanco et al., 2006).

Variation in climatic conditions is another important factor regulating OC pool dynamics on the forest floor. For instance, dry periods during the growing seasons of 1993 and 2001 led to large accumulations of OC on the forest floor. This is most likely attributed to slow OC decomposition rates under drought conditions (Hass et al., 2010). The wet conditions in 2003 maintained favorable soil water levels in the top soil layer, accelerated the decomposition of litter and fresh organic materials, and resulted in a relatively large decline in OC pool on the forest floor during that year. In contrast to obvious OC fluctuations on the forest floor, predicted OC content in the soil profile was relatively stable throughout the study period (Fig. 10). Predicted OC contents in the top 20 cm of the soil profile ranged from 157 to 160 mg g^{-1} soil, with a mean value of 158 mg g^{-1} soil. As shown in Fig. 10, the model predicted that the temporal change in soil OC content closely followed the temporal change in OC pool on the forest floor. Predicted soil OC slightly decreased following the thinning event of 1988 until it reaches minimum level in 1994 and then soil OC begins to accumulate annually at a consistently declining rate. It is expected that the soil OC content will eventually level off when it reaches a quasi-equilibrium state. The thinning operation significantly reduced litterfall rate and accordingly changed soil OC status (Kunhamu et al., 2009). Nevertheless, the relatively constant predicted soil OC dynamics in the drained loblolly pine plantation is consistent with Johnson et al. (2003), who reported that no statistically significant changes in soil OC content were found over 18 yr in a loblolly pine plantation without significant human disturbance.

Nitrogen Predictions

Nitrate Export Predictions

Since both measured and predicted ammonium losses through drainage were very small (<0.1 kg ha^{-1} yr^{-1} on average), ammonium leaching losses are not presented herein. Months with missing and inaccurate drainage measurements during extremely high flow events were excluded when comparing predicted and measured nitrate export.

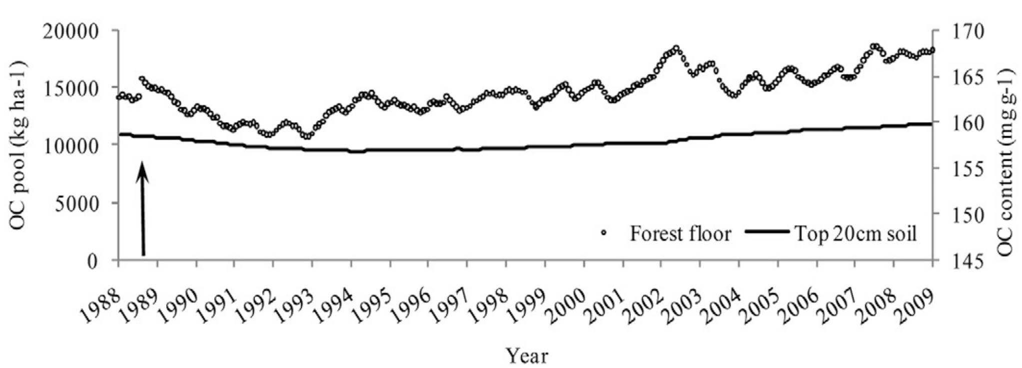

Fig. 10. Temporal dynamics of organic carbon (OC) on the forest floor and in the top 20 cm of soil. The arrow represents a thinning event that occurred in early October 1988.

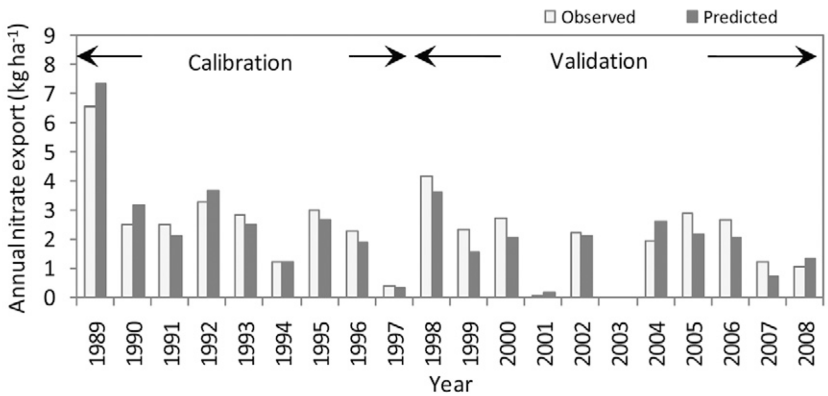

Fig. 11. Comparison between predicted and measured annual nitrate export during model calibration and validation periods.

Predicted annual nitrate loading via subsurface drainage closely followed measured annual nitrate export dynamics (Fig. 11). Predicted mean annual nitrate loss was 2.4 ± 1.6 kg N ha^{-1}, which was very close to the observed value of 2.6 ± 1.5 kg N ha^{-1}. The goodness-of-fit statistics (Table 8) for predicted annual nitrate losses during the whole study period were NSE = 0.91, MAE = 0.39 kg N ha^{-1} yr^{-1}, and NPE = 10%. The MAE was much smaller than the standard deviation (1.6 kg N ha^{-1} yr^{-1}), indicating results were acceptable. The NPEs suggested that annual nitrate export was overpredicted in 10 yr and underpredicted in the other 10 yr, indicating no systematic errors in model predictions of annual nitrate losses. Absolute values of NPEs of annual nitrate export predictions were <10% in 5 yr and <20% in 14 of the 20 simulated years. The relatively large percent errors that occurred in the other 6 yr were mainly caused by the relatively low nitrate loss from the forested site and inaccurate annual drainage predictions. For example, the model overpredicted annual nitrate export by 0.5 kg ha^{-1} in 1994, which was equivalent to 36% of the measured nitrate export during that year. While the nitrate export in 2001 was relatively small and insignificant from both water quality and ecosystem perspectives, the NPE (180%) of predicted nitrate export was the largest, corresponding to poor prediction of annual drainage during this extremely dry year. In 2001, predicted and measured drainage volumes were 110 and 45 mm, respectively, and predicted and measured nitrate export were 0.19 kg ha^{-1} and 0.07 kg ha^{-1}, respectively. Statistical measures, including NSE and MAE, were consistent during the calibration and validation periods (Table 8). However, the largest NPE in 2001 led to the relatively large difference in NPE of annual nitrate predictions between model calibration and validation periods. Nevertheless, excluding the extremely dry year of 2001, above comparisons suggested that the model consistently showed good performance for predicting annual nitrate losses over the whole study.

Predicted monthly rates of nitrate export were also in good agreement with measured monthly nitrate losses through subsurface drainage (Fig. 12). Predicted and measured mean monthly nitrate loadings were 0.20 ± 0.40 kg ha^{-1} and 0.19 ± 0.36 kg ha^{-1}, respectively. The goodness-of-fit statistics (Table 8) for predicted monthly nitrate export were NSE = 0.80 and MAE = 0.08 kg ha^{-1} mo^{-1}, all of which indicated a good performance of the model. The NSEs of predicted monthly nitrate loss were higher during model calibration period, but not statistically significant according to Student's *t* test ($p = 0.13$, df = 16). Meanwhile, MAE values of predicted monthly nitrate losses during the calibration period were very close to those during the validation period, and the differences were not statistically significant ($p = 0.42$, df = 16). Discrepancies between predicted and measured nitrate export can be largely attributed to either inaccurate hydrological predictions or imprecise quantification of N transformations (Youssef et al., 2006). The above explanation is supported by the comparable but consistently poorer goodness-of-fit statistics of predicted nitrate export compared to that of hydrological predictions. In addition, we cannot rule out uncertainties in field measurements (Chescheir et al., 2010), especially measurements during the period between 1994 and 2008 when weekly or biweekly sampling frequencies were used.

Simulated Nitrogen Transformations

Accurate quantification of physical, chemical, and biological processes that regulate N fate and transport in drained forest ecosystems is essential for predicting mineral N export from these drained forests to downstream surface waters. Three sources of mineral N are considered in the DRAINMOD-FOREST model: mineralization of soil organic N, wet deposition, and N fertilizer application. In the study site, assumed mean annual wet N deposition was 9.0 ± 1.1 kg ha^{-1}, which was very close to measured 10 kg ha^{-1} yr^{-1} based on long-term measurements made by the National Atmospheric Deposition Program and National Trends Network (NADP/NTN, 2010) monitoring location (NC06) in Beaufort, NC. Table 9 summarizes predicted annual rates of N transformations over the study period. All means and standard deviations were calculated without year 1989 when N fertilizer was applied. Predicted mean annual net mineralization was 74.0 ± 11.3 kg ha^{-1}, which was the principal N source providing around 90% of mineral N (except for 1989 because of fertilization) for plant uptake. Model predictions of net N mineralization rates are comparable to field measurements obtained by Birk and Vitousek (1986) and Li et al. (2003). Predicted mean annual N uptake was 76.2 ± 11.2 kg ha^{-1} (Table 9). The interannual variations in N uptake were mainly attributed to annual NPP fluctuations controlled by climatic conditions, nutrient availability, and management practices such as thinning in 1988 and fertilization in 1989. Predicted annual N uptake ranged

Table 8. Statistic measures of model predictions for annual and monthly nitrate losses during calibration and validation periods.

Period	Annual nitrate loss			Monthly nitrate loss	
	NSE†	MAE†	NPE†	NSE	MAE
		kg ha^{-1} yr^{-1}			kg ha^{-1} mo^{-1}
Calibration	0.93	0.36	–3%	0.84	0.07
Validation	0.89	0.43	22%	0.79	0.09
Overall	0.91	0.39	10%	0.80	0.09

† NSE, Nash–Sutcliffe efficiency; MAE, mean absolute errors; NPE, normalized percent errors; NPEs of predicted monthly drainage were not provided because of zero drainage volume during several months.

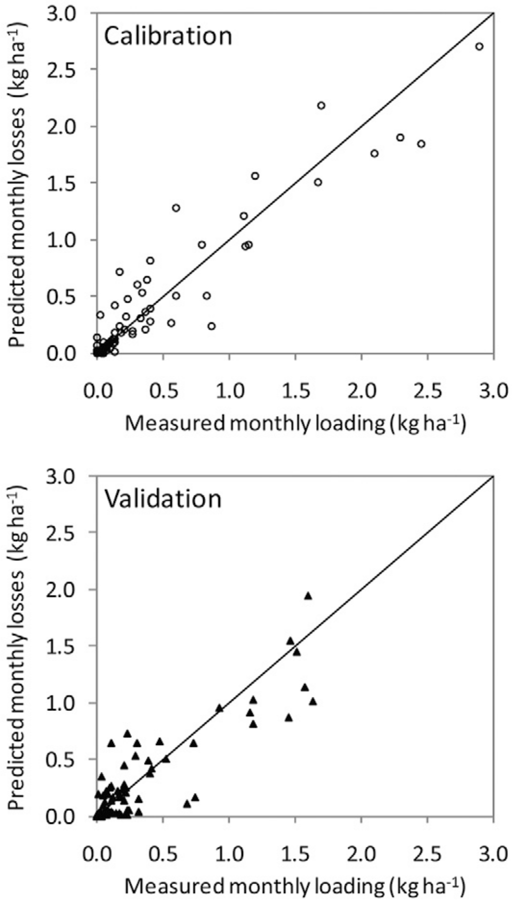

Fig. 12. Comparison between predicted and measured monthly nitrate export during model calibration and validation periods.

from as low as 56.3 kg ha^{-1} in 1993, due to the extremely dry growing season, to as high as 116 kg ha^{-1} in 1989 after thinning and fertilization. According to model predictions, one-third of the high N uptake in 1989 was attributed to temporary growth of understory species because of the reduced canopy cover after thinning. Predicted annual N uptake rates of loblolly pine were comparable to results of Ducey and Allen (2001) and Albaugh et al. (2008), who reported annual N uptake rate of loblolly pine ranging from about 50 to 110 kg ha^{-1} yr^{-1}.

Annual rates of nitrate export were closely related to annual nitrification rates as suggested by a correlation coefficient of 0.83. In this study, predicted annual nitrification rate ranged from 16.2 kg ha^{-1} in 2001 to 113.2 kg ha^{-1} in 1989. The predicted mean annual nitrification rate over the study period (excluding 1989) was 34.8 kg ha^{-1} yr^{-1} with a standard deviation of 8.7 kg ha^{-1} yr^{-1} (Table 9). Model predictions are comparable to annual nitrification rates reported by Stark and Hart (1997) for undisturbed mature coniferous forests.

Unlike agricultural fields where the denitrification process is an important pathway for N loss (Youssef et al., 2006), denitrification rates are relatively small in forested lands (Barton et al., 1999). The 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 high denitrification rate in 1989 was mainly caused by the N fertilizer application. 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}. The model predictions were also consistent with field measurements by Robertson et al. (1987), who reported annual denitrification rates in the range of 0.6 to 5.2 kg ha^{-1} for a clear-cut loblolly pine plantation located in the southeastern United States. 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 113.3 kg ha^{-1} was predicted following the application of the urea fertilizer. The lowest denitrification rate occurred in 2001 because of the drought and low nitrification rate. This analysis verified the model's ability to capture the close relationship between denitrification and substrate availability as well as soil water conditions.

Table 9. Summary of predicted annual rates (means and standard deviations) of nitrogen transformation processes from 1990 to 2008.

Process	Mean†
	kg ha^{-1} yr^{-1}
Net mineralization	74.0 (11.3)
Nitrification	34.8 (8.7)
Denitrification	1.9 (1.7)
Plant uptake	76.2 (11.2)
Nitrate leaching	2.4 (1.6)

† All mean values and standard deviations were calculated excluded data of 1989 because of the nitrogen fertilizer application.

Summary and Conclusions

This paper presented the DRAINMOD-FOREST model for simulating the hydrology, soil C and N dynamics, and tree growth for drained forest lands under various climate conditions and common silvicultural practices. The model integrates a physiologically based forest growth model with the DRAINMOD and DRAINMOD-N II models. The three components, with comparable levels of detail, are inherently linked together to make DRAINMOD-FOREST an integrated, well-balanced, and comprehensive model for drained forest ecosystems. Results of the field testing show that the DRAINMOD-FOREST was able to accurately predict long-term hydrological (drainage, water table depth), biogeochemical (nitrogen transformation and leaching losses), and plant growth for a drained forests under limited management condition. The model has also been successfully applied to predict these processes in two intensively managed loblolly pine plantations located in the eastern United States (Tian et al., 2012). Further testing of the model with more comprehensive field measurements, especially data related to tree growth and forest productivity, is warranted. Because the model requires a relatively large number of inputs, a sensitivity analysis is also needed to identify the set of model inputs that should be included in model calibration or should be measured if feasible.

Appendix A: Main Equations Used in the DRAINMOD-FOREST Model

DRAINMOD and DRAINMOD-N II Models

The water balance at the soil surface (Fig. 1) for each time increment can be written as:

$$P = F + \Delta S + \mathrm{RO} \qquad \text{[A-1]}$$

where P is precipitation (cm) for hydrology of agricultural land and throughfall for forest hydrology, F is infiltration (cm), ΔS is the change in volume of surface water storage, and RO is runoff (cm).

The water balance for the soil column located midway between adjacent drains (Fig. 1) is quantified as:

$$\Delta V_{\mathrm{a}} = Q + \mathrm{ET} + \mathrm{DS} - F \quad \text{[A-2]}$$

where ΔV_{a} is the change in the air volume (cm), Q is lateral drainage (cm), DS is the deep seepage (cm), and ET is evapotranspiration estimated as a function of soil water status in root zone and estimated potential evapotranspiration (PET) using Penman–Monteith method in DRAINMOD-FOREST:

$$\lambda \mathrm{PET} = \frac{\Delta(R_{\mathrm{n}} - G) + 86400\rho_{\mathrm{a}} J_{\mathrm{P}}(e_{\mathrm{s}} - e_{\mathrm{a}})/r_{\mathrm{a}}}{\Delta + \gamma(1 + r_{\mathrm{s}}/r_{\mathrm{a}})} \quad \text{[A-3]}$$

where λ is the latent heat of vaporization (2.45 MJ kg^{-1}), R_{n} is the net radiation (MJ m^{-2} d^{-1}), ρ_{a} is the mean air density at constant pressure, J_{p} is the specific heat of the air at constant pressure of 1.013 × 10^{-3} (MJ kg^{-1} °C^{-1}), ($e_{\mathrm{s}} - e_{\mathrm{a}}$) represents the vapor pressure deficit of the air, Δ represents the slope of the saturation vapor pressure–temperature relationship (kPa °C^{-1}), γ denotes the psychometric constant (kPa °C^{-1}), and r_{s} and r_{a} are the canopy stomatal resistance and aerodynamic resistance (s m^{-1}). Canopy stomatal resistance is simulated as a function of LAI predicted by the forestry module and the stomatal conductance (g_{s}):

$$r_{\mathrm{s}} = \frac{1}{g_{\mathrm{s}} \mathrm{LAI}} \quad \text{[A-4]}$$

The stomatal conductance is estimated based on empirical responses of stomata to a selected set of environmental variables using the multiple nonlinear constraint function similar to the one proposed by Jarvis (1976):

$$g_{\mathrm{s}} = g_{\mathrm{s.max}} \times f(\mathrm{VPD}, T, R) \quad \text{[A-5]}$$

where $g_{\mathrm{s.max}}$ is the maximum stomatal conductance, VPD represents vapor pressure deficit, T is air temperature, and R is solar radiation. A number of different functional forms adapted from Stewart and Verma (1992) and Samanta et al. (2008) were used to simulate the effects of VPD, T, and R on temporal dynamics of stomatal conductance.

The throughfall in Eq. [A-1] is estimated using a modified version of the Gash model (Gash et al., 1995):

$$I = \begin{cases} cP_{\mathrm{G}} + p_{\mathrm{t}} P_{\mathrm{G}} & \text{for } P_{\mathrm{G}} \le P' \\ cP'_{\mathrm{G}} + \dfrac{c\bar{E}}{\bar{p}}\left(p_{\mathrm{G}} - p'_{\mathrm{G}}\right) + p_{\mathrm{t}} P_{\mathrm{G}} & \text{for } P_{\mathrm{G}} > P'_{\mathrm{G}} \\ cP'_{\mathrm{G}} + \dfrac{c\bar{E}}{\bar{p}}\left(p_{\mathrm{G}} - p'_{\mathrm{G}}\right) + S_{\mathrm{t}} & \text{for } P_{\mathrm{G}} > S_{\mathrm{t}}/p_{\mathrm{t}} \end{cases} \quad \text{[A-6]}$$

where I represents the rainfall interception (mm), c is the canopy fraction, P_{G} is the gross rainfall (mm), p'_{G} is the threshold value necessary to saturate forest canopies (mm), $\bar{E}$ is the mean evaporation rate (mm t^{-1}) during rainfall events and $\bar{p}$ is the mean rainfall rate (mm t^{-1}), S_{t} is the trunk storage capacity (mm), and p_{t} denotes the proportion of the rainfall diverted to stem flow. Both S_{t} and p_{t} are user-specified inputs.

The DRAINMOD-N II model simulates the reactive transport (Fig. 1) of mineral N (nitrate and ammoniacal forms) using a finite difference solution to a multiphase form of the one-dimensional ADR equation:

$$\frac{\partial}{\partial t}\left(\theta_{\mathrm{a}} R_{\mathrm{f}} C_{\mathrm{a}}\right) = \frac{\partial}{\partial z}\left(D_{\mathrm{e}} \frac{\partial C_{\mathrm{a}}}{\partial z}\right) - \frac{\partial(\upsilon_{\mathrm{a}} C_{\mathrm{a}})}{\partial z} + S \quad \text{[A-7]}$$

where t is time in units of hours or days depending on accuracy requirement, θ_{a} is soil water content (cm^3 cm^{-3}), R_{f} is a dimensionless retardation factor, C_{a} is N species concentration in aqueous phase (mg cm^{-3}), D_{e} is effective dispersion coefficient (cm^2 t^{-1}), υ_{a} is the volumetric flux of soil water (cm t^{-1}), and S is a source–sink term (mg cm^{-3} t^{-1}) that lumps all mass changes in N species due to biological N transformations and physical transport. Driving hydrologic variables (θ_{a} and υ_{a}) required for the numerical solution of the ADR equation are based on predictions of the hydrologic model DRAINMOD. Nitrogen species concentration in drainage water predicted by DRAINMOD-N II and drainage volumes predicted by DRAINMOD are used internally to calculate N species mass loss with drain outflow. DRAINMOD-predicted soil water and soil temperature distribution along the soil profile is used by DRAINMOD-N II to quantify the effects of soil water and temperature on biological C and N transformations (Fig. 2).

Forest Growth Component

The forest growth model (Fig. 1 and 2) estimates gross primary production (GPP), net primary production (NPP), carbon allocation, and litterfall using physiology-based methods regulated by air temperature, water deficit, stand age, and soil N conditions.

Gross Primary Production

$$\mathrm{GPP} = \alpha \times f_{\mathrm{w}} \times f_{\mathrm{T}} \times f_{\mathrm{N}} \times f_{\mathrm{A}} \times (1 - e^{-k \times \mathrm{LAI}}) \times R \quad \text{[A-8]}$$

where GPP is estimated on a DM basis (t DM ha^{-1} d^{-1}), α is the maximum canopy quantum efficiency in mol mol^{-1}, f_{w} is the water stress modifier, f_{T} is the air temperature modifier, f_{N} is the site nitrogen modifier, f_{A} is the stand age modifier, k is the light extinction coefficient, LAI is the leaf area index (m^2 m^{-2}) estimated as a simple function of leaf biomass and specific leaf area (Landsberg and Waring, 1997), and R is the photosynthetically active radiation available for each plant species (MJ m^{-2} d^{-1}) estimated as the product of canopy fraction and total photosynthetically active radiation of each canopy layer.

Environmental Modifiers

The water stress (f_{w}) modifier is represented by the ratio of ET to PET (Aber and Federer, 1992):

$$f_{\mathrm{w}} = \frac{\mathrm{ET}}{\mathrm{PET}} \quad \text{[A-9]}$$

where PET is the daily potential evapotranspiration (mm), estimated by using the Penman–Monteith method with a dynamics canopy conductance, and ET is the simulated daily evapotranspiration (mm), which is a function of the estimated daily PET, plant root depth, and the soil water conditions (Skaggs, 1978).

Among these modifiers, the temperature (f_{T}) and stand age (f_{A}) modifiers were adapted from the 3-PG model (Landsberg and Waring, 1997):

$$f_{\mathrm{T}} = \begin{cases} 0 & T > T_{\max} \\ \left(\dfrac{T - T_{\min}}{T_{\mathrm{opt}} - T_{\min}}\right)\left(\dfrac{T_{\max} - T}{T_{\max} - T_{\mathrm{opt}}}\right)^{(T_{\max} - T_{\mathrm{opt}})/(T_{\mathrm{opt}} - T_{\min})} & T_{\min} \le T \le T_{\max} \\ 0 & T < T_{\min} \end{cases} \quad \text{[A-10]}$$

where T_{min} is the minimum temperature (°C) below which photosynthesis stops, T_{max} is the maximum temperature (°C) above which photosynthesis stops, and T_{opt} is the optimum temperature (°C) at which photosynthesis proceeds at maximum rate.

$$f_A = \frac{1}{1+[(A/A_x)/r_{age}]^{n_{age}}} \quad \text{[A-11]}$$

where A is age and A_x is the maximum age, r_{age} is the age when f_A is 0.5, and n_{age} is an empirical exponent, usually set to 1.

The nutrients modifier (f_N) was defined as:

$$f_N = \min\left\{1, \frac{N^i_{avail}}{N^i_{need}}\right\} \quad \text{[A-12]}$$

where N^i_{avail} and N^i_{need} (t ha^{-1}) are the available N and needed N for certain tree species, respectively. Available N to each tree species was obtained through partitioning total soil N among tree species as a function of fine root biomass and its vertical distribution:

$$N^i_{avail} = \sum_{j=1}^{n} N^j_T \frac{W^j_{fr.i}}{\sum_{i-1}^{m} W^j_{fr.i}} \quad \text{[A-13]}$$

where j is the layer of soil profile, $W^j_{fr.i}$ is the fine roots biomass (t ha^{-1}) of species i in the soil layer j. N^j_T (t ha^{-1}) is the total available N in soil layer j, which is the sum of the amount of mineral N in that soil layer and is determined by the DRAINMOD-N II model. An exponential function given by Gale and Grigal (1987) is used to describe the vertical distribution of fine root biomass in soil profile.

The daily potential N uptake (N^i_{avail}) is estimated as a function of N content of plant tissues and the potential biomass increments of different plant components without N stresses:

$$N^i_{need} = PG_s[N]_s + PG_f[N]_f + PG_r[N]_r \quad \text{[A-14]}$$

where PG is the potential growth of each tree component without N stress (t ha^{-1}), and [N] (mg g^{-1}) is the N concentration of tree component (s, stem; f, foliage; r, root).

Net Primary Production

The NPP is estimated either as a fixed fraction of GPP:

$$NPP = Y \times GPP \quad \text{[A-15]}$$

where Y is commonly referred to as the carbon use efficiency to quantify the fraction of assimilated C that is converted to tree biomass; or as a difference between GPP and plant respiration:

$$NPP = GPP - R_c - R_f - R_m \quad \text{[A-16]}$$

where R_c is construction respiration (t DM ha^{-1} d^{-1}), R_f is leaf respiration (t DM ha^{-1} d^{-1}), and R_m is maintenance respiration (t DM ha^{-1} d^{-1}). These components of plant respiration are estimated using methods of PROMOD (Battaglia and Sands, 1997) and CABALA (Battaglia et al., 2004) models. Construction respiration is the cost of converting assimilated C into biomass, which is commonly assumed as a constant fraction of NPP (Battaglia and Sands, 1997; Battaglia et al., 2004). Foliar respiration is estimated as a function of temperature and LAI (Battaglia and Sands, 1997). Maintenance respiration of fine roots and woody material is assumed to be temperature controlled and proportional to biomass and tissue N content (Battaglia et al., 2004).

Carbon Allocation and Carbon Balance

Estimated NPP is allocated to four biomass pools: foliage (W_f), stem (W_s), fine roots (W_{fr}), and coarse roots (W_{cr}). Litterfall of foliage, root turnover as well as biomass losses via management practices such as thinning and pruning are considered.

$$\Delta W_r = \eta_r p_n - \gamma_r W_r - \lambda_r (W_r / N)\Delta S \quad \text{[A-17]}$$

$$\Delta W_f = \eta_f p_n - \gamma_f W_f - \lambda_f (W_f / N)\Delta S \quad \text{[A-18]}$$

$$\Delta W_s = \eta_s p_n - \lambda_s (W_s / N)\Delta S \quad \text{[A-19]}$$

$$\Delta W_{fr} = \eta_{fr} \Delta W_r \quad \text{[A-20]}$$

where η_i is the fraction of NPP allocated to each biomass pool (s, stem; r, root; f, foliage), γ_f is the litterfall rate, and γ_r is the root turnover rate; λ represents the fraction of the biomass of tree components that will be returned into soil when a tree dies or removed; W_{fr} is the fine roots biomass (t ha^{-1}), which was assumed as a constant fraction of carbon allocated to root biomass (η_{fr}); and ΔS is the number of trees removed due to mortality, thinning, harvesting, and so on. These carbon allocation fractions are estimated as:

$$\eta_r = \frac{\eta_{Rx}\eta_{Rn}}{\eta_{Rn} + (\eta_{Rx} - \eta_{Rn}) m\phi} \quad \text{[A-21]}$$

$$\eta_s = \frac{1-\eta_r}{1+p_{FS}} \quad \text{[A-22]}$$

$$\eta_f = p_{FS}\eta_s \quad \text{[A-23]}$$

where η_{Rn} and η_{Rx} are the minimum and maximum root allocation ratios, p_{FS} is the ratio of foliage to stem allocation and this parameter is regulated by the tree size and tree age, ϕ represents the effect of age and water condition, and m determines the effects of site fertility condition on allocation through the following equations:

$$m = m_0 + (1-m_0) \times f_N \quad \text{[A-24]}$$

$$\phi = f_A f_w \quad \text{[A-25]}$$

where m_0 is the value of m when f_N is 0 and f_N ($0 \le f_N \le 1$) is the site fertility rating. Based on observed allometric relationships, Landsberg and Waring (1997) established an allocation relationship between foliage and stem. The ratio of foliage biomass partitioning to stem biomass partitioning (p_{FS}) is also expressed as an allometric function of stem diameter D (Landsberg and Waring, 1997):

$$p_{FS} = a_p D^{n_p} \quad \text{[A-26]}$$

$$n_p = \frac{\ln(p_{20}/p_2)}{\ln(10)} \quad \text{[A-27]}$$

$$a_p = \frac{p_2}{2^{n_p}} \quad \text{[A-28]}$$

where a_p and n_p are empirical parameters, and p_2 and p_{20} are P_{FS} values at D = 2 and 20 cm, respectively.

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