

Evaluation of the RZWQM for Simulating Tile Drainage and Leached Nitrate in the Georgia Piedmont

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ABSTRACT

Models have become an important tool for evaluating the impact of agricultural management practices on water quality. We evaluated the Root Zone Water Quality Model (RZWQM version 1.3.2004.213), for simulating tile drainage and NO₃ leaching under conventional and no-tillage management practices in cotton (*Gossypium hirsutum* L.) production and rye (*Secale cereale* L.) cover cropping practices in a Cecil (kaolinitic, thermic, Typic Kanhapludult) soil in Georgia, USA. We calibrated the model for tile drainage and NO₃ leaching in maize (*Zea mays* L.) production and for cotton development and water use in a previous study based on experimental data collected from 1992 through 1993 at Watkinsville, GA. For the current study, we used an independent data set collected from 1997 through 2000. Differences in measured and simulated tile drainage were 926 mm in conventional tillage and 712 mm in no-tillage treatments. Measured and simulated values of leached NO₃ were different by 62 and 73 kg ha⁻¹, respectively, for the two tillage treatments. Some of the differences in simulated drainage compared with the calibration study could be attributed to differences in simulated evapotranspiration and runoff. Comparing the simulated and calculated water balances and winter rye production of the calibration study with the current study, however, the effects of winter cover cropping practices during the 4-yr period at the study site since the model was calibrated have affected the amount of soil water available for drainage and NO₃ leaching at the depth of the drains.

THE attention of the public, policymakers, regulators, and the scientific community has shifted from point source to nonpoint source (NPS) pollution of subsurface soil and water resources. This has been due to the growing reliance on groundwater as a source for drinking water as well as for agriculture (Corwin et al., 1999). The assessment and remediation of NPS groundwater contamination from the historic and continuous use of agrochemicals pose problems with significantly greater economic impacts than those that have long been recognized for point sources (Loague and Corwin, 1996). Agricultural research traditionally focused on the efficient use of water for improving the productivity of food and fiber, but is now equally focused on the quality of the water resource as it impacts drinking water supplies.

An effective methodology to develop agricultural management systems that address NPS pollution is through experimentation and modeling (Ahuja et al., 2000). There

is a considerable effort by both researchers and natural resource managers to model NPS pollution at the watershed scale; however, there continues to be a need for evaluation and improvement of the deterministic, field- and plot-scale models that serve as the basis for these watershed models. Models such as LEACHM (Hutson and Wagenet, 1992), PRZM and PRZM3 (USEPA, 2003), GLEAMS (Leonard et al., 1987), OPUS (Smith and Ferreira, 1992), CROPGRO (Hoogenboom et al., 1992; Boote et al., 1998), CERES-Maize (Jones and Kiniry, 1986; Ritchie et al., 1998), and the RZWQM (Ahuja et al., 2000), are examples of field-scale, deterministic models. They were developed based on the accumulated knowledge of the soil–water–plant continuum processes in agricultural systems over many years of laboratory and field studies. Distributed parameter models such as AGNPS (Young et al., 1989) use model components from field-scale models such as CREAMS (Knisel et al., 1983) to predict soil erosion and nutrient transport and loadings from agricultural watersheds. The SWAT model (Arnold et al., 1993) incorporates features of several agricultural models and is a direct outgrowth of the SWRRB model (Simulator for Water Resources in Rural Basins; Williams et al., 1985; Arnold et al., 1990), using components from the CREAMS, GLEAMS, and EPIC models (Williams et al., 1984; Soil and Water Assessment Tool, 2004). Deterministic models, although originally developed as research models, have been linked or interfaced with geographic information systems such as GRASS (Geographic Resources Analysis Support System; U.S. Army Corps of Engineers, 2004) and decision support systems such as DSSAT (Decision Support System for Agrotechnology Transfer; Tsuji et al., 1994; Hoogenboom et al., 1992). Scientific components and submodels of these models are also currently being linked to the object-oriented modeling system (OMS), a framework that facilitates the assembly of a modeling package and shares different model resources (OMSCentral, 2004). Deterministic models have been developed based on many years of experimental study, and the confidence-building process in model prediction is a long-term and iterative process (Hassan, 2003). Model developers continue to test and refine deterministic models to improve simulation of physical, biological, and chemical processes and systems (Donigan and Huber, 1991).

The goal of this project was to evaluate the performance of the calibrated RZWQM model (Abrahamson et al., 2005) for simulating tile drainage and leached NO₃ in cotton production under conventional tillage (CT) and no-tillage (NT) agricultural management

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Modeling

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Abbreviations: CT, conventional tillage; ET, evapotranspiration; NT, no-tillage; PET, potential evapotranspiration; RZWQM, Root Zone Water Quality Model.

practices in the southern Piedmont of Georgia, USA. The RZWQM is an integrated physical, biological, and chemical process model that simulates plant growth and the movement of water, nutrients, and pesticides over and through the root zone in a representative area of an agricultural cropping system (Ahuja et al., 2000). The model was originally developed to provide a comprehensive simulation of root zone processes that affect water quality, and to respond to a wide range of agricultural management practices and surface conditions. Tillage effects on hydraulic properties, manure management, crop yield response to water stress, and tile drainage are just some of the refinements present in the current version of the model (K.W. Rojas, USDA-ARS-GPSR RZWQM development team, personal communication, 2004). Conclusions drawn from some of the early applications in the literature may not be strictly valid, and may not represent typical behavior of the current model (Ma et al., 2001). In addition, soils and climate in the southeastern USA are very different from the Great Plains and Midwest regions of the USA, where the model was originally developed and tested. If the RZWQM can be applied in a region of the country where soils and climate differ greatly from the region in which it was developed, it will allow wider applicability of the model for simulating the effects of agricultural management practices such as CT and NT on ground-water supplies. It may then be reliably linked to larger scale models with application for the Piedmont region. The RZWQM is currently being linked to the DSSAT model system (Ma et al., 2005) and a geographic information system to study spatially distributed systems at the watershed scale. We evaluated the most recent version of the RZWQM (version 1.3.2004.213) for simulations of tile drainage and NO₃ leaching in the southeastern USA.

MATERIALS AND METHODS

Field Experiments

The experimental data for the evaluation of the RZWQM were collected as part of an ongoing water quality study initiated in 1991 at the USDA-ARS J. Phil Campbell, Sr., Natural Resources Conservation Center in Watkinsville, GA. The major objective of the water quality study in 1991 was to quantify and compare potential impacts of CT and NT and winter cover crop management practices on leached NO₃ in maize production from 1991 to 1994. After the plots were planted in cotton in 1995, the study included poultry litter and mineral fertilizer treatments in a factorial combination with tillage treatments. The current study to evaluate the model includes tile drainage and leached NO₃ data collected from the plots with mineral fertilizer from May 1997 to May 1998 while in cotton production under CT and NT management with a winter rye cover crop.

The water quality study consisted of 12 plots, 10 by 30 m, instrumented with PVC drain tiles with 10-cm i.d. installed at 75- to 100-cm depths on a 1% slope, 2.5 m apart. The plots were hydrologically isolated from each other with polyethylene sheets extending from the soil surface to a depth of 1 m and with plastic borders 10 cm deep. Drainage data were collected with tipping buckets connected to a CR10X data-

logger (Campbell Scientific, Logan, UT), which recorded total drainage tips every hour (Endale et al., 2002b). For every 2 mm of cumulative drainage, a sample was pumped from the beaker into a polyethylene bottle inside an ISCO Model 3700 FR refrigerated sequential waste water sampler (ISCO, Lincoln, NE). An aliquot of this effluent was stored frozen in polyethylene vials and later analyzed for NO₃ using the Griess-Ilosvay method (Keeney and Nelson, 1982). The samples were filtered through a 0.45- μ m filter before analysis.

The management practices for the study from 1997 through 2000 while in cotton production included deep chisel plowing, followed by disk harrowing, and subsequent disking to smooth the seed bed in the CT plots before planting cotton. The only tillage operation performed in the NT plots was the use of a coulter disk during planting (Endale et al., 2002a). Cotton was planted in May of each year and harvested the first week of November. Winter rye was planted as the cover crop within 2 wk of cotton harvest in November each year. Light disking was performed in the CT plots for seedbed preparation and for incorporation of fertilizer in the winter rye. Cotton was fertilized with NH₄NO₃ at a rate of 60 kg N ha⁻¹, and winter rye with 54 kg N ha⁻¹ at planting. Rye was killed with glyphosate [*N*-(phosphonomethyl) glycine] in April each year after the aboveground biomass was sampled. Cotton yield and biomass were hand sampled in October each year before machine harvest in November.

The soil is a Cecil sandy loam, deeply weathered, kaolinitic, acidic, and variably charged. Kaolinite clay makes up >50%, while vermiculite and chlorite make up 10 to 30% (Endale et al., 2002a). The pH normally ranged from 5.5 to 5.8 in the upper layers of the soil profile as measured at the study site; therefore, lime was applied approximately every 3 yr to bring the pH to a value of 6.0 to 6.3 in the surface horizon to increase soil nutrient availability and prevent Al toxicity. Volumetric soil water content was determined for each plot with a 50-cm probe in 1997 using time domain reflectometry (TDR; Evett, 2000) and in increments of 15 cm to a depth of 150 cm using TDR (MoisturePoint, ESI, Victoria, BC) in 1998 through 2000. Soil water content was calculated by using the average measured volumetric content over 50 cm in each case and multiplying by 50 cm to obtain centimeters of soil water. Rainfall and other weather data for the model were recorded at an automated weather station adjacent to the study site (Hoogenboom, 2003).

Model Calibration

The RZWQM model was calibrated based on the water quality field experiment initiated in 1991 at the USDA-ARS J. Phil Campbell, Sr., Natural Resources Conservation Center in Watkinsville, GA. The main objective of the calibration study was to parameterize the RZWQM to simulate tile drainage and NO₃ leaching in a Cecil soil in maize production with a winter rye cover under conventional tillage management practices in the Georgia Piedmont. In addition, we calibrated the model for cotton water use, growth, and development based on a study in cotton production without tile drains next to the water quality study so that we could evaluate the calibrated model for tile drainage and NO₃ leaching in cotton production at the water quality study site after cotton was introduced in 1995. A second objective of the calibration study was to evaluate the model's sensitivity to soil macroporosity in relation to tile drainage since regions of preferential flow are found in Cecil soils of the Piedmont region (Gupte et al., 1996), and to provide other modelers with a detailed description of our calibration approach, which is often omitted in the modeling literature (Abrahamson et al., 2005).

Using a detailed calibration and sensitivity analysis approach with the RZWQM, we were able to simulate tile drainage, leached NO_3 , and maize production within 15% of observed values without using the macroporosity option in the model. With the macroporosity option, we were able to simulate our target response variables of tile drainage and leached NO_3 in maize production within 15% of observed values for the final analysis period. We found, however, that macroporosity confounded the generation of leached NO_3 by the model, and would often produce very large amounts of NO_3 that could not be managed using the same parameters that were used to calibrate the model without macroporosity. Tile drains may have also influenced the model's ability to simulate preferential flow through macropores due to the difference in the flow patterns that are created when tile drains are present in the soil; however, there were no significant differences between simulated tile drainage with and without macroporosity in the model. In addition, in a study of intact dye-stained soil cores from the study area in CT, Gupte et al. (1996) found little evidence of preferential flow in the upper 45 cm of the cores; therefore, we simulated tile drainage and leached NO_3 for the current evaluation study without using the macroporosity option. Total simulated tile drainage in the calibration study was 413 mm, and total measured drainage was 390 mm for the period from 16 Nov. 1992 through 6 Apr. 1993 under winter rye cover when drainage occurred. Total simulated leached NO_3 in the calibration study was 18.1 kg ha^{-1} , and total measured leached NO_3 was 17.2 kg ha^{-1} . Simulated deep drainage was 126 mm for the period, using our calibrated water table leakage rate of 0.0035 cm h^{-1} . Total rainfall for the period was 766 mm.

The calibrated model was able to simulate the pattern of biomass accumulation and leaf area for cotton development relative to the observed pattern until the last 21 d of reproduction during the 1997 calibration period at the study site next to the water quality study. This appeared to be due to the inability of the model to simulate vegetative growth after the crop enters the reproductive stage. It may also have been due to the method by which the model partitions C during the various stages of crop development, which cannot be adjusted except by way of the minimum number of days required to complete each growth stage. We were able to simulate average daily cotton water use to within $<1 \text{ mm}$ of average observed daily water use during the period of peak critical bloom with and without the macroporosity option. Based on our objective to simulate cotton water use as part of the total water balance for tile drainage and NO_3 leaching in cotton production, we considered the simulation of cotton water use satisfactory for the purpose of evaluating the calibrated model for the current study.

Model Evaluation

The main evaluation period for the current study at the water quality study site was 1 Jan. 1997 through May 1998. A drought ensued in June 1998 and no drainage occurred in the field from June 1998 through the end of the study period in December 2000; however, we also compared simulated drainage during this period.

Management practices for the model simulations included the number and type of tillage operations performed in the CT plots during the study period, and a no-till coult planter for cotton for the NT simulations. Planting dates used for cotton were the actual planting dates of 14 May, 14 May, 16 May, and 15 May for 1997 through 2000, respectively. Simulated harvest dates occurred when 97% of the plants were in the fully ripe phenological growth class based on the calibration study. Planting dates used for winter rye were 5 Nov., 13 Nov., and 11

Nov. for 1997 through 1999, respectively. We adjusted the planting date for winter rye in 1997 to 11 Nov. because the cotton harvest date was not simulated until after the original planting date of 5 Nov. 1997. The harvest date for winter rye was set to Day 121 in the year following planting in each growing season based on the average harvest date for winter rye at the study site. The harvest day can only be specified one time when using the Quikplant grass model, a simple growth and yield model in the RZWQM that we used to simulate winter rye development in the calibration study (Ahuja et al., 2000; Abrahamson et al., 2005).

Total measured drainage from a rain event was based on drainage that occurred during a rainstorm and afterward until no more drainage occurred before the next rain event. The amount of simulated drainage for a rain event was accumulated during the same period that drainage occurred in the field study so that the events could be analyzed as discrete events. Each total measured drainage event was regressed on each total simulated event using linear regression (SAS Institute, 2000). We tested for differences between observed and simulated drainage events, and observed and simulated leached NO_3 by testing the slopes and intercepts for CT and NT scenarios. We also tested for the effects of simulated tillage on simulated tile drainage and leached NO_3 .

To account for drainage below the depth of the tile drains (80 cm) that was not measured, we calculated the daily water balance for the entire evaluation period as well as for the cotton growing season in 1997, and compared it with the simulated water balance. The calculated daily water balance was defined as:

$$\begin{aligned} \text{Rainfall} - \text{ET}_c - \text{Tile Drainage} - \text{Runoff} \\ - \Delta\text{SW50} = \text{Deep Drainage} + \Delta\text{SW50}_{125} \end{aligned}$$

where Rainfall, Tile Drainage, and Runoff were measured values, ET_c is daily crop evapotranspiration, and $\Delta\text{SW50} = \text{SW50}_i - \text{SW50}_{i-1}$ was equal to the change in measured soil moisture in a 50-cm profile between Day i and the previous day. The final term, Deep Drainage + ΔSW50_{125} , served as the remaining water after accounting for all other terms.

The Ref-ET software was used to calculate daily reference evapotranspiration (ET_0) based on the FAO 56 Penman-Monteith (P-M) equation (Allen, 2000). Daily crop evapotranspiration (ET_c) was then calculated using the procedure for calculating crop water requirements based on the growth stages for cotton and for winter wheat as a surrogate for winter rye where:

$$\text{ET}_c = K_c(\text{ET}_0)$$

and K_c is a crop coefficient (Allen et al., 1998). Calculated ET_0 was based on measured values of air temperature, wind speed, relative humidity, and solar radiation at the weather station next to the study site, and was the same data used in the RZWQM to simulate potential evapotranspiration (PET). We used the dual crop coefficient approach for calculating ET_c because it calculates the actual increases in K_c for each day as a function of plant development and the wetness of the soil surface. The value of K_c is split into two separate coefficients, one for crop transpiration and one for soil evaporation (FAO, 1998b). The calculated FAO values for ET_0 and ET_c assume evapotranspiration from disease-free, well-fertilized crops, grown in large fields, under optimum soil water conditions, and achieving full production under the given climatic conditions.

The simulated daily water balance was calculated as

$$\begin{aligned} \text{Rainfall} - \text{ET} - \text{Tile Drainage} - \text{Runoff} - \Delta\text{SW50} \\ - \Delta\text{SW50}_{125} - \text{Deep Drainage} = 0 \end{aligned}$$

based on measured rainfall and each simulated component from the model output. The RZWQM uses the extended Shuttleworth–Wallace (S–W) method for PET and accounts for energy exchange between the canopy and soil (DeCoursey, 1992; Farahani and Ahuja, 1996). It explicitly defines a partially covered soil to partition calculated ET into a bare soil and residue-covered fraction to simulate differences in no-till vs. minimum-till or conventional-till practices (Farahani, 1994). Actual ET in the RZWQM is based on the ability of the soil to deliver the potential evaporation rate as determined by the Richards equation. The transpiration rate in the model is calculated according to the method of Nimah and Hanks (1973), and acts as a sink term in the Richards equation to determine the actual rate of transpiration with the upper limit determined by simulated PET (Ahuja et al., 2000).

We compared simulated PET to ET_0 and also to the Priestley–Taylor (P–T) reference ET calculated over short grass at the weather station next to the study site (Hoogenboom, 2003). In the past, P–T reference ET has been used in the humid southeastern USA due to its general performance in humid regions and limited input requirements. A recent study in the southeastern USA comparing the FAO 56 P–M and P–T equations found that P–T overestimated ET and that FAO 56 P–M was more accurate (Suleiman and Hoogenboom, 2005). The FAO Penman–Monteith method is recommended as the standard method for the definition and computation of the reference evapotranspiration, ET_0 based on the performance of the various calculation methods for different locations (Allen et al., 1998); however, the calculated P–T reference ET provided an additional method by which to evaluate the effectiveness of the method used by the RZWQM for simulating PET from an incomplete canopy cover by comparing it to a reference ET over short grass next to the weather station and with the same climate data used to simulate PET in the RZWQM. Finally, we compared the differences between simulated (Tile Drainage + Deep Drainage) and observed (Tile Drainage + calculated Deep Drainage) by assuming that the differences in daily calculated ΔSW_{50_125} and the daily simulated values of ΔSW_{50_125} were small. These approaches allowed us to compare the simulated vs. the observed partitioning of the water balance components and to evaluate simulated differences in drainage under CT vs. NT management practices.

RESULTS AND DISCUSSION

Total measured rainfall was 1805 mm for the evaluation period from 3 May 1997 to 9 May 1998. There were 30 observed drainage events from rainfall during the period (Endale et al., 2002b), which allowed us to compare the differences between total simulated and observed tile drainage and leached NO_3 for each event. Total observed tile drainage for the measurement period was 229 mm and total simulated tile drainage was 1155 mm for the CT treatments. Total measured tile drainage was 448 mm and total simulated tile drainage was 1161 mm for the NT treatments. The maximum observed drainage volume was 88.4 mm for the CT treatment and 86.7 mm for the NT treatment from a 2-d rain event of 132 mm in October 1997. Simulated drainage for this rain event was 111 mm for CT and 115 mm for NT. Cumulative simulated drainage followed the pattern of cumulative rainfall more closely than cumulative observed drainage (Fig. 1). The linear regression analyses of observed drainage on simulated drainage revealed that simulated tile drainage explained 82% of the variability in measured tile drainage

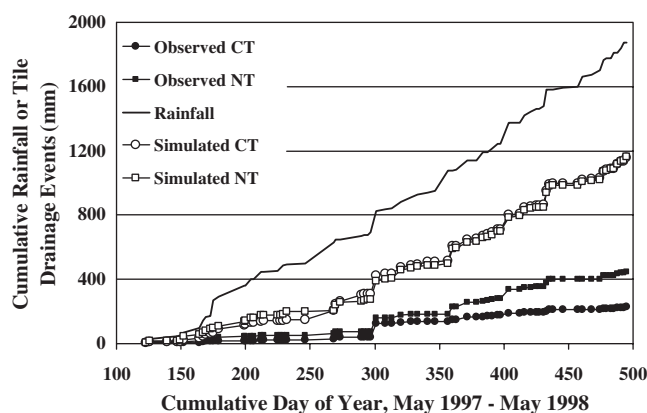


Fig. 1. Cumulative rainfall and observed and simulated tile drainage under CT (conventional tillage) or NT (no-tillage) for the evaluation period.

for the NT treatments. Simulated tile drainage explained 49% of the variability in measured tile drainage for the CT treatments (Table 1). The slopes were significantly different from zero and significantly different from one for both CT and NT treatments although simulated tile drainage for the NT treatment was better correlated with observed than simulated tile drainage for the CT treatment. The intercept was significantly different from zero for the NT treatments but not for the CT treatments, indicating that the differences in simulated and observed tile drainage were smaller in the CT treatment. There were no observed drainage events from June 1998 through December 2000 during the drought; however, the model simulated 793 mm of drainage for CT treatments and 851 mm of drainage for NT treatments for the period.

The calibrated model had accurately simulated maize production in 1991 and 1992, and tile drainage and NO_3 leaching in the winter of 1992 to 1993 under winter rye cover in CT treatments at the water quality study site (Abrahamson et al., 2005). To explain the large differences in simulated and observed tile drainage for the current study compared with the calibration study, we looked at the differences in measured rainfall and simulated PET, air temperature, maize vs. cotton ET, and the water balance in each cropping period as well as the

Table 1. Statistics for measured and simulated CT (conventional tillage) and NT (no-tillage) treatments for tile drainage and leached NO_3 for the evaluation period based on regression analyses. Leached NO_3 was log transformed for the regression analysis.

Treatment	Observed	Simulated	RMSE	r^2	Intercept	Slope
mm						
Tile drainage						
CT	229	1155	7.8	0.49	-2.1†	0.33*
NT	448	1161	6.0	0.82	-2.6**	0.55*
Leached NO_3						
kg ha ⁻¹						
CT	1.4	64	3.5	0.10	-11.7**	0.16*
NT	1.3	74	3.9	0.10	-11.4**	0.17*

* Significantly different from 1 at $P < 0.05$.

** Significantly different from 0 at $P < 0.05$.

† Not significantly different from 0 at $P < 0.05$.

differences in the water balance for winter rye in the calibration study vs. the evaluation study.

Total rainfall for the calibration period from 1 Jan. 1992 through 13 Apr. 1993 was 1905 mm, and the total rainfall for the current study in the same period in 1997 and 1998 was 2095 mm, a difference of 190 mm over 14½ months. The differences in simulated PET compared with reference ET were apparent early in the cotton growing season and at the end of the cotton growing season right before harvest when the soil was under partial canopy cover (Fig. 2). Differences in simulated PET for CT vs. NT treatments were also apparent early in the cotton growing season, reflecting the higher albedo and cooler temperatures from a soil surface covered with fresh residue in NT treatments vs. a bare clay soil in CT treatments. The same pattern emerged between the time the winter rye was killed and before cotton was planted (March–mid-May). For the entire evaluation period, simulated PET for the CT and NT treatments was less than calculated P–T reference ET by 123 and 299 mm, respectively. Simulated PET for the treatments was less than calculated reference ET_0 by 202 and 378 mm, respectively. Simulated PET in the CT treatments during the cotton growing season (May–October) was 55 mm less than P–T reference ET and 156 mm less than P–T reference ET in the NT treatments. The differences between simulated PET for the treatments and reference ET_0 were nearly identical to that of P–T reference ET, with values of 51 and 154 mm less than reference P–M ET_0 . During the period of peak water use in cotton (July–August), however, the differences between simulated PET and both values of calculated reference ET were $<0.25 \text{ mm d}^{-1}$. During the winter rye growing season (November–March), the differences between simulated PET in the CT and NT treatments and P–T reference ET were $<0.06 \text{ mm d}^{-1}$, reflecting the similarities between PET computed over short grass at the weather station and for conditions in winter rye cover simulated by the model. The difference

between simulated PET and P–M reference ET_0 during this period was 0.47 mm d^{-1} for the CT treatments and 0.55 mm d^{-1} for the NT treatments. Although these differences are small, computation of reference ET_0 using the P–M 56 equation overestimated ET even though the same measured climatic data was used to compute P–M ET_0 that was used for simulations of PET by the RZWQM and for computing P–T reference ET at the weather station. The exact reason for this is beyond the scope of this study, but may be due to the fact that the FAO 56 P–M equation will probably deviate at times from true measurements of grass ET_0 (FAO, 1998a). For our purposes of comparing simulated PET to calculated reference ET, the extended S–W–ET model and the P–T reference ET model are in good agreement for winter rye at this location. This indicates that although the FAO 56 P–M was more accurate and that P–T overestimated ET based on a recent study at different locations in Georgia (Suleiman and Hoogenboom, 2005), P–M reference ET_0 may have actually overestimated ET over winter rye at our study site and P–T ET was more accurate. In addition, the extended S–W–ET model used in the RZWQM is an extension of the P–M model with modifications that may have adjusted the P–M calculation for winter rye to better reflect changes in surface evaporation that occur before the surface is fully covered by the winter crop and would also include differences in soil surface albedo based on soil surface residue amounts.

We also looked at the antecedent moisture content of the model calibration scenario in 1992 compared with the 1997 evaluation scenario at the beginning of the data collection period and found little or no difference in them (Fig. 3). Measured rainfall events and rainfall intensity were very similar for the calibration period and for the current study period (data not shown). Total observed runoff for the entire evaluation period in the current study was 138 mm for CT and 91 mm for NT treatments, and total simulated runoff was 38 mm for both CT and NT model simulations; however, a difference of 100 mm or less of runoff between simulated and

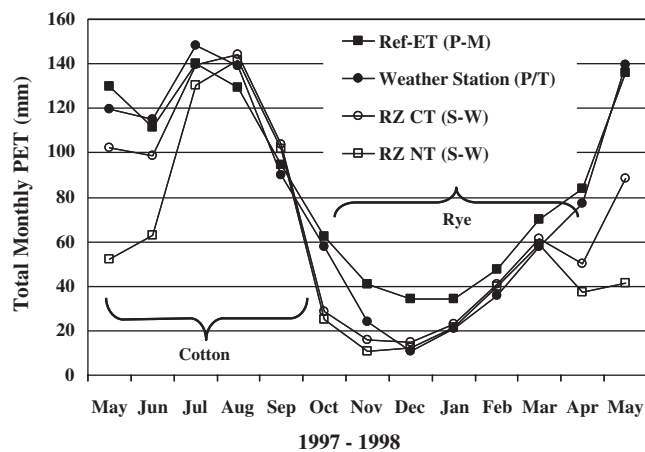


Fig. 2. Calculated daily reference ET_0 (REF-ET potential evapotranspiration) and Priestley–Taylor ET (calculated daily evapotranspiration from the weather station) summed by month compared with simulated daily PET (Shuttleworth–Wallace potential evapotranspiration) summed by month for CT (conventional tillage) and NT (no-tillage) management practices for the evaluation period.

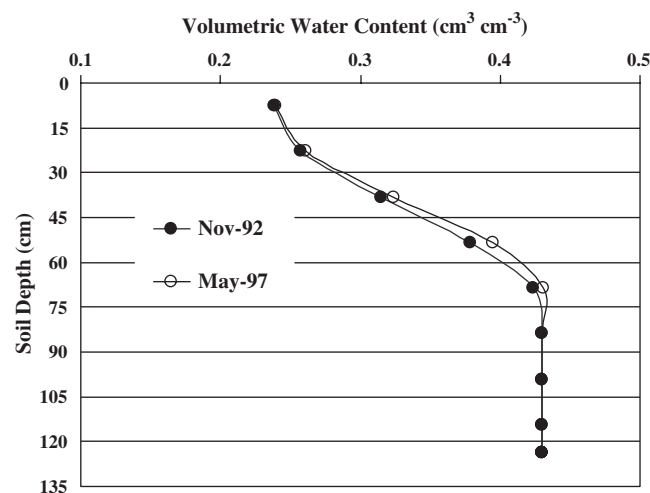


Fig. 3. Initial volumetric soil water content for the calibration simulation in November 1992 and for the current evaluation study in May 1997.

observed runoff did not account for differences of 926 and 712 mm between total observed and total simulated tile drainage in each treatment during the 1997 to 1998 evaluation period.

Total rainfall for the winter rye period (16 November–5 April) in the calibration study was 772 mm and for the same period in the evaluation study was 778 mm. The model accurately simulated tile drainage in the calibration study for the winter rye period (Fig. 4). Simulated tile drainage for winter rye was 390 mm in the calibration study and 548 mm for the evaluation study under CT management practices (Table 2). Simulated tile drainage was the largest difference in the water balance of the two studies for the winter rye period. The difference in ET and runoff between the two study periods for winter rye offset each other. Differences in calculated reference ET₀ and simulated PET also did not explain the large differences in simulated or observed tile drainage for the two studies.

We then considered differences between simulated and observed crop water use that could have affected simulated vs. measured tile drainage. Total simulated cotton biomass was 7.9 Mg ha⁻¹ for the CT treatment and 7.3 Mg ha⁻¹ for the NT treatment. Total cotton biomass production is generally >20 Mg ha⁻¹ in the southeastern USA (Carns and Mauney, 1968; Endale et al., 2002a; Reddy et al., 2004; Schomberg and Endale, 2005); however, the results of simulated cotton production were very similar to the results obtained for cotton production during the calibration of the model. The differences between observed and simulated water use during the period of peak water use were <0.3 mm d⁻¹ based on calculations of rainfall minus observed and simulated soil moisture (Abrahamson et al., 2005). In the current study in 1997, measured cotton lint yield was 1100 kg ha⁻¹ in CT and 1340 kg ha⁻¹ in NT, and simulated yield was 2001 kg ha⁻¹ and 1960 kg ha⁻¹, respectively. The difference between total simulated cotton biomass in the calibration study and the current

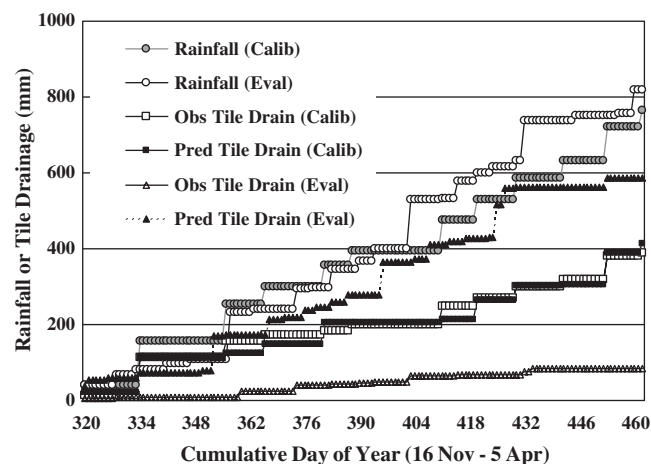


Fig. 4. Cumulative rainfall and observed (Obs) and predicted (Pred) tile drainage for the period in common for the calibration study (Calib) in 1992 and 1993 and for the current evaluation study (Eval) in 1997 and 1998. Winter rye was the cover crop in both studies during the period.

Table 2. Observed rainfall and simulated water balance components for the winter rye season (16 November–5 April) in 1992 and 1993 in the calibration study compared with the same period in 1997 and 1998 in the evaluation study under CT (conventional tillage) management practices.

Water balance component†	Calibration	Evaluation	Calibration minus evaluation	
			mm	
Rainfall	722	778		-55
Evapotranspiration	193	162		31
Runoff	0	37		-37
ΔSW (125-cm profile)	-6	-58		52
Drainage (tiles)	390	548		-158
Deep drainage	119	94		24
Balance	21	-63		84
Potential evapotranspiration (November– March)				
ET ₀ (calculated)	253	227		26
RZ (predicted)	204	156		48
P-T (calculated)	167	149		18

† ΔSW = soil water change; ET₀ = calculated potential evapotranspiration using REF-ET; RZ = simulated Shuttleworth–Wallace potential evapotranspiration; P-T = calculated Priestley–Taylor evapotranspiration from the weather station.

study was 1 Mg ha⁻¹. Although cotton water use can be as high as 6 to 9 mm d⁻¹ during the critical water use period of the growing season (Bednarz et al., 2002), a difference of 1 Mg ha⁻¹ in simulated biomass would result in a difference of <15 mm of actual water use during the cotton growing season based on the average amount of water required to produce 5 Mg of shoot biomass (Hanks, 1983).

The calculation of the simulated water balance for the current study revealed that the simulated ΔSW_{50_125} was small for each treatment (Table 3). Omitting this term from the calculated water balance, calculated deep drainage was 656 mm for the CT treatments. The value of observed tile drainage plus calculated deep drainage was 885 mm, and simulated tile drainage plus deep drainage was 1155 mm or the same as tile drainage for the CT treatment because there was no simulated deep drainage. For the NT treatments, calculated deep drainage was 487 mm and observed tile drainage plus calculated deep drainage was 936 mm; simulated tile

Table 3. Calculated (or observed, Obs) and simulated (Pred) water balances under CT (conventional tillage) and NT (no-tillage) management for the evaluation period (3 May 1997–9 May 1998), with 1805 mm of rainfall. The calculated FAO 56 Penman–Monteith crop ET (evapotranspiration) is shown for observed ET.

Water balance component	CT		NT		Observed minus predicted	
	Obs	Pred	Obs	Pred	CT	NT
	mm					
ET	861	720	861	657	141	204
Runoff	138	38	91	38	101	54
ΔSW ₅₀ †	-79	-92	40	-83	13	122
ΔSW _{50_125} †	-	-31	-	-28	-	-
Drainage (tiles)	229	1155	448	1161	-926	-712
Deep drainage	-	0	-	49	-	-
Balance	656	14	487	10	640	352
Deep drainage + tile drainage	885	1155	936	1209	-272	-398

† ΔSW₅₀ = soil water change in a 50-cm profile; ΔSW_{50_125} = soil water change in the 50- to 125-cm depth increment in the profile.

drainage plus deep drainage was 1209 mm when deep drainage was only 49 mm of the term. The simulated values of ET were less than the calculated values by 141 mm for the CT treatments and 204 mm for the NT treatments during the evaluation period. Simulated and observed runoff were different by 101 and 54 mm, respectively, in the CT and NT treatments. Together the ET and runoff components of the water balance accounted for <300 mm of the 926- and 712-mm differences, respectively, in observed vs. simulated tile drainage in each treatment.

The differences in the observed and simulated water balances for the cotton growing season from 14 May 1997 through 3 Oct. 1997 revealed that calculated and simulated ET were different by 53 and 74 mm for the CT and NT treatments, respectively—a difference of $<0.5 \text{ mm d}^{-1}$ during the growing season; however, simulated and observed tile drainage were different by 219 and 181 mm, respectively (Table 4). The calculated and simulated values for tile drainage plus deep drainage were different by 6 mm for the CT treatments and 22 mm for the NT treatments. The values of simulated deep drainage were large and negative, indicating that the volume of water that did not drain out of the tiles but bypassed the drains was exceeding the calibrated water table leakage rate at the bottom of the profile, causing saturated conditions in the soil below the drains. The RZWQM defines the depth of the water table as the depth at which the pressure head first becomes non-negative and all heads below that depth are non-negative. The water table is allowed to fluctuate according to the Richards equation, with the surface boundary flux defined by the simulated evaporative flux and the bottom boundary condition defined as a unit gradient flux using the Buckingham–Darcy equation (Ahuja et al., 2000). Water moves from one depth to the next according to the Darcy flux and can move upward due to evaporation. We had calibrated the bottom boundary condition (the water table leakage rate) in the previous study (Abrahamson et al., 2005). Deep drainage in maize production in the calibration study was -116

and -160 mm during cotton production in the current study. The maize crop received 91 mm more rainfall in 1992 than cotton in 1997; however, simulated ET was 65 mm greater in maize production in 1992 than in cotton production in 1997. Simulated tile drainage was 3 mm lower under maize production in the calibration study than cotton production in the current study for the growing season before winter rye was planted. The differences in the water balance in maize and cotton production for the two studies did not explain the large differences in simulated drainage between the calibration study and the current study or the differences in observed and simulated tile drainage in the current study.

Next, we looked at the differences in the water balances for the winter rye growing season in the current study. During the winter rye growing season from November 1997 to March 1998, measured tile drainage was 91 mm for the CT treatments and 262 mm for the NT treatments. Simulated tile drainage was 678 and 710 mm for the CT and the NT treatments, respectively. Simulated ET was underestimated by 54 mm for the CT treatments and 78 mm for the NT treatments compared with calculated ET, and total simulated and observed runoff were different by 35 mm for the CT treatments and 7 mm for the NT treatments. The differences in simulated and calculated ET and simulated and observed runoff did not explain all of the differences between total simulated and total measured tile drainage for the winter rye growing season. The calculated observed water balance for the winter rye season revealed that calculated deep drainage was 450 mm and simulated deep drainage was 126 mm for the CT treatment. For the NT treatments, calculated deep drainage was 303 mm and simulated deep drainage was 129 mm. The total observed tile drainage plus calculated deep drainage was 545 mm, while simulated tile drainage plus deep drainage was 804 mm for the CT treatments. For the NT treatments, total observed tile drainage plus calculated deep drainage was 570 mm, while simulated tile drainage plus deep drainage was 838 mm (Table 5). The differences in observed and simulated ΔSW_{50} for both treatments were 162 and 174 mm, respectively. These differences could not be accounted for by the differences in calculated and simulated ET. The majority of water in the soil profile in the field that was not captured by the tile drains or used for ET or runoff drained below the tiles and the simulated 125-cm profile depth. In contrast, the model simulated an upward flux of water that raised the water table depth to the depth of the drains, causing water to flow out the drains. While this system worked well for the calibration scenario, where differences in simulated and measured tile drainage were $<15\%$, it did not explain the large differences in observed tile drainage during the calibration period and the evaluation period that the model did not simulate accurately.

Finally, we looked at differences in winter rye growth in 1992 through 1993 vs. 1997 and 1998. Measured aboveground biomass for rye ranged from 3 to 5 Mg ha^{-1} each year. Annual winter rye is highly tolerant of Al toxicity (Foy, 1988; Rife et al., 1999; Pinto-Carnide and Guedes-Pinto, 2000), which is a common characteristic

Table 4. Calculated (or observed, Obs) and simulated (Pred) water balances under CT (conventional tillage) and NT (no-tillage) management for the cotton growing season (14 May 1997–3 Oct.) in 1997, with 547 mm of rainfall. The calculated FAO 56 Penman–Monteith crop ET (evapotranspiration) is shown for observed ET.

Water balance component	CT		NT		Observed minus predicted	
	Obs	Pred	Obs	Pred	CT	NT
	mm					
ET	512	459	512	438	53	74
Runoff	20	0	9	0	20	9
$\Delta\text{SW}_{50}^\dagger$	-74	-22	-80	-25	-52	-55
$\Delta\text{SW}_{50_125}^\dagger$	-	-7	-	-8	-	-
Drainage (tiles)	35	254	60	241	-219	-181
Deep drainage	-	-159	-	-113	-	-
Balance	53	23	46	13	31	33
Deep drainage + tile drainage	88	95	106	129	-6	-22

$^\dagger \Delta\text{SW}_{50}$ = soil water change in a 50-cm profile; ΔSW_{50_125} = soil water change in the 50- to 125-cm depth increment in the profile.

Table 5. Calculated (or observed, Obs) and simulated (Pred) water balances under CT (conventional tillage) and NT (no-tillage) management for the winter rye cover crop in 1997, with 978 mm of rainfall. The calculated FAO 56 Penman–Monteith crop ET (evapotranspiration) is shown for observed ET.

Water balance component	CT		NT		Observed minus predicted	
	Obs	Pred	Obs	Pred	CT	NT
	mm					
ET	251	197	251	173	54	78
Runoff	72	37	44	37	35	7
Δ SW50 [†]	113	-48	117	-57	162	174
Δ SW50_125 [†]	-	-16	-	-19	-	-
Drainage (Tiles)	91	678	262	710	-587	-447
Deep drainage	-	126	-	129	-	-
Balance	450	5	303	6	445	298
Deep drainage + tile drainage	541	804	570	838	-263	-272

[†] Δ SW50 = soil water change in a 50-cm profile; Δ SW50_125 = soil water change in the 50- to 125-cm depth increment in the profile.

in Cecil subsoils. Unlike cotton roots, which do not extend to depths much greater than 30 to 60 cm due to sensitivity to subsoil acidity (Mitchell et al., 1991; Sumner, 1994; Gascho and Parker, 2001), winter rye roots can extend to depths >180 cm (Frye et al., 1985; Sarrantonio, 1992) and can accumulate up to 150 kg N ha⁻¹ in one growing season (Hoyt and Mikkelsen, 1991; Shennan, 1992; Ditsch et al., 1993). The maximum root depth parameter that we used for winter rye in the model calibration study was 1.25 m, which is also the depth of the soil profile in the model. In addition, we had used a value of 95 kg N ha⁻¹ for maximum N uptake for winter rye based on the total measured above-ground biomass N concentration of 93 kg ha⁻¹ after the first crop was harvested in April 1992 for the calibration (Abrahamson et al., 2005). During the calibration study period, measured NO₃ leaching losses in tile drains were 3.3 kg ha⁻¹ and significantly lower under the winter rye treatments than leaching losses under fallow treatments (McCracken et al., 1995). These researchers attributed the lower leaching losses in winter rye cover treatments to greater soil water and N use by the rye crop than fallow treatments. The total observed leached NO₃ for the current study at the water quality plots was 1.4 kg ha⁻¹ for the CT treatments and 1.3 kg ha⁻¹ for the NT treatments, while simulated leached NO₃ was 64 kg ha⁻¹ for the CT treatments and 74 kg ha⁻¹ for the NT treatments. The differences between simulated and observed values are large, and the model was not able to simulate the pattern of NO₃ transport in these soils (Fig. 5). This may be due to the fact that ion-exchange equations with the soil are included for the major cations only and not for anions adsorbed onto soil sites in the RZWQM (Shaffer et al., 2000). There is evidence of retardation of anions in Cecil soils due to the variable charge on the kaolinitic and oxide surfaces (Gillman and Sumner, 1987), so that the concentration of NO₃ in the soil solution at any one time will be influenced by the exchange of the soil solution with the clay surfaces, which could affect both the amount and time that NO₃ is leached in the profile (Gupte et al., 1996). The regression analyses of the log-transformed

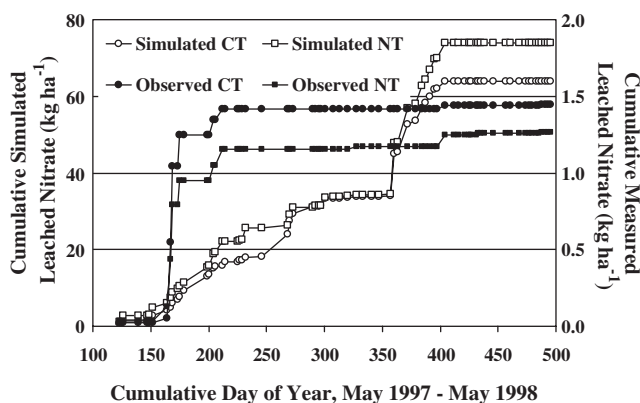


Fig. 5. Cumulative simulated and observed leached NO₃ under CT (conventional tillage) and NT (no-tillage) management during the evaluation period.

observed and simulated leached NO₃ data showed little or no linear relationship between observed and simulated values (Table 1), and there was no effect of simulated tillage on simulated leached NO₃.

Winter rye cover crops can reduce the potential for NO₃ leaching by absorbing and storing N in plant tissue during soil water recharge in winter, and by reducing percolation through transpiration (Bellocchi et al., 2002; Weinert et al., 2002). In those studies, the researchers found that overwintering cover crops such as winter rye lowered soil mineral N by 155 kg ha⁻¹. Similar results were found for winter rye cover cropping practices following continuous maize rotation in a mid-Atlantic Coastal Plain study (Staver and Brinsfield, 1998). Total measured winter rye biomass at the water quality study site in April 1998 was greater than that in 1993 by 1.8 t ha⁻¹ in the CT treatments and 2.0 t ha⁻¹ in the NT treatments (McCracken et al., 1995; Endale, unpublished data, 1998). Although rainfall was greater for the 1997 to 1998 winter rye growing season by 55 mm, greater total winter rye biomass production in April 1998 and the reduction of leached NO₃ by the winter rye crop in 1993 compared with fallow treatments suggest that actual tile drainage and leaching losses may have been reduced by greater water and N uptake due to continuous winter cover crop management practices from 1991 to 1997 at the study site. The winter rye roots may have begun to grow deeper into the soil based on similar studies of rooting depths of winter rye cover crops previously cited. In addition, based on a study of maize followed by a winter rye cover crop in Minnesota, winter rye biomass production decreased when rainfall and temperatures were below normal for the growing season in 2 of 3 yr; however, biomass N concentration increased (Strock et al., 2004). During the 3-yr study, maximum annual biomass production was 3 t ha⁻¹, and average annual production was 1.5 t ha⁻¹. Winter rye cover cropping reduced subsurface drainage by 11%, and reduced NO₃ leaching in subsurface drainage by 13% during the 3-yr period, even with below-average rainfall and temperature conditions in two of the years. The differences between the observed values of tile drainage and leached NO₃ in 1992 and 1993 in the

calibration study compared with the observed values in 1997 and 1998 in the current study, and the large differences between simulated and observed values in 1997 and 1998, appear to be due to the over- and underestimation of some of the simulated water balance components by the model. Based on our evaluation of the differences in total rye biomass in 1992 and 1998, however, the amount of NO_3 and water lost to total drainage in 1998 compared with 1992, and similar studies of winter rye cover crop management practices, it is likely that there is currently less soil water and soil N available for drainage and NO_3 leaching at the depth of the tile drains than there was in 1992 at the study site. This appears to be due to the fact that winter rye can excavate excess soil water and NO_3 by rooting more deeply with time and was using soil water and nutrients that had previously drained through the tiles at the 80-cm depth of the drains in the calibration study. This may also explain why the model predicted tile drainage during the drought period when there was no measured drainage at the study site from June 1998 through December 2000.

Some of the differences in simulated and calculated ET for winter rye may also have been due to the use of the Quikplant submodel in the RZWQM to simulate winter rye growth. The Quikplant submodel bases plant growth and development on a limited number of parameters, such as maximum N uptake and maximum root depth, supplied by the user (Ahuja et al., 2000). In contrast, the full plant production submodel in the RZWQM requires many phenological and physiological parameters that may or may not have been able to simulate physiological growth and ET more accurately; however, many of these parameters are not available or not well established for cover crops such as winter rye. Also, the model had accurately simulated tile drainage and leached NO_3 during winter rye growth for the calibration study, so it does not appear that the Quikplant model was the main cause of the underestimation of ET in the current study.

Phenological and physiological changes occur in crops such as winter rye that can excavate soil water and N differently with time and under variable climatic conditions, as described in similar studies, and this appears to be what influenced the ability of the RZWQM in the current study to accurately simulate tile drainage and leached NO_3 . It also suggests that accurately simulating cover crop development can be an important consideration in modeling studies. This may be particularly important when a model is tested with time for the effects of cover crop management practices on water quality. The ability of a model to accurately represent annual cover crop development with time, as cover cropping becomes a more widely used agricultural management practice, needs to be addressed in future modeling studies.

CONCLUSIONS

The RZWQM (version 1.3.2004.213) accurately simulated tile drainage and NO_3 leaching during a calibration study from 1991 through 1993 at the water quality study site while in maize production with a winter rye

cover crop under CT management practices. The model did not accurately simulate the volume of tile drainage and leached NO_3 for the evaluation period in the current study after the study site was converted to cotton production with a winter rye cover crop under CT and NT management practices; however, total drainage was reasonably well simulated during the cotton growing season based on our analyses of the simulated and observed water balances for the period. The differences in simulated and observed tile drainage and leached NO_3 for the entire evaluation period appears to be due to the underestimation of simulated ET for the cotton and winter rye crops. More likely, the differences in the amount of soil water and soil N currently available at the study site for tile drainage and NO_3 leaching at the depth of the tile drains compared with the period when the model was calibrated may explain the large differences in simulated and measured tile drainage and NO_3 leaching. The model simulated a perched water table that partitioned water between tile drainage, runoff, ET, and soil water storage based on a 1.25-m soil profile. In the field, less water was available at the depth of the tile drains and was stored in the soil, used for ET or runoff, or drained to below 1.25-m where it was used for ET by deeper rooting of winter rye with time.

The lack of significant differences due to tillage for simulated tile drainage and leached NO_3 may have been due to the calibration for CT only, and not for NT management practices; however, it appears that the extended S-W-ET model used by the RZWQM was sensitive to differences in CT and NT management practices at certain times during the cropping season under partial canopy cover conditions and different residue amounts. Although there were no significant differences in simulated tile drainage and simulated leached NO_3 between tillage treatments, a longer simulation period may reveal more differences as simulations of ET with time affect soil water storage, especially during dry periods.

The RZWQM model simulates crop growth based on fixed plant parameters such as maximum N uptake and maximum root depth and cannot exceed these values in order for a crop to respond to various perturbations in soil water and N such as those that may occur in annual winter rye cover crops. Model simulations of annual cover crop development such as those for winter rye could be improved by processes that allow soil water and N uptake to vary as biomass changes and increases from one growing season to the next, similar to that of perennial plants. Accurate simulations of soil water and N use by cover crops would also contribute to more accurate long-term assessments of the impacts of cover crop management practices on soils and water quality and quantity when linked to watershed-scale models.

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