Simulated nitrate leaching in annually cover cropped and perennial living mulch corn production systems

J.S. Andrews, Z.P. Sanders, M.L. Cabrera, N.S. Hill, and D.E. Radcliffe

Abstract: Corn (*Zea mays*) grown in the southern Piedmont requires 200 to 280 kg nitrogen (N) ha^{-1} annually and requires up to 0.87 cm of water per day, making groundwater systems susceptible to nitrate (NO_3^-) leaching. A perennial white clover (*Trifolium repens* L.) living mulch (LM) system may reduce NO_3-N leaching by using legume N to replace mineral N, though little information is available on such a system in the southern Piedmont. Therefore, a HYDRUS-1D model was used to simulate water and NO_3-N flux in three cover crop systems. Cereal rye (*Secale cereal* L.) (CR), crimson clover (*Trifolium incarnatum* L.) (CC), and a white clover LM were fertilized with 280, 168, and 56 kg N ha^{-1}. The HYDRUS-1D model was calibrated and validated with observed water contents and NO_3-N data that were collected over two years. Water and NO_3-N flux models were created for each treatment and evaluated using coefficient of determination, percentage bias, and index of agreement, and showed good agreement to observed data. Nitrate leaching below 1 m in 2015/2016 was 23.5, 12.7, and 21.4 kg ha^{-1} for the CC, LM, and CR treatments, respectively, but was less than 1 kg ha^{-1} for all treatments in 2016/2017 due to prolonged drought. Differences in leached NO_3-N among treatments were attributed to variation in mineral N application rate and NO_3-N uptake by cover crops. Overall, results suggest that the use of a perennial LM system may reduce NO_3-N leaching when compared to annual CC and CR cover crop systems.

Key words: corn—cover crop—HYDRUS-1D—living mulch—nitrate leaching—Piedmont

Intense rainfall events and significant erosion from agricultural practices make soils in the southern Piedmont region of the United States unproductive without careful management of irrigation and supplemental fertilizer (Adams et al. 1970; Endale et al. 2008; Thomas et al. 1989). Water and nitrogen (N) are therefore important inputs for crop production, with higher yielding varieties of crops demanding greater quantities of water and nutrients during the growing season. In this region, 200 to 280 kg N ha^{-1} is required for corn (*Zea mays*) growth annually, applied mainly as mineral N (Lee et al. 2015; Raun et al. 1999). Cecil soils, which comprise roughly two-thirds of the land area of the southern Piedmont (Endale et al. 2008; Hendrickson et al. 1963; Radcliffe and West 2000), are well-drained due to their sandy upper horizons and lower clay horizons with large aggregates and strong structure (Bruce et al.

1983). Soluble N fertilizer combined with well-drained soils make corn production areas of the southern Piedmont susceptible to nitrate (NO_3^-) leaching.

Nitrate losses below the root zone vary depending upon soil type, climate, and crop management practices (Sogbedji et al. 2000). Nitrate leaching may be as high as 100 kg ha^{-1} when corn is produced in tilled land with no cover crop (Gold et al. 1990; Hahne et al. 1977). Conservation practices such as the use of cover crops, no-till planting, and fertilizer management are capable of reducing NO_3-N leaching when properly managed (Angle et al. 1989; Arora and Juo 1982; Kanwar et al. 1988; Kladivko et al 2014; Yadav 1997). Cereal rye (*Secale cereal* L.) and hairy vetch (*Vicia villosa* Roth) cover crops reduce NO_3-N leaching by utilizing and immobilizing excess soil NO_3-N during winter fallow periods (Brandi-Dohrn et al. 1997; Ketterings et al. 2015; Krueger

et al. 2011; McCracken et al. 1994). Annual legumes such as vetch are not as efficient in preventing NO_3-N leaching as cereal rye because of the added N to the system from N fixation (McCracken et al. 1994; Campiglia et al. 2011). Even cereal rye has its limitations to immobilizing excess N, and leaching can be significant when grown in a corn system receiving high rates of mineral N (Rasse et al. 2000). A key to minimizing NO_3-N leaching is quick establishment of the cover crop following row crop harvest (Hashemi et al. 2013; Staver and Brinsfield 1998). Some producers have utilized aerial seeding to establish the cover crop prior to corn harvest in the northern regions of US corn production (Singer 2008).

A problem with utilizing cover crops in corn production systems in the southeastern United States is the delay in late summer harvest and the time when environmental conditions are optimum for cover crop establishment—usually in mid-October. Therefore, other cover crop strategies may be more appropriate than traditional annual cover crops. Living mulches (LM) are perennial cohort crops that provide ground cover throughout the growing season (Hartwig and Ammon 2002). They decrease soil erosion (Siller et al. 2016; Wall et al. 1991), suppress weeds (Enache and Ilnicki 1990; Hiltbrunner et al. 2007), and reduce insect pests (Frank and Liburd 2005; Litsinger and Moody 1976). Similar to annual cover cropping systems, perennial LM systems are capable of reducing NO_3-N leaching through uptake of excess soil N (Liedgens et al. 2004; Ochsner et al. 2010). A perennial white clover (*Trifolium repens* L.) LM system in the southern Piedmont region of the United States has been shown to consistently provide over 100 kg N ha^{-1} to corn and re-establish quickly after harvest (Sanders et al. 2017; Andrews et al. 2018). The perennial nature of LM cover crops eliminates the need for cover crop establishment (Sanders et al. 2017) and, thus,

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may provide additional utilization of excess nutrients following crop harvest. However, N supply from leguminous LM cover crops to corn make such systems potential contributors to N leaching. Additionally, the effect of the white clover LM corn production system on NO_3-N leaching is currently unknown.

Hydrologic and water quality models are increasingly being using to determine the impacts of land use, N fertilization, and other conservation practices on nutrient fate within agroecosystems and are considered appropriate and valuable tools to assess the impact of management practices on N leaching (Berntsen et al. 2005; Moriasi et al. 2015; Tafteh and Sepaskhah 2012; Wang et al. 2014). Model use is particularly valuable when economic or technical conditions make long-term field experiments difficult (Li and Liu 2011), though agreement between observed and predicted data is necessary to reduce the uncertainty of model predictions (Moriasi et al. 2015). Previous research efforts have included modeling of NO_3-N leaching in systems that include white clover as a N source (Berntsen et al. 2005; Wu and McGechan 1999) while other models have focused mainly on corn and mineral fertilizer (Tafteh and Sepaskhah 2012; Wang et al. 2014). Although these studies do not focus on the living mulch corn system, they do show that modeling these crops can be successful when determining NO_3-N fate. HYDRUS-1D was chosen for this experiment as it has been used to simulate NO_3-N leaching in similar studies, provides relative ease of use, and allows models to be quickly evaluated through statistical and graphical performance measures (Moriasi et al. 2015; Tafteh and Sepaskhah 2012; Wang et al. 2014). Therefore, the objectives of this study were to (1) use observed data to calibrate and validate a HYDRUS-1D model to simulate water and NO_3-N transport in three different cover crop corn production systems and (2) use the model to compare water and NO_3-N transport in the three systems.

Materials and Methods

Site Description. The study was performed from October of 2014 through February of 2017 at the J. Phil Campbell Research and Education Center in Watkinsville, Georgia (33°52'09.5" N 83°26'59.8" W). The soil is classified as a Cecil sandy loam (fine, kaolinitic, thermic typic Kanhapludults), which was confirmed by pedological analysis of

a soil profile adjacent to the research plots. A soil moisture release curve based on the van Genuchten (1980) equation was created using the evaporation method (Arya 2002) with a Decagon HYPROP device (Decagon Devices, Pullman, Washington) from several soil cores collected from the plot area. The soil moisture release curve indicated that field capacity (−0.03 MPa) was 0.24 cm³ water cm⁻³ soil and wilting point (−1.5 MPa) was 0.11 cm³ water cm⁻³ soil. Weather data were collected by The Georgia Environmental Monitoring Network station adjacent to the plot area (http://weather.uga.edu/).

Experimental Design. The cereal rye (CR), crimson clover (CC), and LM treatments were assigned to a randomized complete block design with six replications. Soils in the experimental area were sampled and pH and mineral deficiencies amended according to soil test. The CR treatment received a total of 280 kg N ha⁻¹ supplemental fertilization that was split into two applications based on a recommendation from Lee et al. (2015). The CC and LM received lower supplemental N rates based upon N credits from the cover crops established in a previous study to provide a similar amount of available N as the CR treatment (Andrews et al. 2018; Sanders et al. 2017). CR plots were fertilized with 56 kg N ha⁻¹ at planting using granular urea. At the V6 stage of corn development, the CR, CC, and LM treatments received 224, 168, and 56 kg N ha⁻¹, respectively, also as granular urea.

Agronomic Management. Prior to cover crop planting, soils were tested for pH and extractable phosphorus (P) and potassium (K) by the University of Georgia Soil Testing Laboratory using the Mehlich 1 method (Beck et al. 2004). Soils were limed and fertilized so that pH was above 6.2 and extractable P and K were above 45 and 140 ppm, respectively. On October 17, 2014, land was disked and firmed with a cultipacker before CR, CC, and LM cover crop plots were seeded by hand at rates of 100, 28, and 13 kg ha⁻¹, respectively. The CC and CR plots were killed with a broadcast application of dicamba (3,6-Dichloro-2-methoxybenzoic acid) and glyphosate (N-(phosphonomethyl) glycine) at respective rates of 1.20 and 1.12 kg a.i. ha⁻¹ on March 16 and April 8, 2015. All herbicides were applied by a state licensed pesticide applicator, and all applications were made during environmental conditions when risk for off-target movement of pesticides

was low. Additionally, the pesticide formulations, application equipment, and application methods that were used ensured that the risk of off-target movement of pesticides was further reduced (Carlsen et al. 2006). A 20 cm banded application of the herbicides at the same rates was applied to the LM plots on April 8, 2015, using a hooded sprayer. The banded application was centered on 90 cm rows. A John Deere 7300 MaxEmerge no-till planter (John Deere, Moline, Illinois) was used to plant corn (DeKalb DKC64-69, GENVT3P) at a population density of 90,000 plants ha⁻¹ on April 21, 2015. Plot size allowed for eight rows of corn per plot. Corn was harvested on August 16, 2015.

Annual cover crops were reestablished in the same plot areas in October of 2015 using the same seeding rates as 2014. On March 23 and April 4, 2016, herbicide applications were made to the CR and CC plots, while herbicide applications were made to the LM plots on April 14. All herbicides were applied as previously described. Corn was planted at the same seeding rate and methods as the previous year on April 28, 2016. Nitrogen fertilization also occurred in the same rate and method as 2015. Corn from all plots was harvested on August 8, 2016, and cover crops were reseeded on the same plots in November of 2016.

Field Instrumentation, Irrigation Scheduling, and Soil Sampling. Campbell Scientific Model CS625 reflectometers (Logan, Utah) were installed under the corn row to monitor soil water content in the center of each plot. The rods were 30 cm in length and installed at 30 degree angles to measure water content at the 0 to 15 and 15 to 30 cm depths. Water content data were measured and recorded on 10 minute intervals and stored on data loggers within three replications of the experiment. Irrigation was provided on an as-needed basis during the cropping season, which was determined by the soil moisture sensors. Overhead irrigation was used to maintain the water content of the surface 0 to 15 cm between 40% to 90% available water content in 2015, but demand for water from other researchers exceeded the ability of the water resources during 2016, a drought year. Thus, there were occasions when the soil moisture content fell below the desired range.

Two porous cup suction samplers (lysimeters) were placed 1 m apart in the center of each plot alongside the corn row in the

other three replications. A Giddings soil core sampler was used to remove soil to a restrictive Bt2 layer, approximately 75 cm deep. A 1 m long lysimeter was installed with a slurry of Bt horizon soil to cover the sampler's ceramic cup, and a slurry of A horizon soil and kaolinite filled the remainder of the augered hole to prevent preferential flow down the side of the lysimeters. Polyvinyl chloride (PVC) pipes with caps were placed over the tops of the lysimeters to prevent damage to the lysimeters and minimize the opportunity for preferential flow.

Lysimeters were purged weekly and a 7 kPa vacuum was applied using a handheld vacuum pump and kept under vacuum for 18 to 36 hours. Water was aspirated from the lysimeters using a handheld vacuum pump, and a 25 mL aliquot of water from each lysimeter was combined for NO_3-N analysis. Occasionally only one lysimeter per plot contained water from which a 50 mL aliquot was sampled for analysis. Eight soil cores were randomly sampled to a depth of 15 cm weekly from each plot using a 1.5 cm diameter handheld soil probe. Soil cores were taken from the center two rows of the plot, combined, air dried, and stored at 4°C.

Laboratory Analysis. Five grams of soil were extracted with 40 mL of 1 M potassium chloride (KCl) for NO_3-N concentration. Water samples and soil extracts were analyzed for NO_3-N concentration using a Timberline TL-2800 Ammonia Analyzer (Boulder, Colorado).

Weekly changes in clover mass in the LM plots were determined using a rising plate meter (RPM) as described by Sanders et al. (2017). Ten to twelve RPM height measurements were made within the center two rows in each LM plot weekly to determine clover mass. Hand harvested clover samples were subjected to Kjeldahl digestion and N content determined using a Timberline TL-2800 Ammonia Analyzer. Total N in the white clover was calculated weekly as the product of white clover mass and the total N content of the clover. Decline in clover mass from one week to the next was used to estimate N release from the clover.

Model Selection and Description. Porous-cup suction lysimeters are a cost-efficient means of obtaining leachate from a large number of treatments (Andraski et al. 2000). However, they are not capable of quantifying water drainage. Therefore, a modeling approach was used with solute concentra-

tion data to evaluate NO_3-N movement. HYDRUS-1D was selected for simulating water and NO_3-N loss in the different cover crop corn production systems in our study due to the relative ease of use and use in similar research (Tafteh and Sepaskhah 2012; Wang et al. 2010). The model was used to simulate water and NO_3-N movement from planting in April of 2015 and 2016 through February of the following year based on mean data from each treatment. One model was used to simulate each corn-cover crop system per period. The one-dimensional model was developed to simulate the vertical movement of soil water, heat, and solutes in variably saturated-unsaturated media (Šimůnek et al. 2016) using a numerical solution to the Richards (1931) equation 1:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(h) \times \left(\frac{\partial h}{\partial z} + 1\right)\right] - S ,\qquad(1)$$

where h (cm) is the pressure head, z (cm) is the gravitational potential head, t (d) is time, and S (cm d^{-1}) is root water uptake rate.

The van Genuchten (1980) soil water retention equation 2 was used to describe water retention in the experimental soil:

$$\theta(h) = \frac{\theta_s - \theta_r}{[1 + (-\alpha h)^n]^m} + \theta_r ,\qquad(2)$$

where α (cm^{-1}), m (dimensionless), and n (dimensionless) are fitted parameters of the van Genuchten equation; $\theta(h)$ is the volumetric water content (cm^3 cm^{-3}); θ_s is the saturated volumetric water content (cm^3 cm^{-3}); and θ_r is the residual volumetric water content (cm^3 cm^{-3}). The van Genuchten (1980) unsaturated hydraulic conductivity equation 3 was used to describe unsaturated flow in the experimental soil:

$$K(h) = K_s \left|\frac{\theta(h) - \theta_r}{\theta_s - \theta_r}\right|^{0.5}\left(1 - \left\{1 - \left|\frac{\theta(h) - \theta_r}{\theta_s - \theta_r}\right|^{1/m}\right\}^m\right),\qquad(3)$$

where K_s is the saturated hydraulic conductivity (cm d^{-1}), m is the fitted parameter from equation 2, and it is assumed that $m = 1 - 1/n$.

Initial estimates of the water retention parameters for equations 2 and 3 were determined by the evaporation method (Arya 2002) using a Decagon HYPROP device (Pullman, Washington) from soil samples taken from each soil layer in a pit adjacent to

the experiment. Soil water retention parameters were optimized through auto-calibration in the top two soil horizons across all models using collected soil moisture data and the inverse solution function in HYDRUS-1D. Since there were no soil moisture data for the lower two soil layers and the inverse solution function in HYDRUS-1D required data from those depths, the soil water retention parameters in the two remaining soil horizons were not changed from the initial parameters. Soil physical properties and final soil water retention parameters are in table 1. Soil samples for bulk density (ρ_b) (g cm^{-3}) were also collected and measured following standard procedures (USDA 1996).

Model Domain and Boundary Conditions. The HYDRUS-1D model used a 100 cm profile with four materials to simulate four soil horizons and their water retention parameters (table 1). A total of 101 nodes were used in the model space with an equal density of one node per centimeter of model space. The upper boundary condition was an atmospheric boundary with surface runoff and the lower boundary condition was free drainage. Observation nodes were placed at 8 and 23 cm below the soil surface to represent the center of time domain reflectometers installed within the corn rows. Observed data were input at each observation node as the average daily volumetric water content (cm^3 cm^{-3}) of the three replications.

Solute transport had a concentration flux boundary condition at the top of the model space with no concentration gradient as the lower boundary condition. Observation nodes were placed at 8 and 75 cm below the soil surface to represent points where soil water NO_3-N concentration was sampled either by soil sampling or suction samplers. Observed data were input in each observation node as the daily average NO_3-N concentration of the three replications. Granular urea fertilizer N was used as an input time variable for the upper boundary condition and the soil water concentration calculated based upon the amount of irrigation water applied. Nitrogen release from the clover in LM plots was added when clover mass declined from one week to the next.

Water Uptake and Evapotranspiration. The Feddes et al. (1978) model (equation 4) was used to describe root water uptake in HYDRUS-1D:

$$S(h) = \alpha(h)S_{max},\qquad(4)$$

Table 1

Soil properties and hydraulic parameters based on the van Genuchten equation for water retention used in the HYDRUS-1D model for the Watkinsville, Georgia, experimental site. Initial uncalibrated parameters as measured by the evaporation method for the top two soil layers are provided in the last two rows.

Soil layer (cm)	Texture	Particle fraction (%) Sand	Silt	Clay	ρ_b (g cm^{-3})	θ_r (cm^3 cm^{-3})	θ_s (cm^3 cm^{-3})	α (cm^{-1})	n	l	K_s (cm d^{-1})
0 to 18	Sandy loam	55	29	16	1.38	0.04	0.30	0.0062	1.28	0.5	61.1
18 to 38	Clay loam	40	30	30	1.52	0.03	0.27	0.0005	1.33	0.5	66.4
38 to 72	Clay	36	22	42	1.42	0.33	0.54	0.0535	1.40	0.5	89.5
72 to 100	Clay	34	12	54	1.46	0.11	0.46	0.0051	1.42	0.5	10.1
0 to 18	—	—	—	—	—	0.28	0.38	0.0257	3.53	0.5	58.2
18 to 38	—	—	—	—	—	0.21	0.38	0.0036	1.14	0.5	NA

Notes: ρ_b = bulk density. θ_r = residual volumetric water content. θ_s = saturated volumetric water content. K_s = saturated hydraulic conductivity.

where $\alpha(h)$ is the coefficient of root water uptake and S_{max} is the potential water uptake (d^{-1}). Root water uptake is zero at saturation (h_0) due to lack of oxygen (O) and increases linearly as pressure heads decrease to h_1. Root uptake was optimum (no water stress) for pressure heads within the range of h_1 to h_2. From h_2 to h_3, root uptake decreased linearly and stopped at pressure heads below h_3 due to insufficient soil water. Based on R^2 provided in model output, the root water uptake parameters that provided the best fit to observed data and subsequently used in this model for all crops were $h_0 = -15$ cm, $h_1 = -30$ cm, $h_2 = -400$ cm, $h_3 = -15,330$ cm, and $S_{max} = 0.5$ cm d^{-1}. For reference, the parameters used for corn in Wesseling et al. (1991) are $h_0 = -15$ cm, $h_1 = -30$ cm, $h_2 = -600$ cm, $h_3 = -8,000$ cm, and $S_{max} = 0.5$ cm d^{-1}.

Input rooting depth for corn increased linearly from 0 cm at planting to a final depth of 72 cm after 82 days of growth and remained at that depth until harvest (Mengel and Barber 1974). An additional 10 cm of rooting depth was added to the corn in the LM treatment to simulate competitive water uptake by the intercropped clover (Kurtz et al. 1952). Rooting depth increased linearly from 0 to 50 cm for the CC and CR cover crops during both model periods, and from 0 to 40 cm in the LM cover crop during the 2015/2016 model period (Caradus 1990; Sainju et al. 1998). Initial to final rooting depth for all cover crops occurred from planting to 60 days after planting (DAP). In the 2016/2017 model period, rooting depth of the LM cover crop was input as 10 cm at corn harvest and then increased linearly to 40 cm after 45 days of growth. As HYDRUS-1D only allows for one root distribution and two crops are simulated in each model, a root distribution to represent corn and all three cover crops was used. Seventy percent of roots were placed in the top 20

cm of soil, which generally occurs in all four crops (Caradus 1990; Mengel and Barber 1974; Sainju et al. 1998). Rooting distribution decreased linearly from 20 to 72 cm (the top of a restrictive clay layer) for the remaining 30% of roots. While the same rooting distribution was used for multiple cover crop systems, it should be noted that each of the three corn-cover crop simulations was performed independently and not incorporated into one model.

Potential evapotranspiration (PET) was separated into evaporation and transpiration in the HYDRUS-1D model by the input of leaf area index (LAI). In the CC and CR models, LAI of corn increased linearly from 0 to 3.0 from 7 DAP to 67 DAP, and then from 3.0 to 3.5 linearly over the next 30 days and remained until harvest (Timlin et al. 2014). For the LM models, an additional LAI of 1.5 was added to account for competitive water uptake by the white clover (Kurtz et al. 1952). Leaf area index of the CC, CR, and LM plots increased linearly from 0 to 3.0 from 7 days after cover crop seeding (DAS) to 69, 37, and 80 DAS, respectively. Leaf area index increased linearly from 3.0 to 5.1 and 3.0 to 4.6 until 82 and 89 DAS for the CC and LM treatments, respectively (den Hollander et al. 2007; Ellen 1993). The LAI remained constant thereafter until the end of February in the following year (den Hollander et al. 2007). In the next model period, white clover in the LM treatment was not reseeded, so LAI followed the same development as the previous LM model, but began with an LAI of 1.0. Therefore, LAI of the white clover increased linearly from 1.0 to 3.0 after 52 DAS (though no white clover was planted), and then from 3.0 to 4.6 during the 56 to 65 DAS time period.

Soil Nitrogen Transport and Transformation. Linear adsorption and chemical equilibrium in the advection–dispersion equation (ADE) was used to

estimate solute transport in HYDRUS (5):

$$\frac{\partial(\theta c + \rho_b K_d c)}{\partial t} = -\frac{\partial}{\partial t}\left(J_w c - \theta D_e \frac{\partial c}{\partial z}\right) - \theta \mu c - Sc, \quad (5)$$

where c is the dissolved concentration of the solute (g cm^{-3}), t is time (d), K_d is an adsorption coefficient (cm^3 mg^{-1}), D_e is the effective dispersion coefficient (cm^2 d^{-1}), z is the vertical dimension (cm), J_w is the vertical Darcy water flux (cm d^{-1}), and μ is the first-order rate constant for solute transformation processes (d^{-1}).

Mineralization and nitrification can occur rapidly, and concentrations of potentially mineralizable N (PMN) and ammonium (NH$_4$) are low in Cecil soils (Dubey 1968; Anderson 1960; Cabrera 1993). Therefore, PMN and NH$_4$-N in the soil profile were considered together as a bulk solute. Other relevant HYDRUS-1D NO$_3$-N leaching research used a similar strategy involving transformations of PMN and NH$_4$-N into NO$_3$-N (Tafteh and Sepaskhah 2012; Wang et al. 2010).

An N chain model was used to simulate N transformations in the CC, LM, and CR models. The model included the nitrification of NH$_4$-N and PMN to NO$_3$-N as well as denitrification from NO$_3$-N to dinitrogen/nitrous oxide (N$_2$/N$_2$O). The intermediate product of nitrification, NO$_2$-N, was ignored to simplify the chain model (Bradshaw et al. 2013). The first-order reaction rates for the change in NH$_4$-N + PMN (equation 6) and NO$_3$-N (equation 7) concentrations that result from the N chain models were

$$\frac{\partial[\text{NH}_4 - \text{N} + \text{PMN}]}{\partial t} = -k[\text{NH}_4\text{N} + \text{PMN}] \quad (6)$$

and

$$\frac{\partial [NO_3-N]}{\partial t} = -k[NH_4N+PMN] - \mu[NO_3N] \quad , \quad (7)$$

where k and μ are the nitrification and denitrification rate coefficients (d^{-1}), respectively, and t is time (d). It was assumed that these coefficients only applied to N in solution. Based on percentage bias (PBIAS), R^2, and d, the nitrification rate constant of 0.2 d^{-1} was found to provide an acceptable fit to observed data and was within ranges reported in the literature (table 2) (Hanson et al. 2006; Iskandar and Selim 1981; Ling and El-Kadi 1998; Lotse et al. 1992). Complete denitrification of NO$_3$-N was assumed to occur under saturated conditions, and rate constants were set the same as for nitrification (table 2). Adsorption coefficients for NH$_4$-N/PMN and NO$_3$-N were 10 and 0.78 cm^3 g^{-1} for all soil horizons (table 2), and were based on values from Bradshaw et al. (2013). Based on R^2 in model output, the adsorption coefficient was optimized across models using manual calibration to provide a more acceptable fit to observed NO$_3$-N concentrations at the 8 and 75 cm depths.

Water content dependence of nitrification and denitrification were incorporated into the solute models. Water content dependence of reaction rates uses a modified version of the Walker (1974) equation 8:

$$\omega(\theta) = \omega_r(\theta_{ref}) min \left[1, \left(\frac{\theta^B}{\theta_r}\right)\right], \quad (8)$$

where ω_r is the reaction rate constant (d^{-1}) at the reference water content (θ_{ref}), $\omega(\theta)$ is the rate constant (d^{-1}) at the actual water content (θ), and B is a dimensionless solute-dependent parameter. Nitrification and denitrification rates were considered to be optimum at pressure heads of −500 cm and −20 cm, respectively.

Model Initial Conditions and Inverse Data. The initial condition for soil pressure head at the uppermost observation node in each model was set to the corresponding water content that was measured at the beginning of the model period. The rest of the model space was set so that soil water movement was only due to gravitational flow (constant pressure head with depth). Inverse data for water content were input into HYDRUS-1D as the average daily measured volumetric water content of the three replications. Initial NO$_3$-N concentrations were input into the model based on both soil samples and lysimeter samples taken immediately before corn planting. Average soil water NO$_3$-N concentrations were determined by taking the average soil NO$_3$-N level from the three replications and converting it to a concentration using the water content and bulk density of the soil.

Model Performance Criteria. Observed data in the model were average soil water content at the 8 and 23 cm depths and average soil water NO$_3$-N concentration at the 8 and 75 cm depths. As a plot-scale model, no performance evaluation criteria are currently established in the literature for HYDRUS-1D that evaluate the agreement between predicted and observed data, and therefore determined by the objectives and statistical performance measures selected by the user (Moriasi et al. 2015). Therefore coefficient of determination (R^2), PBIAS, and index of agreement (d) were used to assess calibration and validation model performance along with visual inspection of graphical data.

R^2 describes the proportion of the variance in measured data explained by the model (Moriasi et al. 2007). R^2 ranges from 0 to 1, and the degree of collinearity between predicted and observed data increases as values approach 1 (Moriasi et al. 2015). PBIAS measures whether the predicted data tend to be smaller or larger than their observed counterparts (Gupta et al. 1999). Positive values indicate an underestimation of water flow or NO$_3$-N transport while negative values indicate overestimations of the parameters. Index of agreement (d) is the ratio between the mean square error and the potential error with values ranging from 0 to 1. As d values approach 1, the agreement between predicted and observed values increases (Willmott 1984).

Results and Discussion

Meteorological Conditions. The total rainfall during the model period from April 21, 2015, to February 29, 2016, was 1,236 mm, of which 689 mm occurred between November and January (table 3). Drought occurred during most of 2016 to 2017 with rainfall totaling 706 mm between April 28, 2016, and February 26, 2017. Rainfall during the period of November through January in 2016 and 2017 was 311 mm, less than half of that during 2015/2016.

Nitrogen Release from Living Mulch. An estimated 30.9 and 36.6 kg N ha^{-1} were released due to herbicide banding of the white clover in the LM plots in 2015 and 2016, respectively (Andrews et al. 2018). The total cumulative N release from LM clover at the end of the growing season was 139 and 149 kg N ha^{-1} in 2015 and 2016, respectively.

Model Calibration and Validation. Data collected from the three replications of each treatment from April through August of 2015 were averaged and used to calibrate each model. Data collected from the three replications of each treatment from April of 2016 through February of 2017 were averaged and used to validate each model. Water flow calibration and validation R^2 values ranged from 0.57 to 0.70 and 0.67 to 0.71, respectively (table 4). The PBIAS values for water flow ranged between −2.9% and 10.8% for both calibration and validation models, and d values ranged between 0.77 and 0.89. Fitted values for the hydraulic parameters for the 0 to 18 and 18 to 38 cm depths differed from the initial values measured by the evaporation method (table 1). In the 0 to 18 cm depth, for example, θ_r decreased from 0.28 to 0.04, θ_s decreased from 0.38 to 0.30, α decreased from 0.0257 to 0.0062, and n decreased from 3.53 to 1.28. These changes resulted in a less steep water retention curve and unsaturated $K(h)$ curve. However, it is not uncommon for fitted HYDRUS hydraulic parameters to differ from measured values (Bradshaw et al. 2013; Wang et al. 2010).

Calibration and validation R^2 values for NO$_3$-N transport ranged from 0.83 to 0.91 and 0.41 to 0.77, respectively (table 4). Percentage bias values ranged from −38% to 14.5% and from −8.1% to 0.4% for calibration and validation, respectively. The calibration and validation d values ranged between 0.81 and 0.97, which is similar to those reported in other HYDRUS model simulations (Doltra and Muñoz 2010; Hu et al. 2008; Mubarak et al. 2009; Li et al. 2011). Generally, the level of agreement between observed and predicted data was not as strong for NO$_3$-N transport when compared to the water flow models. This relationship is common for water and nutrient transport models, and the level of agreement necessary for nutrient transport modeling is typically lower than for water flow modeling (Moriasi et al. 2015). Graphical evaluation of model performance is presented in figures 1 through 3.

Table 2

Adsorption coefficients for ammonium-nitrogen (NH_4-N) + potentially mineralizable N (PMN) and nitrate-N (NO_3-N), nitrification rate, and denitrification rate used for N transformation and transport in the HYDRUS-1D models.

	Adsorption coefficient K_d (cm³ g⁻¹)		Nitrification rate	Denitrification rate
Soil layer (cm)	NH_4-N + PMN	NO_3-N	k (d⁻¹)	μ (d⁻¹)
0 to 18	10.0	0.78	0.20	0.20
18 to 38	10.0	0.78	0.20	0.20
38 to 72	10.0	0.78	0.20	0.20
72 to 100	10.0	0.78	0.20	0.20

Table 3

Monthly precipitation (P), irrigation (I), potential evaporation (PET), and average temperature in 2015, 2016, and 2017 at the J. Phil Campbell Research and Education Center in Watkinsville, Georgia.

	2015/2016					2016/2017				
Month	P (mm)	I (mm)	P + I (mm)	PET (mm)	Avg. temp. (°C)	P (mm)	I (mm)	P + I (mm)	PET (mm)	Avg. temp. (°C)
March	86	0	86	58	13.1	53	0	53	84	15.1
April	208	0	208	84	17.9	58	19	77	120	17.0
May	47	78	125	138	21.6	32	95	127	143	20.8
June	59	76	135	145	25.4	117	152	269	172	26.1
July	131	19	150	147	26.7	33	114	147	169	27.2
August	198	0	198	136	25.1	142	0	142	130	26.4
September	109	0	109	100	21.8	29	19	48	114	24.4
October	149	0	149	59	16.0	1	25	26	78	18.9
November	235	0	235	25	13.3	40	57	97	37	13.0
December	341	0	341	13	13.3	102	0	102	9	8.1
January	113	0	113	23	5.3	167	0	167	28	10.3
February	109	0	109	39	8.1	38	0	38	46	10.9
Total	1,785	173	1,958	967	—	812	481	1,293	1,130	—

Table 4

Coefficient of determination (R^2), percentage bias (PBIAS), and index of agreement (d) comparing agreement between observed and predicted water contents and nitrate-nitrogen (NO_3-N) concentrations in the crimson clover (CC), living mulch (LM), and cereal rye (CR) HYDRUS-1D models.

		Water content			NO_3-N concentration		
System	Period	R^2	PBIAS	d	R^2	PBIAS	d
CC	Calibration	0.70	6.6	0.84	0.91	−38.0	0.94
	Validation	0.67	−2.9	0.89	0.61	0.4	0.87
LM	Calibration	0.57	4.1	0.82	0.83	14.5	0.90
	Validation	0.68	−2.5	0.89	0.41	−8.1	0.92
CR	Calibration	0.67	10.8	0.77	0.90	−12.0	0.97
	Validation	0.71	1.2	0.88	0.77	−1.8	0.92

Soil Water. Predicted cumulative water loss below 1 m was similar among the different cover crop treatments when calibrating the HYDRUS-1D model (figure 4). The majority of water moved through the soil profile after the corn was harvested in the fall of 2015. This can be attributed to the fact that precipitation + irrigation was equal to crop evapotranspiration during the corn growing season (Andrews et al. 2018). Therefore, little surplus water was available to move through the soil profile. The annual growth habit of corn limited crop water use after harvest, but the soil rehydrated and percolation occurred when rainfall exceeded evapotranspiration. This was particularly evident following intense rainfall in December of 2015 (figure 4).

The validation model predicted considerably less water loss at the 1 m soil depth in 2016/2017 (figure 4). Precipitation + irrigation was less than crop evapotranspiration during the corn growing season, which limited surplus water availability for vertical movement (figure 4). Cumulative water loss after corn harvest in 2016 was less in the LM treatment than the other cover crop treatments. Water use by the perennial white clover exceeded that of the reseeded annual cover crops during drought conditions in the fall and winter of 2016/2017. Predicted cumulative water loss in the LM system was less than that in the CC and CR systems, respectively (figure 4).

Nitrate Leaching. The calibration models predicted that <1 kg NO_3-N ha⁻¹ was leached below 1 m during the corn growing season in 2015 (April through August) regardless of cover crop treatment (figure 4), likely due to reduced water flow during that period. However, rainfall events in the fall and winter of 2015/2016 caused soils to become saturated, and NO_3-N leached for more than two months after corn harvest. There were no differences in water flow at 1 m among the cover crop treatments, though the LM treatment had approximately 50% less cumulative NO_3-N transport than the CC or CR treatments (figure 4).

The validation models predicted that there was limited NO_3-N leaching in all treatments, mostly due to reduced precipitation and lower water percolation than the previous model period (figure 4). In fact, evapotranspiration exceeded total precipitation and irrigation during corn growth in 2016, and may have led to reduced mineralization of white clover residue (Andrews et al. 2018).

Reduced NO_3-N leaching in the white clover LM system is consistent with similar

Figure 1

Observed and predicted HYDRUS-1D model data for the crimson clover (CC) system for water content and soil water nitrate-nitrogen (NO_3-N) concentration at the 8 cm depth, as well as soil water NO_3-N concentration at the 75 cm depth. Calibration (2015/2016) data is in the left column and validation (2016/2017) data is in the right column, both beginning 0 days after corn planting (DAP) in April of each year.
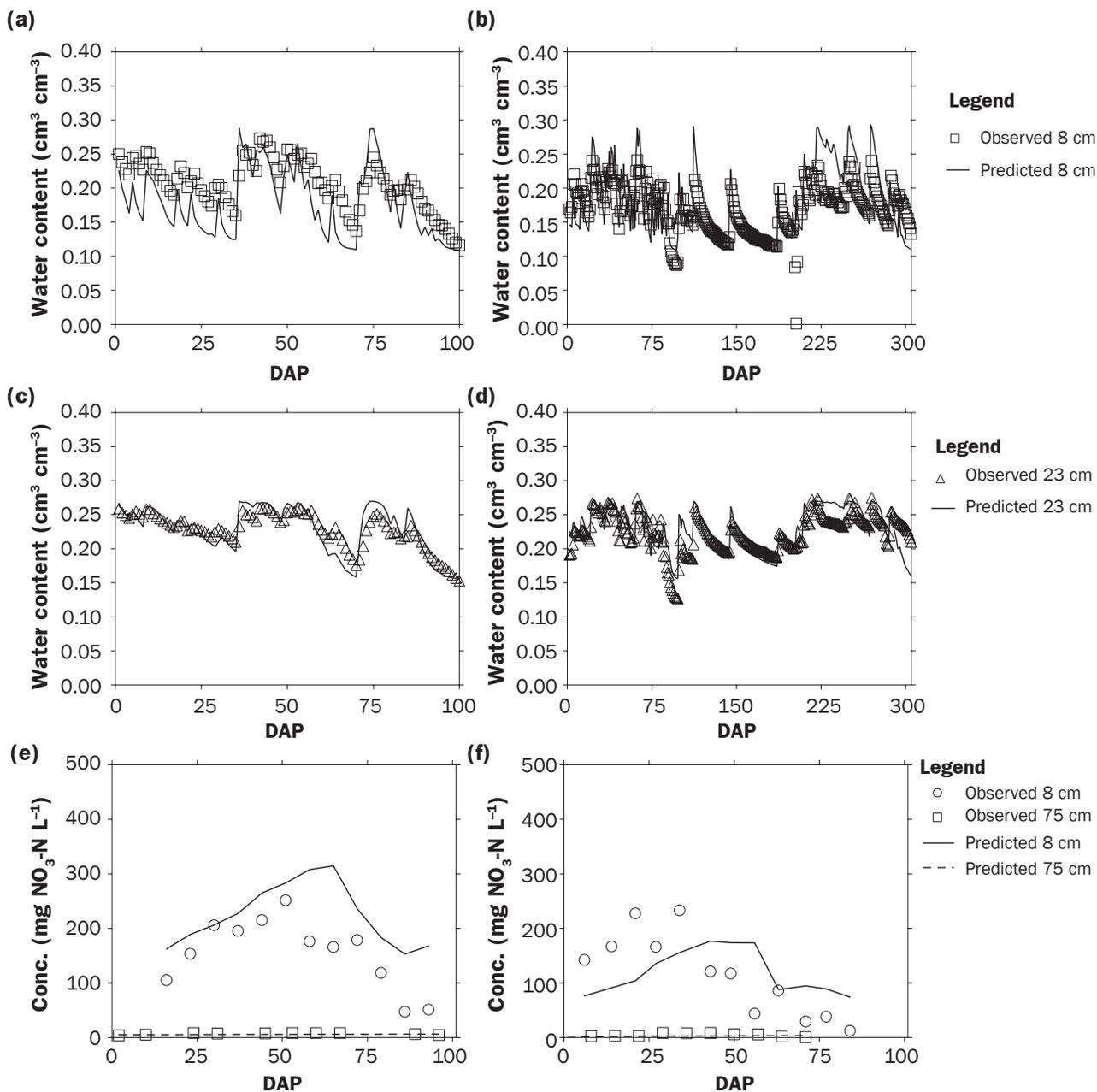
LM research (Liedgens et al. 2004; Ochsner et al. 2010). Leguminous LM systems have been found to have reduced soil N during and after the corn growing season, leading to less N vulnerable to leaching (Andrews et al. 2018; Ochsner et al. 2010; Zemenchik et al. 2000). These reductions have been attributed to competitive N uptake by the intercropped clover and reduced N mineralization during

unfavorable environmental conditions, and can have a negative impact on overall corn growth and yield (Andrews et al. 2018; Kurtz et al. 1952; Liedgens et al. 2004; Ochsner et al. 2010). Reductions in soil moisture have also been reported in leguminous LM systems due to additional evapotranspiration by the intercropped clover, but this does not seem to dramatically affect percolation

(figure 4) (Sanders et al. 2018; Ochsner et al. 2010; Zemenchik et al. 2000). Therefore, reduced soil N is likely the main cause of reduced NO_3-N in leguminous LM systems (Ochsner et al. 2010).

The results herein are unique in that they show a reduction in NO_3-N leaching in a perennial legume cover crop when compared to either grass or legume annual

Figure 2

Observed and predicted HYDRUS-1D model data for the living mulch (LM) system for water content and soil water nitrate-nitrogen (NO_3-N) concentration at the 8 cm depth, as well as soil water NO_3-N concentration at the 75 cm depth. Calibration (2015/2016) data is in the left column and validation (2016/2017) data is in the right column, both beginning 0 days after corn planting (DAP) in April of each year.
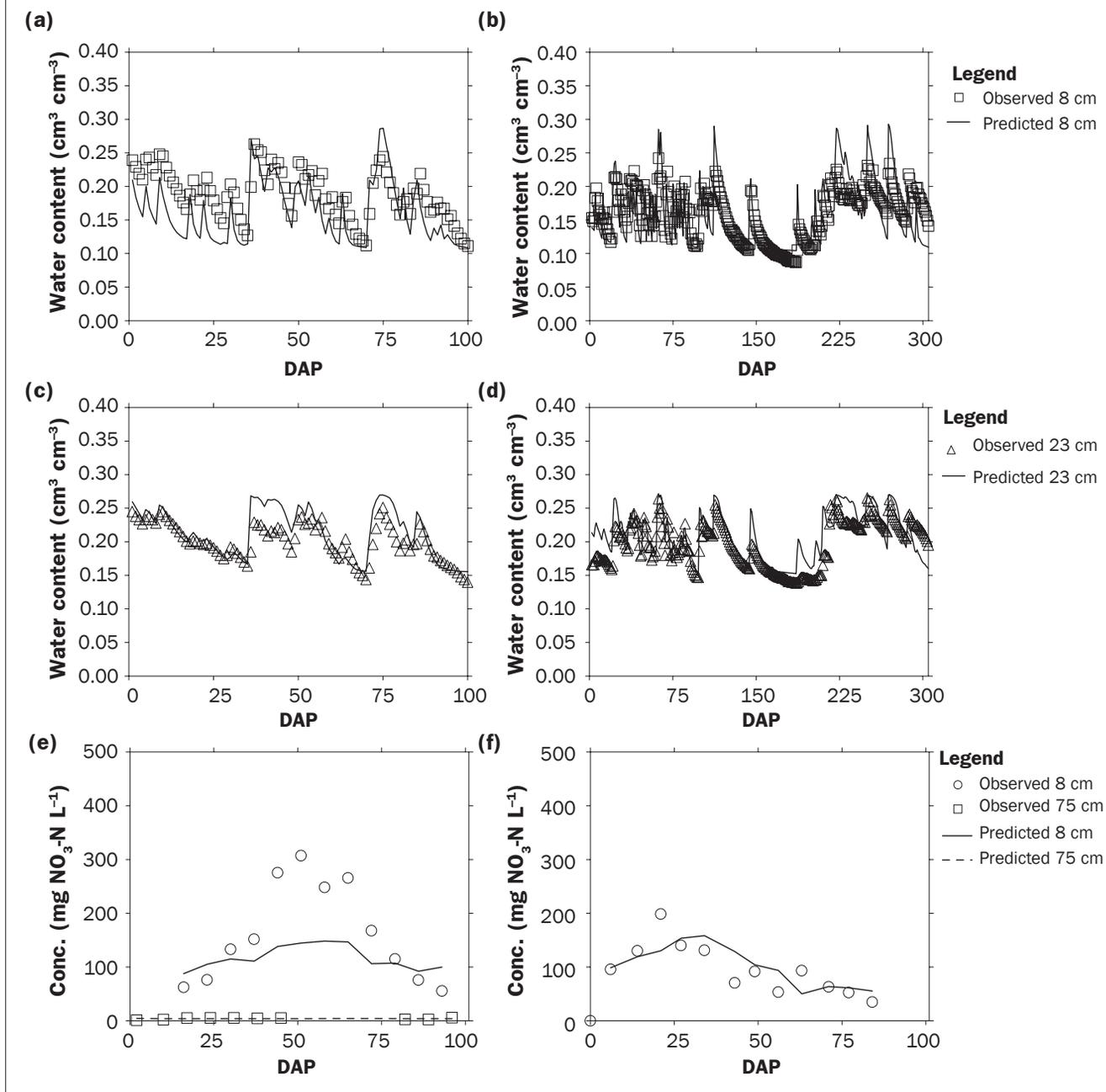
cover crops. In addition to reduced soil N after corn harvest, this may be attributed to residual N uptake by the white clover during regrowth. Although known for their N-fixing capabilities, perennial legume cover crops may preferentially utilize excess soil N, leading to a reduction of soil N susceptible to leaching (McCracken et al. 1994; Svenning and Macduff 1996). Nitrogen uptake in the white clover may also be aided by rapid white clover re-establishment, which has been shown to exceed 80% basal cover 100 days after corn harvest. However, cereal rye is considered to have a greater N uptake potential than legumes, and different levels of soil N after harvest make it difficult to compare N scavenging potential of the three systems (Andrews et al. 2018; Dabney et al. 2007).

Summary and Conclusions

The HYDRUS-1D model was able to successfully simulate the vertical water and NO_3-N movement in LM and annual cover cropped corn production systems. Model predictions revealed that little leaching occurred during the corn growing season, but did occur during the dormant season when precipitation exceeded the water

Figure 3

Observed and predicted HYDRUS-1D model data for the cereal rye (CR) system for water content and soil water nitrate-nitrogen (NO_3-N) concentration at the 8 cm depth, as well as soil water NO_3-N concentration at the 75 cm depth. Calibration (2015/2016) data is in the left column and validation (2016/2017) data is in the right column, both beginning 0 days after corn planting (DAP) in April of each year.
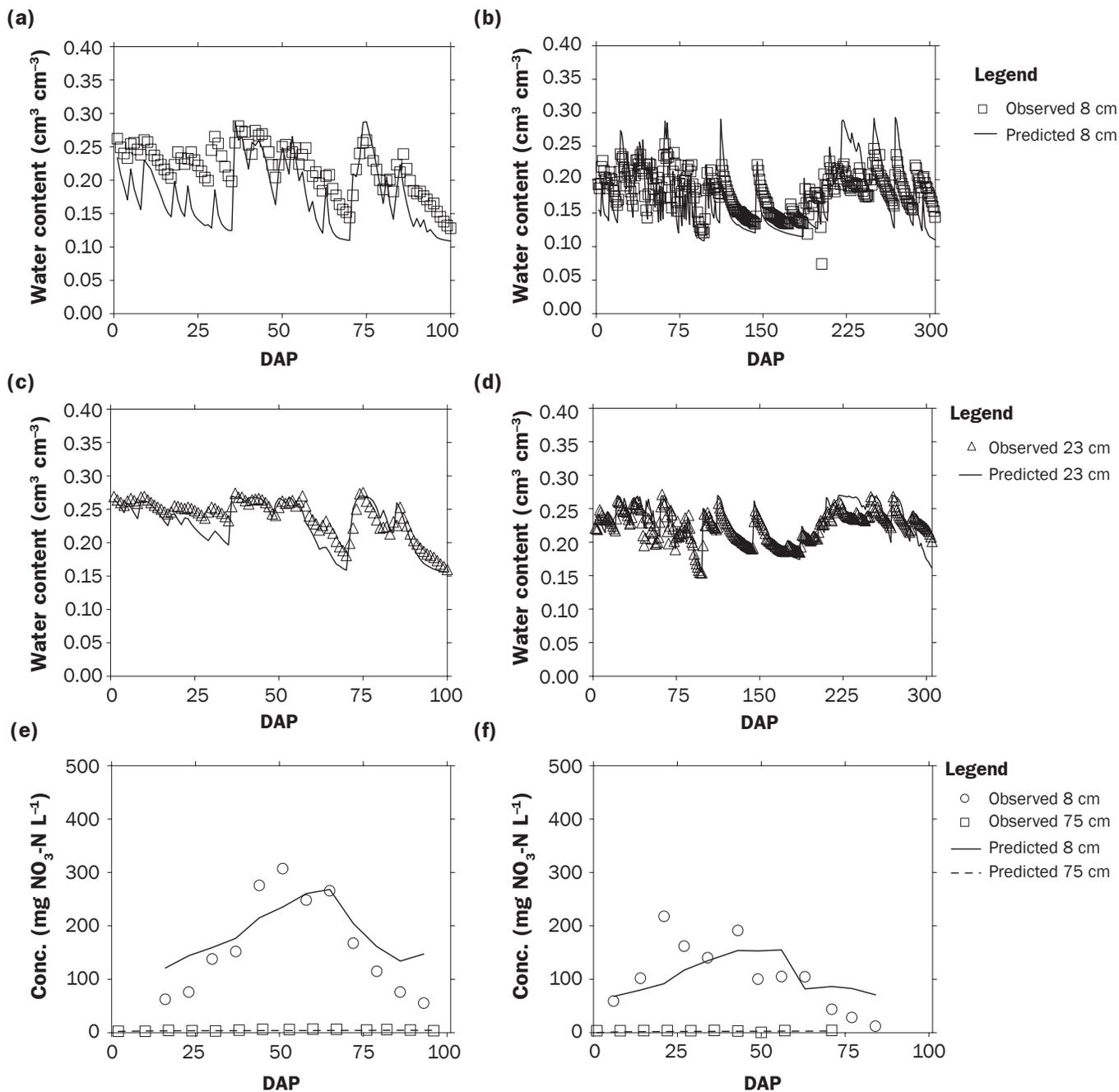
holding capacity of the soil. This study may be unique in that it suggests that NO_3-N leaching in corn production may be reduced by a perennial LM cover crop when compared to annual cover crops. Reductions in NO_3-N leaching are attributed to less residual soil N after corn harvest and N uptake by the white clover during regrowth. Therefore, the LM system may be enticing to producers as it reduces both mineral fertilizer inputs and N leaching losses without the need to re-establish like in annual cover cropping systems. However, future work is necessary to determine surface nutrient losses, atmospheric emissions, long-term N release from cover crops and soil organic matter, weed competition and herbicide use, and economic efficiency of the LM system for it to be fully considered a viable production strategy.

Figure 4

Water drainage and nitrate-nitrogen (NO$_3$-N) leaching during the two model periods from 0 to 315 days after planting (DAP), starting at corn planting in (a and c) April of 2015 through February of 2016 and from corn planting in (b and d) April of 2016 through February of 2017. Water and NO$_3$-N loss during the two periods is shown for the crimson clover (CC), living mulch (LM), and cereal rye (CR) corn production systems.
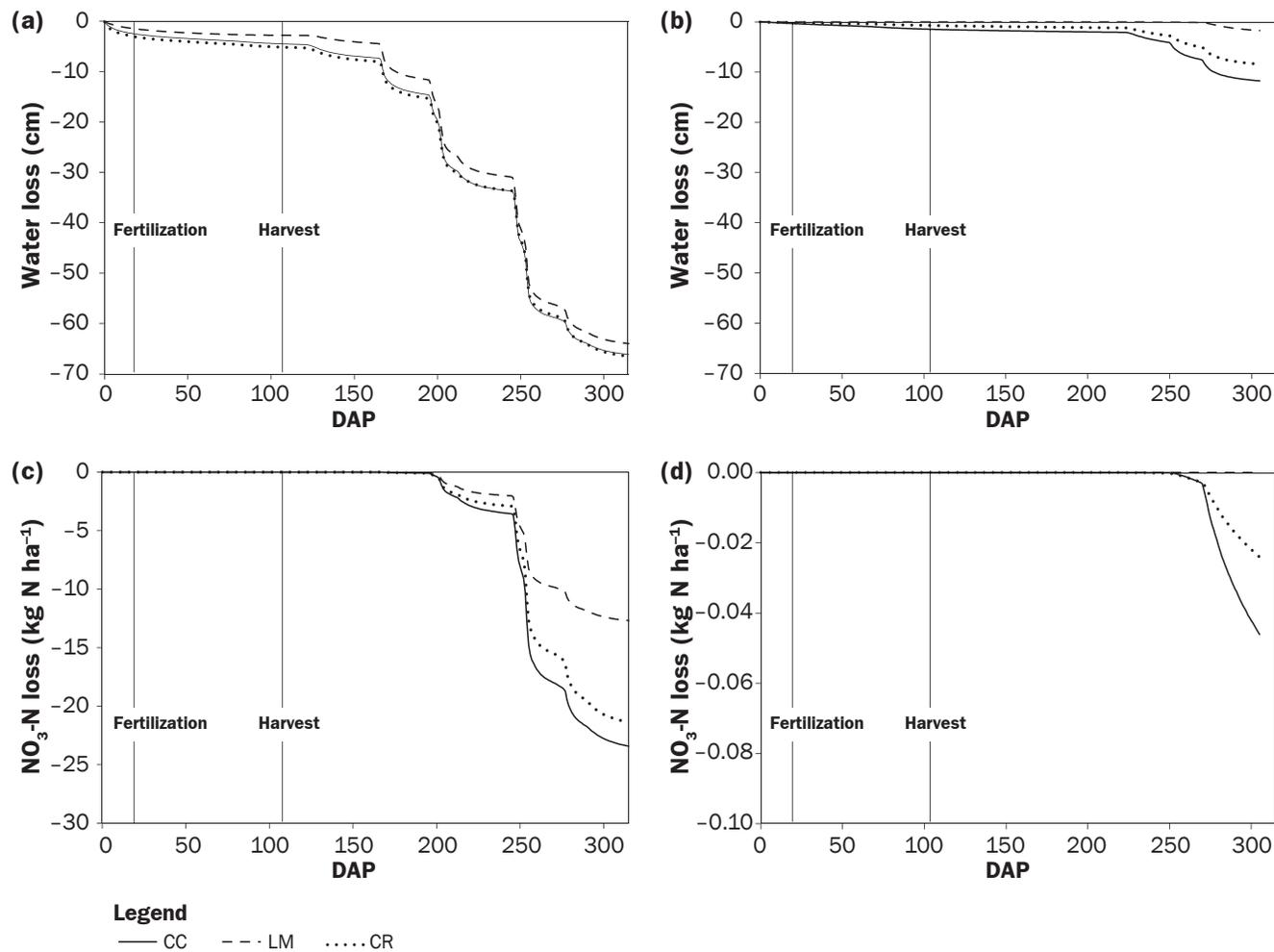
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