Estimating Nitrogen Mineralization from Cover Crop Mixtures Using the Precision Nitrogen Management Model


ABSTRACT

Cover crops influence soil N dynamics and N availability to a subsequent crop. Dynamic simulation models, if properly calibrated and tested, can simulate C and N dynamics of a terminated cover crop and estimate crop-available N over diverse production environments. We calibrated and tested a dynamic simulation model modified to simulate C and N cover crop residue dynamics in maize (Zea mays L.) production systems. Data from a 2-yr field study of different cover crop residue mixtures, fertilizer rates, and tillage practices were used in model calibration and testing. First order rate constants governing cover crop residue decomposition were calibrated so that statistical measures of model best fit were optimized. Calibration resulted in a good fit between measured and modeled N release from the terminated cover crop mixtures (root mean square error [RMSE] = 14 kg N ha⁻¹; Willmott’s index of agreement (IA) = 0.92). The calibrated model performed reasonably well in the testing phase (RMSE = 25; IA = 0.88) with significantly better performance for the no-till (NT) treatments compared to the incorporated treatment. Accounting for cover crop components (leaf, stem proportions), calibration of the temperature and moisture response functions that modify the calibrated rate constants, and testing over a wider range of soils, management practices and climates are potential areas for model improvement. The revised, calibrated model will be used in a decision support tool for N management in maize production and in studies of N dynamics in maize agro-ecosystems that include cover crops.

Core Ideas

- The precision N management model performed reasonably well for estimating cover crop N mineralization.
- Model performance was sufficient to justify incorporation into an N decision support tool.
- Cover crops as a best management practice can be assessed with the calibrated model.

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Abbreviations: ET, evapotranspiration; IA, index of agreement; NT, no-till; PNM, precision nitrogen management; PPL, pelleted poultry litter; SOM, soil organic matter; Ts, transpiration; VWC, volumetric water content.
impact these factors (Thorup-Kristensen and Dresbøll, 2010; Meisinger et al., 1991; Ritter et al., 1998; Weinert et al., 2002; Hively et al., 2009; Snapp et al., 2005). Soil physical properties (soil organic matter [SOM], texture, bulk density, water content, and temperature) and chemical properties (e.g., soil ammonium N (NH₄–N) and NO₃–N in the crop root zone) following termination exert additional controls on the decomposition and N availability of cover crops (Vigil and Kissel, 1995; Cabrera et al., 2005).

Because of these multiple factors impacting cover crop decomposition and N release, providing N management guidance for maize growers who use cover crops and estimating the impact of long-term cover crop use in agro-ecosystems is difficult. One approach is to use dynamic simulation models combined with experimental data to estimate changes in crop-available N (NH₄–N, NO₃–N in the crop root zone) from cover crop decomposition (Hasegawa et al., 1999; Zubillaga et al., 2007). These models can integrate the dynamic and complex interrelationships among the factors affecting crop-available N over a range of growing conditions, and estimate how the soil/crop system, including crop-available N, changes over time. If these models are well calibrated and tested, they can provide information that could be used in decision support tools for growers to adjust N applications to more precisely match crop N demand (Kersebaum, 1995; Smith et al., 1997; Shaffer et al., 2001) and in long-term agro-ecosystem studies that include cover crops.

Models of C and N dynamics in soils that include crop residue mineralization and N release typically require the total dry biomass of the residues, C or N content of the biomass, and C/N ratio of the residues as inputs (Shaffer et al., 2001). Some models also partition the residues into different pools based on chemical composition. For example, the CERES-N model separates residues into three pools, soluble carbohydrates, cellulose, and lignin, and uses first order kinetics to estimate mineralization of those pools where each pool has a unique first order rate constant (Schomberg and Cabrera, 2001; Hasegawa et al., 1999; Zubillaga et al., 2007). Schomberg and Cabrera (2001) showed that CERES-N model performance was improved when field data on the pool sizes were available. We have developed the precision nitrogen management (PNM) model (Melkonian et al., 2005, 2007), a daily time step dynamic simulation model that simulates crop and soil water, and C and N dynamics in maize cropping systems. It has two components: a soil process model (LEACHN; Hutson, 2010) and a maize N uptake, growth, and yield model (Sinclair and Muchow, 1995). The LEACHN component of the PNM model has been tested in several studies (Jabro et al., 1994; Jemison et al., 1994; Sogbedji et al., 2001b) with the same time step and approach to soil process modeling as several other widely used soil process models (e.g., CERES, DAYCENT; Shaffer et al., 2001). Like these models, LEACHN can account for mineralization of plant residue additions to the soil and estimate the contribution of these additions to C and N pools, including crop-available N, over time. Data required by the PNM model to simulate crop residue mineralization include the total C (kg C ha⁻¹) and total N (kg N ha⁻¹) of the residue at termination. The C in the residue is mineralized using a first order rate equation and rate constants based on PNM model calibration studies (Sogbedji et al., 2006; Marjerison et al., 2016). Residue N is either released to the soil (net mineralization) or temporarily immobilized depending primarily on the residue C/N ratio. Values for the rate constants were initially obtained from published studies or research plots, and then were adjusted based on statistical analyses of model output vs. measured data. The measured data were obtained from a 3-yr field study (1998–2000) located at the Cornell University Research Farm in Willsoboro, NY (44°22' N, –73°26' W) (Sogbedji et al., 2006), and from two multi-year studies located at the Willsoboro research farm (1995–1999) and the University of Minnesota Southern Outreach and Extension Center (44.07° N, –93.52° W) (1994–1999) (Marjerison et al., 2016). The PNM model has been calibrated and tested for different maize production systems (Sogbedji et al., 2006; Melkonian et al., 2010). These production systems included plant residue mineralization from a sod crop in a multi-year rotation with maize but not for maize production systems that include cover crops.

The PNM model is currently being applied to assess growing season crop-available N (NH₄–N and NO₃–N) and N losses to the environment from maize production systems both historically and under projected future climate scenarios. Incorporation of cover crops into maize management is hypothesized to be a “best management” practice that can reduce N losses and deliver crop-available N to the main crop. The PNM model is also being used in a cloud-based N management decision support tool, “Adapt-N” (Agronomic Technology Corp; www.adapt-N.com). An increasing number of growers using Adapt-N also use cover crops in their maize production so that there is a need to account for the impact of these crops on N management and environmental N losses.

The PNM model does not currently include calibrated and tested algorithms estimating mineralization of terminated cover crops. Therefore, we modified the relevant processes in the PNM model to estimate N mineralization from terminated grass (cereal rye) and legume (hairy vetch [Vicia villosa Roth]) cover crops, alone and in combination, in a maize production system. The objective of this study was to calibrate rate constants of the first order rate equations for mineralization of these cover crop combinations in the modified model and test model performance using cover crop litter bag decomposition data for those combinations from a 2-yr field study (Poffenbarger et al., 2015b). In this study, detailed data on litter bag mineralization, soil temperature, and soil moisture were collected from maize planting to harvest. Although the study was limited to similar soil types and locations, it did include relatively broad ranges of N treatments and cover crop combinations, as well as two different tillage systems.

METHODS

Field Experiment

A field experiment was conducted in 2011–2012 (North Farm) and repeated at a different site in 2012–2013 (South Farm) at the USDA-ARS Beltsville Agricultural Research Center in Maryland (Poffenbarger et al., 2015a, 2015b). The experimental methods outlined below as well as the measured data for comparison with the PNM model were obtained from Poffenbarger et al. (2015b). Both experiments had the same treatments and similar crop rotations, including organic
fertility additions. The soil series at the sites were classified as fine-loamy, mixed, mesic Typic Endoaquult (Hatboro series) (2012, North Farm) and fine-loamy, mixed, active, mesic Fluvaquentic Dystrudept (Codorus series) (2013, South Farm). Measured textural and bulk density data for the soil series at both sites were obtained as model inputs for the simulations in the study reported here (Table 1).

Six hairy vetch/cereal rye cover crop mixture percentages (0:100, 20:80, 40:60, 60:40, 80:20, 100:0) where the percentages reflect the species monoculture seeding rate were sown in early fall of 2011 and 2012. In the spring of 2012 and 2013, four pelletized poultry litter (PPL) and tillage treatments: starter only/NT, subsurface banded/NT, broadcast/NT, and pre-plant broadcast and incorporated, were applied in a split-block design with three replicates each year. In this study, we used data from the starter only/NT, subsurface banded/NT, and broadcast/incorporated treatments in the model calibration and testing. Nutrient properties of the PPL are shown in Table 2. All treatments in both years received starter PPL at a rate of approximately 0.5 Mg ha$^{-1}$ (~4 kg ha$^{-1}$ NH$_4$-N and ~14 kg ha$^{-1}$ organic N). Additional PPL (subsurface banded NT and pre-plant incorporated treatments) was applied at a rate of ~ 3.6 Mg ha$^{-1}$ (~24 kg ha$^{-1}$ NH$_4$-N and ~90 kg ha$^{-1}$ organic N) in 2012, and ~ 3.4 Mg ha$^{-1}$ (~30 kg ha$^{-1}$ NH$_4$-N and ~91 kg ha$^{-1}$ organic N) in 2013.

Cover crops were terminated using a roller/crimper (I&J Manufacturing, Gap, PA) in the NT plots, and flail-mowed and disked in the incorporated plots several days prior to maize planting. In 2012 (North Farm), hairy vetch was in full flower and cereal rye was in the soft dough stage (growth stage 85 on Zadoks scale) at the time of rolling. In 2013 (South Farm), hairy vetch was at 50% flowering and cereal rye was in the milk stage (growth stage 75 on Zadoks scale). These termination dates were relatively late to maximize cover crop biomass production for the roller/crimper system.

Maize was planted in the NT and incorporated treatments on the same day that the cover crop in the NT plots was terminated. All treatments received a starter application of PPL.

<table>
<thead>
<tr>
<th>Year</th>
<th>Percent</th>
<th>Moisture</th>
<th>Total N</th>
<th>NH$_4^+$-N</th>
<th>Organic N</th>
<th>PAN</th>
<th>P$_2$O$_5$</th>
<th>K$_2$O</th>
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<td>11</td>
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<td>2.0</td>
<td>3.4</td>
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Table 2. Nutrient properties of the pelletized poultry litter used in the North Farm (2012) and South Farm (2013) experiments. Litter samples were collected and analyzed just prior to maize planting each year. PAN, plant-available nitrogen; P$_2$O$_5$, available phosphate; K$_2$O, water soluble potash. Plant available N was calculated assuming 90% of the NH$_4^+$-N and 50% of the organic N would be available for uptake by the maize crop (Poffenbarger et al., 2015b; University of Maryland Extension, 2009, 2011).

<table>
<thead>
<tr>
<th>Depth</th>
<th>Bulk density</th>
<th>Soil texture</th>
<th>Volumetric water content</th>
<th>Organic C</th>
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<tr>
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<td>mg m$^{-3}$</td>
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### Hatboro loam (North Farm, 2012)

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<th>Depth</th>
<th>Bulk density</th>
<th>Soil texture</th>
<th>Volumetric water content</th>
<th>Organic C</th>
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<td>mg m$^{-3}$</td>
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### Codorus loam (South Farm, 2013)

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<th>Volumetric water content</th>
<th>Organic C</th>
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<td>1.35</td>
<td>84</td>
<td>6</td>
<td>10</td>
</tr>
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</table>
and all treatments except for the starter only/NT treatment received the same primary PPL application. Weed control was either mechanical or with glyphosate \([N-(phosphonomethyl)glycine]\) applied at the recommended rate. Irrigation was applied as necessary to avoid significant water stress in the maize crop.

**Litter Bag Methods**

Cover crop decomposition in each treatment was monitored over time using nylon mesh litter bags (0.30 by 0.30 m dimensions, 1 mm mesh size). The mass per unit area of fresh cover crop in each bag was adjusted to the approximate targeted total dry biomass levels, based on average field cover crop biomass, of 8.0 Mg ha\(^{-1}\) in 2012 and 9.0 Mg ha\(^{-1}\) in 2013. The targeted hairy vetch/cereal rye dry biomass percentages for the litter bags (0:100, 25:75, 50:50, 75:25, and 100:0) were slightly different from the percentages that were sown in the treatment plots. The actual litter bag dry biomass percentages, C/N ratios of the 100% hairy vetch and 100% cereal rye applications, total oven-dry biomass of the cover crop residues applied to the field plots (kg dry mass ha\(^{-1}\)) and the % C of the total biomass applications are shown in Supplemental Table S1. Although the actual litter bag percentages differed slightly from the target percentages, hereafter we will refer to the cover crop litter bag treatments percentages by the target values above (hairy vetch/cereal rye dry biomass percentages of 0:100, 25:75, 50:50, 75:25, and 100:0).

Litter bags for the incorporated plots were prepared by placing fresh material cut to 10-cm lengths that had been weighed to obtain the appropriate biomass percentage and total mass, mixed, and placed in the bag. The litter bags were placed at a soil depth of approximately 20 cm immediately after cover crop mowing and disking. This depth was chosen because it was within the depth of cover crop incorporation by disking. Eighteen litter bags were prepared for each cover crop mixture (six bags per replication) per tillage treatment and placed in the treatment plots to allow periodic removal of litter bags for analyses so that cover crop decomposition could be tracked over time. Litter bags for the NT plots were prepared in the same way prior to rolling (i.e., cover crop termination), only the material was cut to 25 cm to lay flat in the bag. Residue was removed from randomly selected locations within plots of the three NT treatments. The litter bags were pinned against the soil surface in these bare areas.

A litter bag was collected from each of three replicate sets of bags per treatment plot at each of six sampling times, approximately corresponding to cover crop termination and maize emergence, three-leaf stage (V3), eight-leaf stage (V8), silking, and blacklayer formation. Dry weight of the cover crop in each litter bag was determined and analyzed for ash content, and C, and N content. The N remaining in the cover crop was calculated as the mean N content of the litter bags for each treatment scaled up to kg N ha\(^{-1}\). These scaled-up measures of remaining cover crop N were then compared with model simulations of remaining cover crop N at each of the six sampling times for a given tillage \(\times\) manure N \(\times\) cover crop mixture treatment. The impact of the litter bags themselves on decomposition was not evaluated. However, this methodology is widely used, particularly for comparative studies like this field study, and the mesh size used in the study (1 mm) allowed access to a wide range of soil organisms involved in litter decomposition (Bokhorst and Wardle, 2013).

Soil temperature and moisture sensors logged hourly temperature (°C) and volumetric water contents (VWC) readings in a representative subset of NT (sensor placement: 5-cm depth) and incorporated (sensor placement: 20-cm depth) plots from maize planting through harvest. These depths for sensor placement were chosen to track the temperatures and VWC in the zones where litter bag decomposition was taking place (NT and incorporated). The soil temperatures were used to calculate degree days of cumulative thermal time from cover crop termination using average daily temperature and a base temperature of 0°C. No measured data on soil N (NO\(_3^–\)N, NH\(_4^+\)N) were available so we were unable to compare simulated and measured changes in crop-available soil N over the course of cover crop mineralization.

**Soil Process (LEACHN) Component of the PNM Model**

Soil water flux in the PNM model is simulated using the “tipping bucket” option in the LEACHN model (Hutson, 2010; Jones and Kiniry, 1986). Nitrogen (NO\(_3^–\)N, NH\(_4^+\)N, urea-N) fluxes associated with the movement of water through the soil profile are simulated using a “capacity” model (Addiscott and Wagenet, 1985). The LEACHN model also simulates C mineralization, and N mineralization/immobilization, nitrification, denitrification, ammonia volatilization and urea hydrolysis. The major C and N transformation processes in the soil are modeled using first order rate equations (nitrification, urea hydrolysis, ammonia volatilization, and animal manure, SOM, and plant residue mineralization) or a combination of first order and second order rate equations (denitrification). The rate constants (d\(^{-1}\)) in the first order rate equations were calibrated based on multi-year replicated field experiments representing a range of N management practices for maize production (Sogbedji et al., 2001a, 2001b; Sogbedji et al., 2006). All soil processes are modeled by soil layer (50 mm thickness) over the root zone and model simulations were done on a daily time step.

The LEACHN model also simulates NH\(_4^+\)-N, NO\(_3^–\)-N, and urea-N pools by soil layer. Nitrogen from mineral fertilizers or the inorganic N component of animal manures is added directly to one or more of these pools, depending on the form of the addition. The organic C and N of animal manure and plant residue additions in the model are assigned to separate pools (“manure-C”, “manure-N”, “Residue-C”, and “Residue-N”). In this study, the LEACHN model was modified to simulate cover crop additions in a similar fashion. Hairy vetch and cereal rye cover crop organic C and N additions were assigned to separate pools (“grass-C”, “grass-N”, “legume-C”, “legume-N”) because of the different rates of litter bag N remaining reported for these two crops as monocultures, with litter bag N remaining from the vetch/rye mixtures varying between the values for the 100% hairy vetch and 100% cereal rye litter bags (Poffenbarger et al., 2015b). Ammonium N released as a result of mineralization of the “legume” (vetch) and “grass” (rye) C pools goes into the NH\(_4^+\)-N pool. This is described in more detail below.
The first step in processing organic C and N of manure, plant residue, and cover crop additions in the model is mineralization of organic C by soil layer using calibrated rate constants or rate constants obtained from the literature (Supplemental Fig. S6) where, prior to C and N processing, all rate constants, including the mineralization rate constants (and with the exception of the ammonia volatilization rate constant), are modified based on soil temperature and moisture response functions (Johnsson et al., 1987; see below). The modified rate constants are then used in a series of equations that mineralize C and release (or immobilize) N. First, a maximum potential rate of C mineralization is calculated:

\[ C_{\text{max}} = \max \left( 0, C_{\text{conc}} \times [1 - \exp(kt)] \times BD \right) \tag{1} \]

where \( C_{\text{max}} \) is the maximum organic C mineralized (mg C dm\(^{-3}\) soil d\(^{-1}\)) over the time step (daily), \( C_{\text{conc}} \) is the mg C kg\(^{-1}\) soil for the cover crop component by soil layer for the time step, \( k \) is the first order rate constant (d\(^{-1}\)) modified by the soil temperature and moisture response functions, and BD (soil bulk density) converts mg C kg\(^{-1}\) soil to mg C dm\(^{-3}\) soil. If the C/N ratio of the cover crop component is ≤20, the “allowable” or actual organic C mineralized for that soil layer and time step is equal to the maximum C mineralized. If the C/N ratio of the cover crop component is >20, the actual mineralized cover crop C is calculated as follows:

\[ C_{\text{allowable}} = \frac{C/N_{\text{mb}} \times C/N_{\text{residue}} \times \text{Soil N} / (f_e \times C/N_{\text{residue}})}{1 + f_e} \tag{2} \]

where \( C_{\text{allowable}} \) (mg C dm\(^{-3}\) soil) for each soil layer is the organic C mineralized from the cover crop component when the C/N ratio of that component is >20, \( C/N_{\text{mb}} \) is the C/N ratio of the microbial biomass pool (=10 in the PNM simulations reported here), \( C/N_{\text{residue}} \) is the C/N ratio of the cover crop residue component that is updated daily based on the extent of C mineralization and release or immobilization of N, Soil N (mg N dm\(^{-3}\) soil) is the NH\(_4\)-N and NO\(_3\)-N available to the microbial biomass for C mineralization in the soil layer at that time step, and \( f_e \) is the fraction of mineralized cover crop C that goes to the SOM and microbial biomass C pools (=0.5 in the PNM simulations reported here). Early C and N loss from surface residues is by leaching of soluble N and C compounds into the surface soil layers (Cotrufo et al., 2015), and mineralization is assumed to most active at the residue—soil boundary (Findeling et al., 2007). It was assumed, therefore, that, for the NT treatments, NH\(_4\)-N and NO\(_3\)-N in the 0 to 5 cm soil layer were available to the decomposer (microbial) population for C and N mineralization of the surface residues.

The actual C mineralized from the cover crop (\( C_{\text{mineralized}} \)) is equal to the minimum of \( C_{\text{allowable}} \) and \( C_{\text{max}} \):

\[ C_{\text{mineralized}} = \min (C_{\text{allowable}}, C_{\text{max}}) \tag{3} \]

At each time step (daily) of the simulations, the mineralized C is then partitioned into three pools: the microbial respiration (CO\(_2\)) pool, microbial biomass pool, and SOM C pool (Supplemental Eq. [S1]–[S3]). The \( f_e \) term partitions cover crop C between the CO\(_2\) pool, and the microbial biomass and SOM pools. Partitioning of cover crop C between the SOM and microbial biomass pools (after partitioning to the CO\(_2\) pool) is determined by a humification factor (= 0.2 in the PNM simulations reported here). In the simulations here, 40% of the mineralized C went to the microbial biomass C pool, 50% went to CO\(_2\), and 10% went to the SOM C pool. Nitrogen that is released by C mineralization goes to a microbial biomass N pool, soil organic-N pool, and the NH\(_4\)-N pool. The addition to the NH\(_4\)-N pool is positive if there is nit mineralization, or negative if there is immobilization. This depends on the extent of C mineralization, the C/N ratio of the plant residue, manure or cover crop addition, and the assumed C/N ratios of the microbial biomass and SOM pools (= 10 in the simulations reported here). Carbon mineralized from the SOM pool goes to CO\(_2\), and the N released by SOM C mineralization goes to the NH\(_4\)-N pool. The flux of cover crop N to the microbial biomass and SOM N pools that accompanies the C partitioning is calculated as:

\[ \text{Cover N} \rightarrow \text{Microbial biomass N pool} \tag{4} \]

\[ N_{\text{mb}} = C_{\text{residue} \rightarrow \text{mb}} / C/N_{\text{mb}} \tag{5} \]

\[ \text{Cover N} \rightarrow \text{SOM N pool} \tag{6} \]

\[ N_{\text{SOM}} = C_{\text{residue} \rightarrow \text{SOM}} / C/N_{\text{SOM}} \tag{7} \]

where \( N_{\text{mb}} \) and \( N_{\text{SOM}} \) are the cover crop N partitioned to the microbial biomass and SOM N pools, respectively, \( C/N_{\text{mb}} \) and \( C/N_{\text{SOM}} \) are the C/N ratios of the microbial biomass pool and SOM pools, respectively, and \( C_{\text{residue} \rightarrow \text{mb}} \) and \( C_{\text{residue} \rightarrow \text{SOM}} \) are the cover crop C (mg C dm\(^{-3}\)) partitioned to the microbial biomass and SOM C pools, respectively.

Net release or immobilization of NH\(_4\)-N from the cover crop accompanying C mineralization is calculated as:

\[ \text{NH}_4\text{-N} = C_{\text{mineralized}}/C/N_{\text{cover}} - N_{\text{mb}} - N_{\text{SOM}} \tag{8} \]

If NH\(_4\)-N is positive, it is added to the NH\(_4\)-N pool for that soil layer and time step. If NH\(_4\)-N is negative, there is temporary immobilization of that NH\(_4\)-N (Supplemental Fig. S7 illustrates the pools and N flows for this process). In the LEACHN model, the manure and residue pools and the microbial biomass pool are treated as a single residue/manure—microbial biomass complex (Johnsson et al., 1987), analogous to other, similar soil process models (Shafer et al., 2001). Therefore, for both the hairy vetch (legume) and cereal rye (grass) residues pools, any immobilized NH\(_4\)-N from mineralization of those pools is considered part of the legume or grass cover crop residue N pool and was added back to that pool at the end of each time step.

**Soil Temperature and Moisture Adjustments**

Prior to application in Eq. [1], the inputted rate constants were multiplied by soil temperature (“\( t_{corr} \)” and soil moisture (“\( w_{corr} \)” response functions. These response functions regulate the soil C and N transformations in the LEACHN model.
(Johnsson et al., 1987; Hutson, 2010). For a given soil layer, the VWC range where wcorr is at an optimum (wcorr = 1) is from just below saturation for that layer to the VWC at ~300 kPa. At VWCs above or below these limits, wcorr declines to 0.5 (Supplemental Fig. S1). The parameters governing wcorr response above and below the optimum VWC range are set by the user. The temperature response function, tcorr, is a $Q_{10}$-type function (Shaffer et al., 2001) (Supplemental Fig. S2) and is equal to 1 at the base temperature set by the user (20°C in all simulations presented here). For both response functions, we used the same parameters in the calculations that have been used for similar soils in previous studies with the LEACHN/PNM model (Sogbedji et al., 2006; Marjerison et al., 2016).

The soil temperatures and VWCs at the 20-cm soil depth were used to calculate tcorr and wcorr for the incorporated treatment simulations. For the NT treatments, no measurements of surface residue temperature or moisture content were made, and the LEACHN model does not currently model these variables for a surface residue. Therefore, for the NT treatments, tcorr and wcorr were calculated using the soil temperature and VWC of the surface (0–5 cm) soil layer.

**Cover Crop Mineralization Rate Constants—Calibration and Testing**

Model calibration was done using data on litter bag N remaining from the 2012 field season ("calibration" year) and testing of the calibrated model was done using data on litter bag N remaining from the 2013 field season ("model testing" year). Separate rate constants were assigned to cereal rye ("grass") and hairy vetch ("legume") based on a number of studies reporting significantly different decomposition dynamics for legume and grass cover crops (Schomberg et al., 1994; Schomberg and Cabrera, 2001; Quemada and Cabrera, 1995; Poffenbarger et al., 2015b). For each cover crop type (grass, legume), separate rate constants were then assigned based on tillage (NT, incorporated) and cumulative degree-days from termination (Table 3).

Separation by tillage was done because it was assumed that there were differences in potential mineralization, possibly due to factors (Holland and Coleman (1987) not accounted for by the tcorr and wcorr functions or soil N availability to the microbial biomass, that contribute to the well-documented differences in residue decomposition between surface and incorporated residues (Wilson and Hargrove, 1986; Schomberg et al., 1994; Jahanzad et al., 2016). The rate constants were further divided into an initial, higher rate constant and a lower rate constant after 275 degree days of cumulative thermal time, where thermal time was calculated as described earlier (section "Litter Bag Methods"). The reduction to a lower rate constant after 275 degree days represents the shift from readily decomposable to more recalcitrant components of the terminated cover crops. We used cumulative thermal time as a driver for this shift because the calibration and model testing data sets in this study had no data on the relative proportions of readily decomposable and more recalcitrant components of the terminated hairy vetch and cereal rye (Poffenbarger et al., 2015b). The degree days of cumulative thermal time for the transition to lower rate constants (275 degree days) is within the range reported by Ji (2013), Poffenbarger et al. (2015b), and Honeycut et al. (1988) for the shift from higher to lower rates of mass loss (Ji, 2013; Poffenbarger et al., 2015b) and C mineralization (Honeycut et al., 1988) of organic residues including terminated legume and grass cover crops. If cover residue tissue or chemical composition measurements become routine in crop management, the LEACHN model could be easily modified to replace the dependence on degree days with separate pools for the different components. The assumptions for the rate constant assignments by cover crop type, tillage practice, and thermal time are reviewed in the Discussion.

Pre-calibration rate constants (Mulvaney et al., 2010) were assigned to each crop by tillage treatment and degree-day period (Table 3). These rate constants were calculated for soybean and oat (Avena sativa L.) residues, and were not, therefore, directly equivalent to the hairy vetch and cereal rye data used in the calibration. However, modeling of mineralization was similar enough to the approach taken in the LEACHN model that we used these as starting values in our calibration. The pre-calibration rate constants (Table 3) were calibrated as follows. For each cover crop addition the calculated C (kg ha$^{-1}$) in the hairy vetch and cereal rye additions for each cover crop mixture (Supplemental Table S1a) was mineralized as separate pools, and N in those additions was either released or immobilized, as described above. The simulated N content of the cover crop residue was updated daily based on the N release/immobilization. Calibration of the rate constants was done by adjusting them incrementally to minimize two measures of model goodness of fit, root mean square error (RMSE; Willmott and Matsura, 2005) and mean absolute error (MAE; Willmott and Johnsston, 1967).

Table 3. (a) Pre-calibration (starting) values (Mulvaney et al., 2010) and (b) post-calibration values of the rate constants (d$^{-1}$) for the first order rate equations estimating hairy vetch and cereal rye C mineralization in the PNM model. Separate calibrations were done by crop, and for the no-till (“NT”) treatments and the incorporated (“Incor”) treatment. Note that two rate constants are given for each crop/tillage treatment: an initial value for 0 to 275 degree days (0°C base temperature) and a second (lower) value for >275 degree days. See text for explanation.

<table>
<thead>
<tr>
<th>Vetch</th>
<th>Rye</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>a. Pre-calibration first order rate constants, d$^{-1}$</strong></td>
<td></td>
</tr>
<tr>
<td>Tillage</td>
<td>0–275 Degree days</td>
</tr>
<tr>
<td>NT</td>
<td>0.0298</td>
</tr>
<tr>
<td>Incor</td>
<td>0.1178</td>
</tr>
<tr>
<td><strong>b. Post-calibration first order rate constants, d$^{-1}$</strong></td>
<td></td>
</tr>
<tr>
<td>Tillage</td>
<td>0–275 Degree days</td>
</tr>
<tr>
<td>NT</td>
<td>0.115</td>
</tr>
<tr>
<td>Incor</td>
<td>0.235</td>
</tr>
</tbody>
</table>
These statistics were calculated using cumulative measured vs. simulated mass of cover crop N remaining over cumulative thermal time at the six sampling times for each of the five cover crop additions for the two NT tillage treatments and the incorporated tillage treatment (Supplemental Table S2 and Supplemental Fig. S3). This method, adjusting the parameter for calibration to minimize statistical measures of model goodness of fit, has been applied in similar studies (Honeycutt et al., 1988; Sogbedji et al. (2001a, 2001b); Sogbedji et al., 2006; Zubillaga et al., 2007; Marjerison et al., 2016). The model with the calibrated cover crop rate constants was then tested using input data from the model testing year (Tables 1 and 2; Supplemental Table S1b).

Additional Model Inputs

The LEACHN model assumes a layered soil profile. In this study, soil layer inputs included measured textural and bulk density data for the soil series at both sites (calibration year: Hatboro series/North Farm; model testing year: Codorus series/South Farm) and water retention parameters calculated using a pedotransfer (PTF) function (Rawls and Brakensiek, 1985) (Table 1). The simulated root zone depth was 1 m for both years. Maximum crop available water in the LEACHN model was modeled as 95% of the water held between field capacity (inputted by the user) and −1500 kPa by layer, summed over the user-input root zone depth. Soil temperature was simulated with a heat transfer routine (Hutson, 2010) using daily average air temperature and the current VWC to calculate heat flow between soil layers. Weather inputs to the PNM model included daily solar radiation, total precipitation (including irrigation applications), and maximum and minimum air temperature. All simulations were done with temperature and precipitation data obtained from weather stations located at each field site. Solar radiation data were obtained from a nearby airport. Maize planting dates, cultivar information, plant population, tillage (incorporated treatment), and PPL additions data for both years of the study were included in the model input files (Poffenbarger et al., 2015b). Cover crop total biomass, C/N ratios and % C of the biomass used in the model input files for the calibration and testing years are shown in Supplemental Table S1a and 1b.

Statistical Analyses

We used three well-established statistics for model accuracy: MAE and RMSE to evaluate goodness of fit between the simulated and measured cover crop N remaining, and IA, a measure of the efficiency of the simulation (Willmott, 1981). Although MAE and RMSE are similar measures for model accuracy, we include MAE for comparison because the RMSE calculation can be dominated by a relatively small number of cases with particularly high variances, making interpretation of the statistic more difficult (Willmott and Matsura, 2005). Both RMSE and MAE are in the same units as the measured parameter and, for both statistics, a value of 0 indicates a perfect fit. For the IA statistic, a value of 1 indicates a perfect fit. Model calibration and testing were also evaluated using simple linear regression of predicted vs. measured cover crop N remaining in addition to the statistics above, using the “confint” function of the base statistics package in R. This function was used to conduct least squares regression analysis on the simulated vs. measured cover crop N remaining across all treatments in the calibration and testing years (R Core Team, 2014). To obtain p values, the linear hypothesis that the slope of the model = 1 and intercept of the model = 0 were independently and jointly tested using the “linearHypothesis” function in the car package of R (R Core Team, 2014). A residuals plot was also used to determine whether there were trends in the residuals (Wallach, 2006).

RESULTS

Model Calibration

The measured and simulated cover crop N remaining in the calibration year using the calibrated rate constants (Table 3) are shown in Supplemental Fig. S3. Regression statistics and model fit statistics are shown in Fig. 1a and Supplemental Table S2, respectively. There was a slight but statistically significant bias of the calibrated model for simulation of cover crop N remaining. This bias was the result of overprediction of cover crop N remaining at lower measured N remaining (treatments where the proportion of rye in the cover crop mixture increased above approximately 50%). In these treatments, the model calculated increased immobilization of soil NH4–N and NO3–N by the microbial biomass in the mineralization of C from...
the high C/N ratio rye. This immobilized N is added to the simulated cover crop N remaining at the end of each time step (day) (Methods) but may not have been included in the measured residue N as a result of the sample preparation process (Poffenbarger et al., 2015b).

Simulated and measured soil temperature and VWC for the calibration year are shown in Fig. 2a and 2b (5-cm soil depth—NT treatments) and Fig. 2d and 2e (20-cm soil depth—incorporated treatment). Soil temperature at 5-cm soil depth was slightly overestimated by the model compared to measured values, particularly later in the season (Fig. 2a). Soil temperatures at 20-cm soil depth (incorporated treatment) were underestimated early and slightly but consistently overestimated compared to measured values later in the season (Fig. 2d).

Soil VWCs at 5 cm were generally overestimated by the model, particularly following precipitation events, and later in the calibration year (Fig. 2b). The field capacity VWC for the soil series in the calibration year (Hatboro), estimated by the PTF, is 0.33 for the 0 to 5 cm soil layer. The model simulated drainage to field capacity VWC within 1 to 2 d following precipitation events > ~ 5 mm. (All measured VWCs were below the estimated field capacity VWC, even after precipitation events > ~25 mm d⁻¹.) Evapotranspiration (ET) drives changes in VWC below field capacity during periods with no precipitation. We compared the measured and simulated rate of change in VWC during these periods as a check on simulation of ET. On average, the model estimated a more rapid decrease in VWC at 5-cm soil depth compared to the measured data (~0.016 d⁻¹ vs. -0.011 d⁻¹) during these periods, with crop transpiration (Ts) contributing ~70% to the decrease in VWC and soil evaporation contributing ~30%. Soil VWCs at 20 cm (incorporated treatment) in the calibration year were reasonably well represented by the model (Fig. 2e) although, as with the simulated vs. measured VWC at 5 cm, the model tended to overestimate VWC at 20 cm, particularly later in the season. Changes in simulated VWC in this soil layer (20 cm) at VWC below the estimated field capacity are driven by Ts alone (soil evaporation is restricted to the top 10 cm in the LEACHN model). The simulated and measured rates of change in VWC during a dry period later in the growth season were similar.
(−0.012 d⁻¹ vs. −0.010 d⁻¹) but not earlier in the growing season (starting at approximately 650 degree days) when the model simulated a slower decrease in VWC (lower simulated Ts) compared to measured VWC (Fig. 2e).

The product of the tcorr and wcorr response functions in the calibration year, calculated using simulated and measured VWC and temperature, are shown in Fig. 2c (NT) and 2f (incorporated). There is a close correspondence between measured and simulated values early in the season, when 60 to 90% of the N loss from the litter bags occurs. However, after approximately 1000 degree days, tcorr×wcorr calculated from the simulated VWC and temperature increases by 50 to 150% above tcorr×wcorr calculated from measured VWC and temperature in all treatments (Fig. 2c, 2f). This increase is largely because of higher simulated VWC at that time. The differences between simulated and measured VWC after approximately 1000 degree-days is greater for the NT treatments (Fig. 2c) compared to the incorporated treatment (Fig. 2e). This may be related to the impact of the surface residue on soil evaporation from the 0- to 5-cm layer that is not accounted for in the model (see Discussion).

Model Testing

The measured and simulated cover crop N remaining in the model testing year for the NT treatments and the incorporated treatment are shown in Fig. 3. For the hairy vetch and vetch/rye mixtures in the NT treatments, the initial decrease in litter bag N remaining was well simulated by the calibrated model. The model overestimated the litter bag N remaining in most of the remaining sampling times, with increasing overestimation as the rate percentage in the mixture increased (Fig. 3a–3d, 3f–3i). For the hairy vetch and vetch/rye mixtures in the incorporated treatment, the calibrated model consistently underestimated the litter bag N remaining (overestimated cover crop N release) for the cover crop treatments with higher proportions of vetch (Fig. 3k–3m), particularly for the first two sampling periods of those treatments. For the 100% rye cover crop, the calibrated model simulated almost no change in litter bag N remaining in the NT treatments and incorporated treatment, similar to the measured data (Fig. 3e, 3j, 3o).

Regression statistics and model fit statistics are shown in Fig. 4 and Table 4, respectively. There was a statistically significant bias of the calibrated model for simulation of cover crop N remaining (slope = 0.74; intercept = 25 kg N ha⁻¹). This bias was partly the result of overprediction of cover crop N remaining at lower measured N remaining (cereal rye ≥ 50%) in the NT treatments as described in the Model Calibration section. Underprediction of N remaining in the incorporated treatments with higher vetch proportions (Fig. 3) also contributed to the bias in the regression model in the testing year.

Simulated and measured soil temperature and VWC in the model testing year are shown in Fig. 5a and 5b (5-cm soil depth–NT) and Fig. 5d and 5e (20-cm soil depth–incorporated). Soil temperature at 5-cm soil depth was slightly overestimated by the model in both tillage treatments, particularly later in the season (Fig. 5a). Soil temperatures at 20-cm soil depth (incorporated treatment) were well simulated early in the season and slightly but consistently overestimated compared to measured values later in the season (Fig. 5d).

Soil VWCs at 5-cm soil depth (NT treatments) in the model testing year were generally underestimated by the model (Fig. 5b). The increases in VWC following precipitation events were relatively well simulated (early season) or slightly over simulated (late season). However, the rate and magnitude of the decrease in VWC between major precipitation events, and at VWC below field capacity, were greater in the simulated (rate ~ −0.017 VWC d⁻¹, maximum decrease = 0.14 VWC) vs. measured (rate ~ −0.007 VWC d⁻¹, maximum decrease = 0.21 VWC) data. Transpiration accounted for approximately 65% of the decreases at VWC below field capacity. Simulated and measured VWCs at 20 cm (incorporated treatment) in the model testing year matched reasonably well up to approximately 800 degree days. During this period, the simulated vs. measured rate of change in VWC during a period of low precipitation were very similar (~0.009 vs. −0.008 d⁻¹).

However, later in the season, the rate and magnitude of the decrease in VWC between major precipitation events was greater in the simulated (rate ~ −0.015 VWC d⁻¹, maximum decrease = 0.14 VWC) vs. measured (rate ~ −0.003 VWC d⁻¹, maximum decrease = 0.19 VWC) data.

The tcorr×wcorr values in the model testing year are shown in Fig. 5c (NT) and 5f (incorporated). There is relatively close correspondence between tcorr×wcorr values calculated from the measured and simulated data until approximately 800 degree days, except for a period between 140 and 200 degree days in the NT treatments when the simulated tcorr×wcorr values exceeded the measured values with a maximum difference of 1.7 (simulated) vs. 1.2 (measured). Most of the litter bag N loss occurred in this period (0–800 degree days) (75–95% in the NT treatments; 75–90% in the incorporated treatment). After approximately 800 degree days, simulated tcorr×wcorr was generally over estimated compared to measured tcorr×wcorr in the NT treatments, while, in the incorporated treatment, the simulated tcorr×wcorr were 0.5 and 1.0 compared to measured tcorr×wcorr of 1.0 to 1.5 except for two periods around large precipitation events (~950 and ~1700 degree days) (Fig. 5f).

DISCUSSION

Model Performance

Initial testing of the modified PNM model demonstrated reasonably good model performance under the climate conditions, soils and management practices in the field study. The RMSE in the model testing year was similar to RMSE reported for cereal rye and crimson clover mineralization simulated by the CERES-N model after calibration (25 kg N ha⁻¹) (Schomberg and Cabrera, 2001). The slope (0.74) and intercept (25 kg N ha⁻¹) of the linear regression fit (Fig. 4a) were also within the range reported for the calibrated CERES-N model (slopes: 0.64–1.13; intercepts: −9–64 kg N ha⁻¹) (Schomberg and Cabrera, 2001).

More generally, the statistical measures of goodness of fit in the model testing year reported here compare favorably with other similar studies of modeling efficiency (Sogbedji et al., 2006; Jemison et al., 1994; Marchetti et al., 2004).

The calibrated rate constants were generally consistent with the expected impacts of cover crop type (legume, grass), thermal time (representing the shift in mineralization kinetics
Table 4. Statistical measures of goodness of fit (RMSE, MAE) and calibrated model performance indicator (IA) during model testing for predicting the N remaining in the litter bag treatments. NT: no-till treatment.

<table>
<thead>
<tr>
<th>Name</th>
<th>Starter only/NT</th>
<th>Subsurface banded/NT</th>
<th>Incorporated</th>
<th>Combined NT and incorporated treatments</th>
<th>Perfect fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMSE</td>
<td>19</td>
<td>24</td>
<td>30</td>
<td>25</td>
<td>0.00</td>
</tr>
<tr>
<td>MAE</td>
<td>17</td>
<td>20</td>
<td>22</td>
<td>20</td>
<td>0.00</td>
</tr>
<tr>
<td>IA</td>
<td>0.94</td>
<td>0.91</td>
<td>0.66</td>
<td>0.88</td>
<td>1.00</td>
</tr>
</tbody>
</table>
related to cover crop composition), and tillage (Table 3b). Rate constants for hairy vetch were higher than for cereal rye, with values broadly consistent with those reported by Quemada and Cabrera (1997) based on an incubation study comparing crimson clover (Trifolium incarnatum L.) and cereal rye. Higher mineralization rates for legume compared to grass cover crops have been well documented and likely result from generally higher concentrations of soluble C and N in legumes compared to grasses (Schomberg et al., 1994; Quemada and Cabrera, 1997; Schomberg and Cabrera, 2001). The differences in mineralization between legumes and grasses have been noted across C/N ratios for the grass crop ranging from ≈25 to 90 (Schomberg et al., 1994; Ruffo and Bollero, 2003; Quemada et al., 1997).

The shift to lower rate constants with increasing thermal time has been reported in other studies (Ji, 2013; Honeycutt et al., 1988) and, in the PNM model, is assumed to represent the shift from readily decomposable to more recalcitrant components of the terminated cover crops during decomposition. No data on the dry weights of leaves, stems, and roots, or the chemical composition of the cover crop residues (e.g., carbohydrate, cellulose, lignin) were collected so that, in the PNM model, C/N ratio of the residue is the primary determinant of N release or immobilization from C mineralization (Eq. [6]). If data on the residue components or compounds are available, and separate pools and rate constants for those pools can be defined, model simulations of cover crop decomposition can improve compared to C/N ratio alone (Schomberg et al., 1994; Quemada et al., 1997; Hasegawa et al., 1999; Trinsoutrot et al., 2000; Cabrera et al., 2005; Mulvaney et al., 2010). This would remove the degree-day dependence for a shift of mineralization to more recalcitrant components currently in the PNM model, and potentially improve the model fit to measured data. However, the LEACHN component of the PNM model was developed at a model resolution to use generally available field data (Johnsson et al., 1987) and crop composition data are usually not available from field studies and production fields. Even if these data were available, increasing the number of C and N pools in the PNM model would increase the number of required parameters, making parameterization more difficult, and potentially limiting the scope of the model. Mineralization processes in the PNM model can be revised if crop composition data become routinely available and model testing indicates that the increased model complexity is warranted.

The incorporated treatment rate constants were higher than the NT treatments for hairy vetch (>275 degree days; Table 3b). These differences due to tillage are not as large as reported by Schomberg et al. (1994) based on a similar field study, but follow the same trend. Assignment of different rate constants by tillage treatment was based on assumptions that the inorganic N in the 0- to 5-cm soil layer was well simulated by the PNM model and was available to the microbial biomass for C mineralization of the surface residue, and that the simulated tcorr and wcorr response functions accurately describe the physical controls on the mineralization rate constants in both the NT treatments and the incorporated treatment. Since a single rate constant, regulated by simulated tcorr, wcorr, and inorganic soil N did not provide a good fit to the litter bag N remaining in the calibration year, it was assumed that factor(s) not accounted for in the model, perhaps related to decomposer composition and activity (Holland and Coleman, 1987) justified assigning separate rate constants based on tillage. These two assumptions are examined in greater detail in the section below (Control of Residue Mineralization).

**Immobilization in the PNM Model**

Immobilization of soil NH₄⁺–N and NO₃–N by the microbial biomass during mineralization of residues with higher C/N ratios and a higher percent of recalcitrant compounds (e.g., lignin) has been well documented (Schomberg et al., 1994; Cabrera et al., 2005). In this study, the C/N ratio of the cereal rye was well above the range where there is a shift from net N mineralization to immobilization, and the PNM model predicted an average N immobilization by the microbial biomass from the 100% cereal rye treatment of 20 kg N ha⁻¹ in the model calibration year (Supplemental Fig. S3e, S3j, and S3o) and 9 kg N ha⁻¹ during the model testing year (Fig. 3e, 3j and 3o). In the model, N obtained from the soil solution and immobilized by the microbial biomass pool is added back to the residue N pool at the end of each time step (day). It is possible that the differences between the simulated and measured N remaining in both years may have been related to partitioning of immobilized N to the residue N pool by the model, since it is unknown whether the measured N remaining for these treatments included the N and C in the microbial biomass. Because N immobilization by the microbial biomass impacts the soil
inorganic N pool, future testing of the model using field data from cover crop studies with measured soil N data will be important. This will also allow testing of the model assumption that the NO₃⁻N and NH₄⁺-N in the 0- to 5-cm soil layer is a source of N for the microbial biomass responsible for mineralization of surface residues (NT treatments).

**Control of Residue Mineralization**

A strength of the PNM model is that it represents key soil-crop processes with a focus on input, calibration, and testing data that are generally available from agricultural field research. This required making simplifying assumptions where these could be justified. In the simulations presented here, we assumed that separate rate constants for the NT treatments and the incorporated treatment were necessary because the differences between these two tillage treatments could not be accounted for by access of the microbial biomass to inorganic soil N, and by the tcorr and wcorr response functions calculated from soil temperature and VWC. Accurate simulation of tcorr and wcorr are particularly important because of their impact on microbial activity and, therefore, C mineralization, and N immobilization or release to the soil (Coppens et al., 2007; Quemada and Cabrera, 1997).

**Inorganic Nitrogen**

It was assumed that the microbial biomass had access to inorganic N in the soil (0–5 cm and 15–20 cm, respectively, for the NT treatments and the incorporated treatment), and that the entire residue mass was subject to mineralization in both tillage treatments. This assumption was likely justified for the incorporated treatment (Coppens et al., 2007). However, for the NT treatments, it is likely that active C mineralization only occurred in the portion of the residue in contact with the soil where the microbial biomass had access to the inorganic soil N (Findeling et al., 2007). It is possible, therefore, that a single rate constant for both tillage treatments could have been assigned, regulated by the physical environment at the two depths, and where mineralization for the NT treatments would be restricted to some fraction of the surface residue mass. We have an ongoing, long-term field experiment measuring surface residue temperature, moisture, and mineralization dynamics of a range of cover crops that will be used to test whether one rate constant, properly adjusted, can be used for both surface terminated and incorporated cover crops.

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![Figure 5. Model test year (2013, South Farm). (a) No-till measured vs. simulated soil temperature (°C), (b) volumetric water content, and (c) wcorr×tcorr (soil temperature/moisture correction factor) at 5 cm over cumulative thermal time. (d) Incorporated measured vs. simulated soil temperature (°C), (e) volumetric water content, and (f) wcorr×tcorr at 20 cm over cumulative thermal time. Error bars represent standard error of measured soil temperature and volumetric water content.](image-url)
Temperature (tcorr) and Moisture (wcorr) Response Functions

The driving variables for the tcorr and wcorr functions are simulated soil temperature and VWC. In the simulations presented here, we assumed that the simulated soil temperature and VWC at 0 to 5 cm and 15 to 20 cm, respectively, could be used as proxies for the surface and incorporated residue temperatures and VWCs. We then assumed that simulated soil temperature and VWC at 0- to 5-cm and at 15- to 20-cm soil depths, respectively, were reasonable estimates of measured values for the NT treatments and the incorporated treatment (Fig. 2a, 2b; Fig. 5a, 5b). Finally, we assumed that the impacts of the physical environment on the cover crop mineralization rate constants are well represented by the tcorr and wcorr response functions. These assumptions are discussed below.

Surface Soil Temperature and Volumetric Water Content as Proxies for Residue Values. No residue temperature and moisture data for the NT treatments were available so simulated soil temperature and VWC at 0 to 5 cm were used as proxies for these data. There are few reports examining the relationship between soil temperature and moisture, and surface residue decomposition (Quemada and Cabrera, 1997; Coppens et al., 2007; Findeling et al., 2007). Quemada and Cabrera (1997) showed different responses to moisture, temperature, and their interaction for C mineralization from surface soil SOM and crop residues on the soil surface in controlled environment experiments. This suggests that either different forms of the tcorr and wcorr response functions should be applied to surface residues than those used for incorporated residues in the PNM model, or that the current forms should be parameterized differently for surface vs. incorporated residues. Findeling et al. (2007) showed very large fluctuations in soil moisture response function and their interaction for C mineralization from surface soil SOM and crop residues on the soil surface in controlled environment experiments. This suggests that either different forms of the tcorr and wcorr response functions should be applied to surface residues than those used for incorporated residues in the PNM model, or that the current forms should be parameterized differently for surface vs. incorporated residues. Findeling et al. (2007) showed very large fluctuations in soil moisture response function and their interaction for C mineralization from surface soil SOM and crop residues on the soil surface in controlled environment experiments.

Simulated vs. Measured Soil Temperature and Volumetric Water Content. Soil temperatures at both depths were simulated reasonably well in both the calibration and model testing years. There were periods, however, when simulated and measured temperatures at 0 to 5 cm were several degrees different (Fig. 2a, 5a). Given the Q10-type tcorr function, this had a significant impact on calculated tcorr at this depth (Supplemental Fig. S4a and S5a). Surface residues alter the energy balance at the soil surface compared to bare or tilled soil (Sauer et al., 1998) resulting in near-surface temperature and VWC that are different than soil temperature and VWC with no residue cover (Horton et al., 1994; Lemon, 1956). Currently, when crop residues are present on the soil surface (NT treatments), the PNM model uses simple empirical adjustments to the simulated near surface soil temperature and VWC based on reported residue impacts on these variables (Sinclair et al., 2007; Salado-Navarro and Sinclair, 2009; Ussiri and Lal, 2009). However, there are models that simulate heat and vapor transport through surface residue to better estimate near-surface soil temperature and VWC when a surface residue is present (Flerchinger et al., 2003; Findeling et al., 2007). These are relatively complex models, requiring inputs not generally available in field studies and so were not incorporated into the PNM model. However, the current empirical adjustments to near surface soil temperature and VWC in the model will be re-evaluated based on ongoing field experiments characterizing temperature and moisture content of surface-terminated cover crop residues and near-surface soil temperature and VWC under those residues.

Volumetric water content was less well simulated than soil temperature. Simulated VWC at both depths were more variable than measured VWC, particularly following precipitation events (Fig. 2b, 2e; Fig. 5b, 5e). Some of the differences in simulated and measured VWC for both the NT treatments and incorporated treatment may be related to the method used to calculate daily measured VWC. These data were daily averages of hourly VWC measurements while the simulated VWC were calculated on a daily time step. If the precipitation event was large, the model simulated a VWC in the top soil layer(s) that was close to or at saturation on the day of the event, while the daily average of the hourly VWC included early drainage from those top layers, so that these daily averaged VWC were damped compared to the simulated VWC for 1 to 2 d following a large precipitation event.

For the NT treatments, differences between simulated and measured VWC may have also been due to the impact of the surface residues on infiltration by changing soil wet aggregate formation and stability (Horton et al., 1994; Kladiško, 1994). Currently, there is no adjustment to infiltration in the PNM model when surface residues are present. Future PNM model testing should include such adjustments, based on measured infiltration rates through a surface crop residue, if model performance is improved by doing so (Kladiško, 1994; Flerchinger et al., 2003; Sauer et al., 1998).

Simulated Ts of the maize crop had a significant impact on changes in simulated VWCs at both depths, particularly at or below field capacity when all changes in VWC were driven solely by ET (0–5 cm) or Ts (15–20 cm). Most of the impact of Ts on VWC occurred after approximately 500 degree days in both the calibration and model testing years when Ts consistently above 1 mm d⁻¹ were simulated. Two possible sources of error related to Ts may have contributed to the lack of fit between measured and simulated VWC (Fig. 2b, 2e; 5b, 5e). First, the PNM model implicitly assumes an exponential decline in root mass (Mucho and Sinclair, 1991). Violation of this assumption is unlikely since root mass decrease with depth in crops like maize is well fitted.
using an exponential model (Dwyer et al., 1996). A second possible source of error is that daily Ts were not well simulated. In the PNM model, daily Ts is simulated based on the simulated daily biomass production (Sinclair and Muchow, 1995). The relationship between Ts and biomass production is well established for crops (Sinclair, 2011) so that, in this study, differences in VWC related to Ts may have been due to differences in simulated vs. measured daily biomass production. This does not appear to be the case, at least based on total aboveground dry biomass at harvest. Although measured dry biomass data were quite variable in both years, average simulated total aboveground biomass at harvest were similar to measured values for the two tillage treatments (NT, incorporated) in the calibration year (measured: 8.1–10.7 Mt ha⁻¹; simulated: 8.1–10.9 Mt ha⁻¹) and were only slightly underestimated by the model in the model testing year (measured: 13.2–20.6 Mt ha⁻¹; simulated: 11.7–18.3 Mt ha⁻¹). Future testing of the model for cover crop mineralization will include analysis of simulated and measured main crop growth and yield.

**Temperature (tcorr) and Volumetric Water Content (wcorr) Response Functions.** Parameterization of these functions, and the impact of varying function parameters are shown in Supplemental Fig. S1 and S2. Temperature and soil moisture response functions vary among models similar to the PNM (LEACHN) model (Shaffer et al., 2001). Several models, including the PNM model, use a $Q_{10}$ expression as the temperature response function, and, like the PNM model, have an optimum soil moisture range for the soil moisture response function that is relatively broad. In the PNM model, the default parameters governing the tcorr and wcorr response functions, and the sensitivity of these functions to incremental changes in these defaults, are shown in Supplemental Fig. S1 and S2. These defaults were used in previous calibration and testing of the PNM model (Sogbedji et al., 2001a, 2001b; Sogbedji et al., 2006; Marjeron et al., 2016) and the Adapt-N tool based on the LEACHN/ PNMs models has performed well (Sela et al., 2016) so we did not calibrate these in this initial testing. However, it is possible that these parameters could be adjusted to improve representation of residue decomposition as field data on residue temperature, moisture, and decomposition become available (Quemada and Cabrera, 1997; Coppens et al., 2007).

**SUMMARY**

Tools for determining the benefits of cover crops (e.g., N fertilizer reductions) and how they affect cropping system profitability are needed by the agricultural community. We calibrated and tested a daily time step soil and crop process model (PNM model), modified to simulate cover crop C mineralization and N release, using data on decomposition of different hairy vetch/cereal rye cover crop mixtures from a 2-y field experiment. First year data on N remaining in terminated cover crops over a maize growing season were used to calibrate hairy vetch and cereal rye rate constants for the C mineralization first order rate equation in the model. The calibrated model was tested using data from the second year of the field experiment. In the model testing year, the calibrated model simulated N remaining in hairy vetch and cereal rye residues over time reasonably well under the conditions of this study (IA = 0.88; RMSE = 25 kg N ha⁻¹; MAE = 20 kg N ha⁻¹). Potential areas of improvement include more accurate representation of the temperature and moisture response functions modifying the rate constants, and modification of the cover crop mineralization rate constant as a function of cover crop residue quality. Overall, application of the PNM model, modified to estimate changes in crop-available soil N from terminated hairy vetch/cereal rye cover crop mixtures, is warranted for maize production systems with similar climate and soils. Continued testing of the model over a broader range of soils and climate years should lead to further model improvements.

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**SUPPLEMENTAL MATERIAL**

The Supplemental Material section includes additional information regarding: (i) cover crop C partitioning in the PNM model (Hutson, 2010), including equations; (ii) total biomass, C/N ratios, and %C (biomass) of the field data used for model calibration and model testing (Table S1); (iii) model calibration RMSE, MAE, and IA statistical test results (Table S2); (iv) measured vs. simulated cover crop N remaining for the model calibration year (Fig. S3); (v) Additional information on the tcorr and wcorr functions used to modify the cover crop mineralization rate constants (Fig. S1, S2, S4, S5); (vi) schematics for the N and C mineralization pathways in the PNM model (Fig. S6 and S7).

**REFERENCES**


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