

Nitrogen Dynamics in Living Mulch and Annual Cover Crop Corn Production Systems

J. S. Andrews, Z. P. Sanders, M. L. Cabrera, U. K. Saha, and N. S. Hill*

ABSTRACT

Successful living mulch (LM) systems may be capable of meeting the N requirements of corn (*Zea mays* L.) despite competition during corn development. This study compared corn N dynamics in a perennial white clover (*Trifolium pratense* L.) LM system and annual cereal rye (*Secale cereale* L.) (CR) and crimson clover (*Trifolium incarnatum* L.) (CC) systems. Corn in the LM, CC, and CR cover crop systems received 56, 168, and 280 kg N ha⁻¹, respectively. The mean total N provided from the cover crops was 145, 105, and 25 kg ha⁻¹ in the LM, CC, and CR cover crop systems, respectively. Water uptake by the LM reduced soil water content, soil N availability, N uptake, and plant-available N (PAN) compared with the CC and CR cover crop systems. Average grain yield was 10.4, 13.3, and 13.0 Mg ha⁻¹ for the LM, CC, and CR cover crop systems, respectively. Nitrogen internal utilization efficiency was not different among systems, but fertilizer N partial nutrient balance and partial factor productivity was greatest for LM and least for CR. Overall, the LM system had lower soil N availability, grain yield, and PAN, but it supplied a significant amount of legume N to corn and minimized the need for mineral N. We concluded that success of the LM system is dependent on N mineralization of the white clover residue and that yearly weather variation significantly affects mineralization of cover crop residues and PAN.

Core Ideas

- White clover (living mulch), crimson clover, and rye cover crops were used for corn production.
- Plant-available N was determined for each cover crop system to estimate N release.
- Soil N forms and the timing of N availability varied among the cover crops.
- Internal N use was similar but partial factor productivity and partial nutrient balance was greatest in the living mulch cover crop.

MOST SOILS in the Piedmont region of Georgia are considered dispersive and subject to erosion (Langdale et al., 1992). Cover crops are one way of preventing soil erosion and providing supplemental N to a row crop (Schomberg et al., 2006) and crimson clover (*Trifolium incarnatum* L.) (CC) and cereal rye (*Secale cereale* L.) (CR) cover crops are used in the southeastern United States because of their ease of establishment, rapid growth, or ability to fix atmospheric N for subsequent row-crop use (Snapp et al., 2005; Young-Mathews, 2013). Recent attempts have been made to use a living mulch (LM) system in corn (*Zea mays* L.) to provide supplemental N and provide protection against soil erosion (Zemenchik et al., 2000; Sanders et al., 2017). Perennial living mulches are crops planted either before or with a main crop and maintained throughout the growing season, as opposed to annual cover crops that are terminated prior to planting (Hartwig and Ammon, 2002). Using white clover (*Trifolium pratense* L.) in a LM cover crop system attempts to capitalize on the perennial growth habit and N fixing capability of the clover to supply nutrients to crops without having to annually re-establish the cover crop (Echtenkamp and Moomaw, 1989; Zemenchik et al., 2000).

The modern emphasis of using perennial leguminous LM cover crops was proposed during the organic movement of the 1960s as a practice to reduce inputs and to use “natural fertilizers” (Paine and Harrison, 1993). The reasoning of the concept was to offset the polluting potential of N fertilizer as well as reduce the fossil fuel demand required for NH₃ production via the Haber–Bosch process (Smil, 1997). Vegetable growers were the primary early adopters of LM systems (Paine and Harrison 1993), but recently interest has been emerging among grain crop producers (Rasse et al., 1999; Zemenchik et al., 2000; Duda et al., 2003; Nakamoto and Tsukamoto, 2006; Kramberger et al., 2009; Sanders et al., 2017). A concern with use of LM systems is the potential of a perennial cover crop competing with the cohabitating row crop (Kurtz et al., 1952; Zemenchik et al., 2000; Affeldt et al., 2004). In the southern Piedmont, corn requires 200 to 280 kg mineral N ha⁻¹ to achieve maximum economic yield (Raun and Johnson, 1999; Lee et al., 2015).

Published in Agron. J. 110:1309–1317 (2018)

doi:10.2134/agronj2017.10.0609

Available freely online through the author-supported open access option

Copyright © 2018 by the American Society of Agronomy
5585 Guilford Road, Madison, WI 53711 USA

This is an open access article distributed under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>)

J.S. Andrews, Univ. of Georgia, College of Agricultural and Environmental Sciences, Athens, GA 30602; Z.P. Sanders, M.L. Cabrera, and N.S. Hill, Univ. of Georgia, Dep. of Crop and Soil Sciences, Athens, GA 30602; U.K. Saha, Univ. of Georgia, Feed and Environmental Water Lab., Athens, GA 30602. Received 25 Oct. 2017. Accepted 3 Apr. 2018.
*Corresponding author (nhill@uga.edu).

Abbreviations: CC, crimson clover; CR, cereal rye; DAP, days after planting; IUE, internal utilization efficiency; LM, living mulch; PAN, plant-available nitrogen; PFP, partial factor productivity; PNB, partial nutrient balance.

Nitrogen deficiency during vegetative or reproductive growth stages can be detrimental to grain yield (Uhart and Andrade, 1995; Scharf et al., 2002; Lee et al., 2015).

Sanders et al. (2017) developed a planting configuration within the white clover LM system, which promotes re-establishment of clover following a corn crop so that subsequent crops can take advantage of fixed legume N rather than depend on fertilizer N. Their study was conducted on thermic soils in the humid, southeastern United States, whereas other LM studies were conducted on temperate mesic or frigid boreal soils (Rasse et al., 1999; Tonitto et al., 2006; Nakamoto and Tsukamoto, 2006; Zemenchik et al., 2000). Mineralization conditions for organic matter at the soil surface are likely to be greater under thermic conditions found in the humid, southeastern United States, making comparisons to other LM systems difficult (Quemada and Cabrera, 1997). However, mineralization in the LM system described in Sanders et al. (2017) may be similar to other corn production systems commonly used on thermic soils in the southeastern United States, though no comparison has been made. Nitrogen availability in the white clover LM system has not been studied and is likely dependent on environmental variables affecting N mineralization and competition between the corn and intercropped clover. This leads to the hypothesis that the LM system may have reduced N availability to corn when compared with traditional production methods. Therefore, the objective of this study was to compare the soil N dynamics of a perennial LM and annual CC and CR cover crop systems and to determine the effects of the cover crop systems on N uptake, corn growth, and corn grain yield.

MATERIALS AND METHODS

Site Description

The study was performed from October 2014 through February 2017 at the J. Phil Campbell Research and Education Center in Watkinsville, GA (33°52'09.5" N 83°26'59.8" W; 219 m elevation). 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. Weather data were collected by a weather station located adjacent to the plot area (University of Georgia, 2017b). Potential evapotranspiration was calculated from the environmental variables using the FAO-56 Penman–Monteith method (Suleiman and Hoogenboom, 2007).

Field Operations

Prior to land preparation, soils were tested for pH, P, and K by the University of Georgia Soil Testing Laboratory. Lime, P, and K were applied so that pH was above 6.2 and available P and K were at least 45 and 140 ppm, respectively, as tested by the Mehlich 1 method (Beck et al., 2004). Land was prepared by disking the soil twice, which was followed by leveling and firming the ground with a cultipacker. The cultivars Wrens Abruzzi CR and Dixie CC were seeded by hand using the University of Georgia recommended rates of rates of 100 and 28 kg ha⁻¹, respectively (USDA-NRCS, 2015). The cultivar Durana white clover was planted at a rate of 13 kg ha⁻¹ in accordance with the LM system developed by Sanders et al. (2017). All plots were planted on 17 Oct. 2014. Plots were cultipacked a second time

to ensure good seed-to-soil contact. The CR plots were sprayed at the boot stage of development using a broadcast application of glyphosate (N-(phosphonomethyl)glycine) and dicamba (3,6-dichloro-2-methoxybenzoic acid) on 16 Mar. 2015, at rates of 1.12 and 1.20 kg a.i. ha⁻¹, respectively. A broadcast application of the same herbicides and rates were applied when the CC was in the bud stage, and applied in 20-cm bands centered on 90-cm rows in the LM plots on 8 Apr. 2015. The corn variety DeKalb DKC64-69 with GENVT3P was planted on 21 Apr. 2015, using a 7300 MaxEmerge (John Deere, Moline, IL) no-till planter at a population density of 90,000 plants ha⁻¹ planted on 90-cm rows. All plots received a herbicide application of pendimethalin (3,4-dimethyl-2,6-dinitro-N-pentan-3-yl-aniline) and atrazine (1-chloro-3-ethylamino-5-isopropylamino-2,4,6-triazine) at rates of 1.20 and 1.12 kg a.i. ha⁻¹, respectively, at the vegetative emergence stage of development. The herbicides were applied as broadcast applications to the CC and CR systems but were limited to a 20-cm band over the corn rows in the LM plots. Plots were 6.1 × 7.3 m, allowing for eight rows of corn per plot.

Nitrogen fertilization for the CR system was based on the University of Georgia recommendation of 280 kg N ha⁻¹ (Lee et al., 2015). The N was applied in split applications of 56 kg N ha⁻¹ at planting, and 224 kg N ha⁻¹ at the six-collared leaf (V6) stage of development. A potentially mineralizable N calculator (University of Georgia, 2017a) was used to quantify N from the CC using published values of N and cell wall contents of CC at the bud stage of development (Lloveras and Iglesias, 2001). Corn in the CC system was top-dressed with an additional 168 kg ha⁻¹ N at the V6 stage in both years. Supplemental mineral N fertilizer of 56 kg ha⁻¹ in the LM was based on response to N from previous studies (Sanders et al., 2017) to attempt to provide similar available N as the CR system. All N treatments used a dry urea (340 g N kg⁻¹ fertilizer) formulation and was applied approximately 5 cm to one side of the corn row.

Soil water content was measured using CS625 reflectometers (Campbell Scientific, Logan, UT) placed at two different soil depths between the corn rows. The rods were 30 cm in length and installed at an angle of 30 degrees from the surface. One rod was inserted at the soil surface to measure water content from 0 to 15 cm and another inserted at 15 cm to measure water content from 15 to 30 cm. All reflectometers were located within the center and between the center rows of each plot. A soil moisture release curve based on the van Genuchten (1980) equation was created using the evaporation method (Arya, 2002) with a HYPROP device (Decagon, Pullman, WA) 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. Water content data were measured and recorded on 10-min intervals, stored on data loggers, and downloaded weekly. Data were averaged over 10-d periods from planting until 100 d after planting (DAP). Overhead irrigation was applied to maintain soil water between 40 and 90% plant-available water based on soil water data from the reflectometers. Soil volumetric water content was converted to soil water pressure head based on the soil moisture release curve. Corn was harvested on 10 Aug. 2015.

The annual cover crops were reestablished in October 2015 in the same plot areas and at the same seeding rates as 2014.

Herbicide applications were made to the CR and CC plots on 23 Mar. 2016 and 4 Apr. 2016, respectively, and to the LM plots on 14 April as previously described. Corn was planted on 28 April with a population density of 90,000 plants ha⁻¹ and pendimethalin and atrazine applied at the vegetative emergence stage of development as previously described. All plots were harvested on 8 Aug. 2016.

Cover Crop Biomass and Living Mulch Nitrogen Release

Immediately before herbicide application to cover crops in 2015 and 2016, two cover crop biomass samples were obtained from each plot using a 0.1-m² quadrat per sample to estimate total cover crop biomass. Weekly changes in white clover mass in the LM plots were determined using a pre-calibrated rising plate meter (FarmWorks Precision Farming Systems, Feilding, New Zealand) as outlined by Sanders et al. (2017). Ten to 12 rising plate meter measurements were made within the center two rows in each LM plot weekly to determine clover mass. All hand-harvested cover crop samples were dried at 65°C, subjected to Kjeldahl digestion (Baker and Thompson, 1992), and N content determined using a TL-2800 Ammonia Analyzer (Timberline, Boulder, CO). Total N in the white clover was calculated on a weekly basis as the product of white clover mass and the N concentration in the clover. Potential N release was estimated by weekly changes in total N in the LM clover mass.

Soil Nitrogen

Eight soil cores were randomly sampled to a 15-cm depth 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, the cores combined, air-dried, and stored at 4°C. Five grams of soil from each sample was extracted at 21°C with 40 mL of 1M KCl for NO₃-N and NH₄-N analysis. Total N was extracted from 3 g of soil with 20 mL of 2M KCl at 100°C for 4 h. Soil extracts were analyzed for NO₃-N and NH₄-N concentration using a TL-2800 Ammonia Analyzer. Soil inorganic N concentration was calculated as the sum of the cold KCl NO₃-N and NH₄-N values (Campbell et al., 1994). Two soil pits were dug on the periphery of the plots and 5 × 5 cm brass rings were inserted into the top 15-cm of soil. The rings and soil were dried at 105°C and the soil bulk density calculated. The bulk density was used to calculate per hectare mass of NH₄-N, NO₃-N, and soil inorganic N.

Corn Growth and Yield

Corn height measurements were taken weekly from eight randomly selected plants in the center two rows of the plots. Light interception by the corn was monitored weekly in each plot using a LI 191sb Line Quantum Sensor (LI-COR, Lincoln, NE). Measurements were taken from above the plant canopy and at the soil surface (CC and CR systems) or top of the white clover canopy (LM system) immediately thereafter at two locations between the center two rows of the plots. Percent light interception was calculated as:

$$\% \text{ light interception} = \frac{1 - \text{light at soil (clover) surface}}{\text{light above corn canopy}} \times 100 \quad [1]$$

Five corn plants were harvested weekly from the second row from the outside of the plot beginning at 25 DAP by cutting the plants at the soil surface. Plants were dried at 65°C, weights recorded, and crop biomass calculated. The corn samples were ground and analyzed for total N using near infrared reflectance spectroscopy. A subset of 20 samples was analyzed for total N using Kjeldahl digestion (Baker and Thompson, 1992) and used to correct for bias of the near infrared reflectance spectroscopy data (Schomberg et al., 2006). Corn N uptake was calculated as the product of crop biomass and N content. Plant and soil samples were taken on the same day, and plant-available N (PAN) was calculated as the sum of inorganic soil N and corn N uptake (Dharmakeerthi et al., 2005). All soil, corn height, LM clover mass, and light interception data were sampled on the same day unless cloudy conditions prevented acquisition of light interception. At the end of the growing season, corn ears from the center 3.0 m of the center two rows of each plot were hand-harvested and dried at 65°C. Corn was hand-shelled, grain weighed, and weights adjusted to 15% moisture to calculate yield. Internal utilization efficiency (IUE), partial nutrient balance (PNB), and partial factor productivity (PFP) of fertilizer N by the corn plant (Fixen et al., 2015) were calculated as:

$$\text{IUE} = \frac{\text{grain yield (kg ha}^{-1}\text{)}}{\text{N uptake (kg ha}^{-1}\text{)}} \quad [2]$$

$$\text{PNB} = \frac{\text{N uptake (kg ha}^{-1}\text{)}}{\text{fertilizer N applied (kg ha}^{-1}\text{)}} \quad [3]$$

$$\text{PFP} = \frac{\text{grain yield (kg ha}^{-1}\text{)}}{\text{fertilizer N applied (kg ha}^{-1}\text{)}} \quad [4]$$

Experimental Design and Statistical Analysis

Cover crops were arranged in a randomized complete block design with three replications. The experimental area was on a 4% slope, with two blocks located on a sideslope and one block located on the footslope. Total N uptake, total corn biomass, grain yield, IUE, PNB, and PFP were analyzed using the PROC MIXED analysis of variance subroutine of SAS (SAS Institute, Cary, NC), where years were considered random effects and replication and cover crop systems considered fixed effects. There were cover crop and year effects for corn biomass, N uptake, and PNB but there were no year × cover crop interactions for these response variables. Partial factor productivity and grain yield had a year × cover crop interaction, so data were sorted by year and analyzed for cover crop effects using the PROC GLM subroutine of SAS. All means were separated using a Fisher's protected LSD at the *P* = 0.05 level of significance.

White clover mass, corn height, light interception, total inorganic N, and PAN response variables were analyzed using covariate analysis within the PROC MIXED analysis of variance subroutine where sampling date (DAP) was a repeated measure and therefore used as the covariate. Replication (block) and cover crop systems were considered fixed effects and years was considered a random effect. The covariate analysis determined that there were significant year × cover crop system interactions for each of these variables. Data were sorted by year and DAP, and

Table 1. Monthly precipitation (P), irrigation (I), potential evaporation (PET), and average temperature by month in 2015 and 2016 at the J. Phil Campbell Research and Education Center in Watkinsville, GA.

Month	2015					2016				
	P	I	P+I	PET	Avg. temp.	P	I	P+I	PET	Avg. temp.
	mm					mm				
	°C					°C				
Mar.	86	0	86	58	13.1	53	0	53	84	15.1
Apr.	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
Aug.	198	0	198	136	25.1	142	0	142	130	26.4
Total	729	173	902	708		435	380	815	818	

the PROC GLM subroutine of SAS (SAS Institute, Cary, NC) was used to determine differences among the response variables due to cover crop systems. All means were separated using a Fisher's protected LSD at the $P = 0.05$ level of significance.

Soil water pressure head values were graphed for visual observation of the data. The graphs suggested that the 0- to 15-cm soil water pressure head values were impacted by cover crop systems at 0 to 40 DAP but that soil water pressure head was similar among systems from 40 to 100 DAP. These time periods represent conditions before and after corn canopy closure. Thus, soil water pressure data were analyzed using covariate analysis within the PROC MIXED analysis of variance subroutine where mean values between 0 and 40 DAP and 40 to 100 DAP were the covariate. There was a year \times DAP interaction for soil water pressure head. Data were sorted by year and DAP and analyzed with PROC GLM to compare cover crop systems. Means were separated using a Fisher's protected LSD at the $P = 0.05$ level of significance.

RESULTS

Meteorological Conditions

Average temperature and total precipitation at the J. Phil Campbell Research and Education Center from March through August was 21.6°C and 729 mm in 2015 and 22.1°C and 435 mm in 2016 (Table 1). An additional 173 mm of irrigation water was applied in 2015 and 380 mm in 2016. Rainfall plus irrigation exceeded potential evapotranspiration in 2015 but potential evapotranspiration exceeded rainfall plus irrigation in 2016. The 30-yr average temperature and precipitation for the same time period at the location is 21.7°C and 725 mm, respectively. Thus, 2015 was considered a normal climatic year, whereas 2016 was considered an abnormal drought year.

Cover Crop Biomass, Living Mulch Clover Mass, Potential Nitrogen Release, and Soil Water Content

Average dry CC and CR biomass and N content before the broadcast herbicide application in 2015 was 3254 and 1743 kg ha⁻¹ with 34 and 12 g N kg⁻¹ dry matter, respectively. In 2016, there was 2884 and 1346 kg ha⁻¹ with 35 and 21 g N kg⁻¹ dry matter, respectively, for the CC and CR cover crop systems. Thus, total N in CC and CR cover crop systems were 110 and 21 kg ha⁻¹ N, respectively, in 2015, and 101 and 28 kg ha⁻¹ N, respectively, in 2016. Average dry clover biomass in the LM system before the banded herbicide application was 2782 kg ha⁻¹ in 2015 and 3292 kg ha⁻¹ in 2016. Also, average N content of the LM

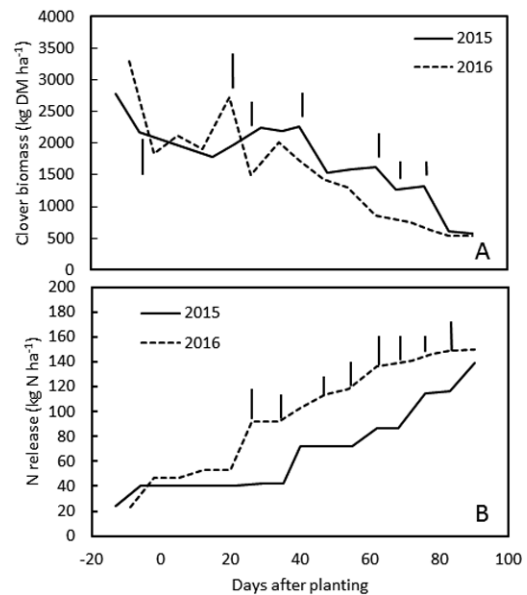


Fig. 1. Aboveground biomass (A) and cumulative potential N release (B) from white clover (*Trifolium pratense* L.) in the living mulch (LM) system during the 2015 and 2016 corn (*Zea mays* L.) growing seasons. Vertical bars represent least significant differences at the 0.05 level of probability.

white clover in 2015 and 2016 was 36 and 35 g N kg⁻¹, respectively. An estimated 30.9 and 36.6 kg N ha⁻¹ were released by the LM clover in response to the herbicide band applied prior to planting corn in 2015 and 2016, respectively. White clover in the LM system persisted for a longer period under the corn canopy in 2015 than in 2016 and the potential release of N from the clover occurred later in the season in 2015 than in 2016 (Fig. 1). However, white clover mass was at its minimum and estimated mean N release from the white clover was 139 kg ha⁻¹ at 87 DAP in 2015 and 149 kg ha⁻¹ in 2016 (Fig. 1). Thus, mean total N added to the cover crop systems from inorganic and organic sources was 195, 278, and 301 kg ha⁻¹ in 2015 and 205, 269, and 308 kg ha⁻¹ in 2016 for the LM, CC, and CR cover crop systems, respectively.

Soil water pressure head in the LM system was significantly lower than in the CC and CR systems during the growing seasons (data not shown). The soil water pressure head at the 0- to 15-cm soil depth was lower in the LM system (-0.14 MPa) than in the CC and CR systems (-0.05 MPa) from 0 to 40 DAP in 2015, and in 2016 the pressure head was -0.35 MPa in the LM but -0.09 MPa in the CC and CR systems. The water pressure head from 40 to 100 DAP was -0.19 MPa in both years of the

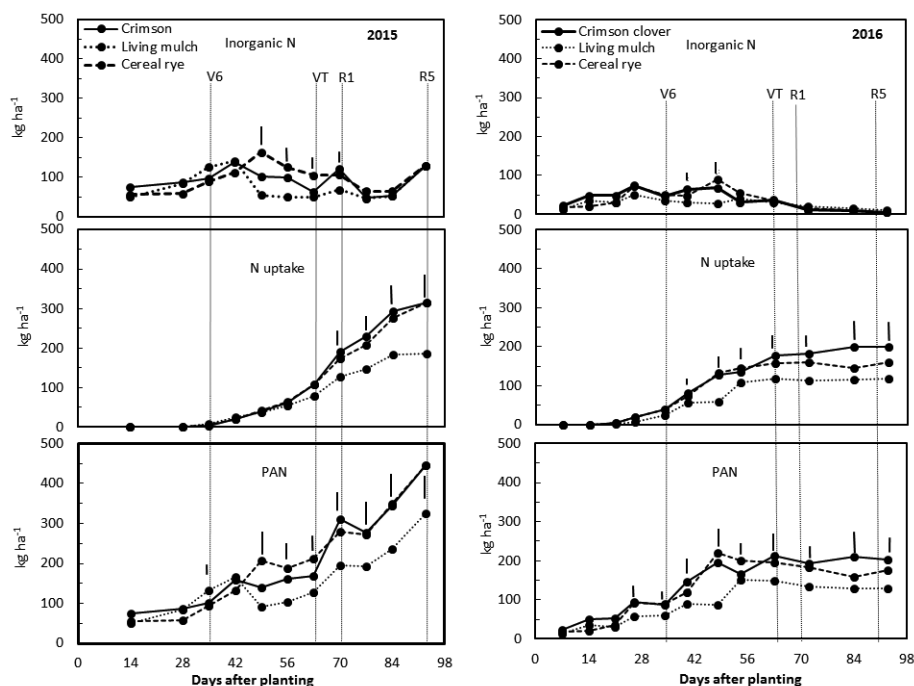


Fig. 2. Inorganic soil N at the 0- to 15-cm depth, corn (*Zea mays* L.) N uptake, and plant-available N (PAN) in the white clover (*Trifolium pratense* L.) living mulch (LM), crimson clover (*Trifolium incarnatum* L.) (CC), and cereal rye (*Secale cereale* L.) (CR) cover crop systems up to the R5 stage of corn development in 2015 and 2016. Vertical bars represent least significant differences at the 0.05 level of probability. Plant-available N is the sum of inorganic soil N and corn N uptake. Vertical lines at the V6, VT, R1, and R5 represent timing of the six collar leaf, tassel, silking, and dent stages of corn development, respectively.

Table 2. The effect of cover crop systems and year on total corn (*Zea mays* L.) N uptake, final aboveground corn plant biomass, and corn grain yield.

System	N uptake kg ha ⁻¹	Corn biomass Mg ha ⁻¹		Grain yield
CC†	225	20.7	13.3	
LM	151	16.9	10.4	
CR	183	18.0	13.0	
LSD (0.05)	48	3.2	1.0	
2015	215	21.3	13.0	
2016	158	15.8	11.5	
LSD (0.05)	40	2.6	0.8	

† CC, crimson clover (*Trifolium incarnatum* L.); LM, white clover (*Trifolium pratense* L.) living mulch; CR, cereal rye (*Secale cereale* L.).

LM system vs. -0.14 MPa for both years in the CC and CR systems. Soil water pressure head at the 15- to 30-cm depths were not different among systems in either year.

Soil Inorganic Nitrogen, Nitrogen Uptake, and Plant-Available Nitrogen

Soil inorganic N was significantly greater in the CC and CR systems than in the LM system 14 d after side dressed applications of N were applied at the V6 stage of corn growth in 2015 (Fig. 2). Soil inorganic N cover crop system effects persisted until the silking (R1) stage of corn growth in 2015 but drought conditions of 2016 likely reduced N mineralization and cover crop system effects were not as prominent as in 2015. Total N uptake was greater in the CC and CR systems than the LM system in 2015 beginning at the R1 stage and continued to the dent (R5) stage of corn development. Similarly, corn grown in the LM system had lower N uptake than the CR and CC systems in 2016, but the differences among the cover crop systems

were expressed approximately 7 d after the V6 stage. Total N uptake by the CR system, as estimated from plant samples taken at the R6 stage of development, was not different from either the CC or LM system when averaged across both years (Table 2). Plant-available N was least for the LM system from the V6 until the R5 stages in 2015 and from 7 d before V6 until the R5 stages in 2016 (Fig. 2). Plant-available N was less among all cover crop systems during the drought year of 2016 than in 2015 because of lower inorganic soil N and lower corn N uptake.

Crop Growth, Light Interception, and Yield Parameters

Generally, corn height was similar among cover crop systems in 2015 until 56 DAP, after which the corn in the LM system was shorter than corn in the other cover crop systems (Fig. 3). In 2016, corn in the CC and CR systems were taller than corn in the LM system at 35 DAP and thereafter. Light interception was not significantly different among systems throughout the 2015 growing season; however, in 2016 the LM system had significantly less light interception than both the CC and CR systems at 35 DAP and thereafter. Aboveground corn biomass was not different among the cover crop systems during the 2015 growing season (Fig. 4). In 2016, the LM system had the lowest biomass from 56 DAP and thereafter, but the CR system was not different from the LM system 64 DAP and thereafter.

Total corn biomass was greatest for the CC and least for the LM systems (Table 2). Total corn biomass in the CR system was not different from either of the other cover crop systems. Total corn biomass was greater in 2015 than in the drought year of 2016. Grain yield was greatest for the CC and CR systems and

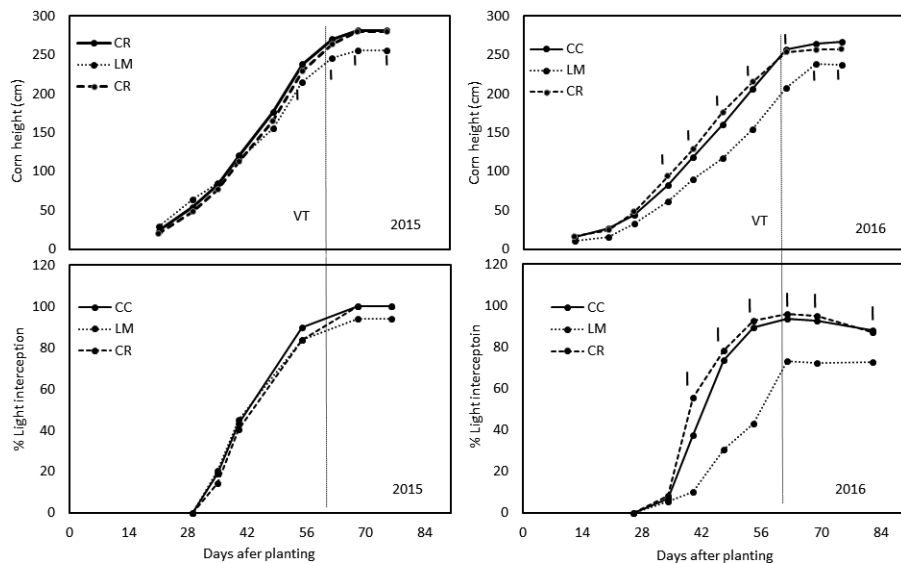


Fig. 3. Corn (*Zea mays* L.) height and percent light interception as affected by the white clover (*Trifolium pratense* L.) living mulch (LM), crimson clover (*Trifolium incarnatum* L.) (CC), and cereal rye (*Secale cereale* L.) (CR), cover crop systems during the 2015 and 2016 growing seasons. Vertical bars represent least significant differences at the 0.05 level of probability. Vertical line at VT represents the time at which tasseling occurred.

least for the LM system. Grain yield was lower for all cover crop systems during the drought year of 2016 than in 2015.

There were no differences for N IUE among systems or years (Table 3). Although there was an interaction between years and cover crop systems for PFP, the interaction was magnitudinal in nature and the order of lowest to highest PFP values did not change among the cover crop systems. Thus, only cover crop system means across years, and means for years across cover crop systems are presented. Both PNB and PFP of fertilizer N were greatest in the LM system, intermediate in the CC system, and lowest in the CR system in both years. Partial nutrient balance and PFP of fertilizer N was lower in 2016 than in 2015.

DISCUSSION

The pattern of available soil inorganic N from the LM-corn system in Georgia (Fig. 2) was similar to soil $\text{NO}_3\text{-N}$ patterns in the LM-corn system when the legume was kura clover (*Trifolium ambiguum* M. Bieb.) in Wisconsin (Zemenchik et al., 2000). Nitrogen supply was nearly 100 kg N ha^{-1} in both studies in the first year but was significantly lower in the second year unless N fertilizer was added. Although responses were similar, the reasons for lower mineral N supply in the two studies were different. Cool spring temperatures permitted kura clover to recover from chemical suppression and compete with the corn, presumably for soil N (Zemenchik et al., 2000). The reduced inorganic N in the LM system herein was associated with drought conditions, which likely reduced decomposition and mineralization from the senesced white clover. The optimum soil moisture range for N mineralization is between -0.03 and -0.01 MPa , when soils are at field capacity or slightly saturated (Stanford and Epstein, 1974; Myers et al., 1982). Water consumption by the white clover in the LM plots decreased the water content and lowered the soil pressure head in the top 15 cm of the soil, which, in turn, reduced the mineralization of the detrital N to inorganic forms (Fig. 2). Reduced mineralization of LM-N, combined with legume N release from shading by the corn, suggests a significant amount of organic N remained

in the detrital layer of clover laying on the soil surface and was not available for uptake by the crop. Likewise, the soil inorganic N was lower in the CC and CR cover crop systems in this study throughout the growing season of 2016 when compared with 2015. Nitrogen uptake was greatest in both the CR and CC cover crop systems, presumably because greater amounts of mineral N was applied.

Nitrogen uptake in the LM, CC, and CR, cover crop systems was not different until the R1 stage of corn development in 2015, after which the demand for N surpassed the ability of the LM system to supply inorganic N (Fig. 2). Although legumes are capable of fixing their own N, they prefer mineral N over their physiological investment in the N fixation biochemical pathway (Svenning and MacDuff, 1996). Reduced inorganic soil N in the LM cover crop system may be due to less total N applied, competition from intercropped clover for $\text{NO}_3\text{-N}$, and reduced mineralization of clover residue. Other studies found similar grain yield reductions in living mulch systems and also concluded that early season competition between clover and corn was a mechanism for yield reductions (Scott et al., 1987; Echtenkamp and Moomaw, 1989; Zemenchik et al., 2000; Affeldt et al., 2004). A similar N uptake response in this study was noted in 2016, except differences in N uptake occurred earlier in the growing season and just after the V6 stage of corn development. All cover crop systems had lower N uptake in the drought year of 2016 even though supplemental irrigation was applied. Periods of corn water stress were evident when demand from other research efforts resulted in limited opportunities for irrigation application. Regardless, mean N uptake and grain yields in this study (Table 2) were similar to N treatments in the kura clover system (Zemenchik et al., 2000; Affeldt et al., 2004).

Nitrogen IUE is defined as grain yield divided by N uptake (Fixen et al., 2015) and can be interpreted as the ability of the crop to utilize N for grain production. Similar IUE in this study, therefore, indicated that all systems utilized N in the same manner regardless of whether it was derived from a mineral or cover crop residue source. Differences in yield would therefore

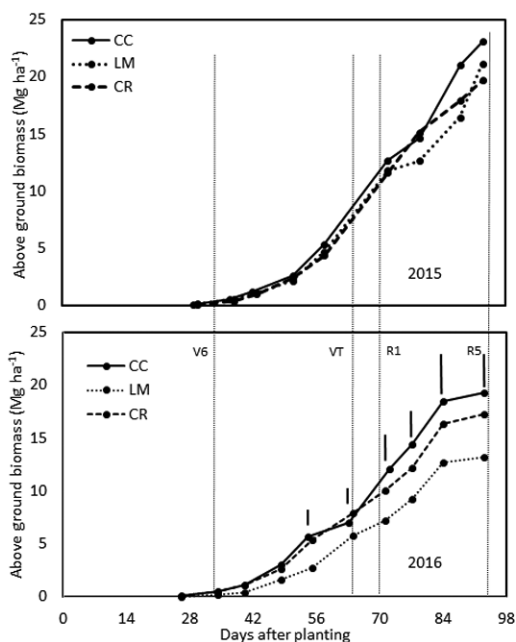


Fig. 4. Cumulative aboveground corn biomass through the R5 stage of development as affected by white clover (*Trifolium pratense* L.) living mulch (LM), crimson clover (*Trifolium incarnatum* L.) (CC), and cereal rye (*Secale cereale* L.) (CR), and cover crops in 2015 and 2016. Vertical bars represent least significant differences at the 0.05 level of probability. Vertical lines at the V6, VT, R1, and R5 represent timing of the six collar leaf, tassel, silking, and dent stages of corn (*Zea mays* L.) development, respectively.

be expected to be a result of reduced N uptake of a particular cover crop system rather than a difference of corn N partitioning. Accordingly, N uptake and grain yield were similar among the CR and CC systems but were least in the LM system (Table 2).

Fertilizer N PNB is interpreted based on whether values are greater or less than 1.0 (Fixen et al., 2015). Values less than 1.0 indicate the crop is utilizing only a portion of the fertilizer N applied to the crop, whereas values greater than 1.0 indicate the crop is utilizing other sources of N than that applied. In this experiment the corn grown in the LM and CC cover crop systems had values of 2.0 or greater, indicating both were obtaining the majority of their N nutrition from sources other than N fertilizer (Table 3). It is assumed, therefore, that the non-fertilizer source of N was the main source of N nutrition and that the legume cover crops were the source of that N. Conversely, only 70% of the fertilizer N was utilized by corn in the CR system, indicating that the non-utilized N was either immobilized by the high C content of the CR (Fageria et al., 2005) or lost via leaching or volatilization (Fageria and Baligar, 2005).

Fertilizer N PFP is interpreted as the relative contribution of fertilizer N to grain yield. Because the LM and CC cover crop systems had greater PNB values, it might be expected that PFP values would be greatest for the legume-based cover crop systems. Fertilizer N PFP was greatest for the LM system even though it had the least grain yield (Table 3). The fertilizer N PFP for the CC system was less than that for the LM system but greater than that for the CR system. This presents an interesting paradox for fertilizer N. The CR cover crop system was the least efficient from a fertilizer perspective but had greater yield than the LM cover crop system, indicating use of fertilizer N could be more profitable during eras of low fertilizer prices.

Table 3. Internal utilization efficiency (IUE), partial nutrient balance (PNB), and partial factor productivity (PFP) of fertilizer N in cover crop systems.†

System	IUE	PNB	PFP
CC‡	67.7	2.02	118
LM	78.2	2.74	187
CR	74.7	0.69	47
LSD (0.05)	NS	0.59	14
2015	70.9	2.12	127
2016	76.2	1.49	107
LSD (0.05)	NS	0.50	11

† IUE = grain yield (kg ha^{-1})/N uptake (kg ha^{-1}); PNB = N uptake (kg ha^{-1})/fertilizer N applied (kg ha^{-1}); PFP = grain yield (kg ha^{-1})/fertilizer N applied (kg ha^{-1}).

‡ CC, crimson clover (*Trifolium incarnatum* L.); LM, white clover (*Trifolium pratense* L.) living mulch; CR, cereal rye (*Secale cereale* L.).

However, the LM cover crop system had the greatest PFP value and was, therefore, more efficient from a fertilizer N perspective, and may be more profitable when high N fertilizer prices prevail.

Despite the potential of legume-based LM systems, year-to-year yield variation is likely to be an impediment to technology adoption. Chemical assessment of soil N will be vital in determining whether supplemental mineral N will be needed to provide optimum economic yields in LM systems. However, traditional chemical tests for soil N status are not good predictors of fertilizer N response (Scharf, 2001; Scharf et al., 2002, 2005; St. Luce et al., 2011) and may, therefore, be unreliable for use in the LM system. Furthermore, environmental variables affecting the decomposition of surface organic matter and N mineralization are likewise poorly understood (Quemada and Cabrera, 1997; St. Luce et al., 2011), making predictions of the interaction between soil N supply, mineralization of cover crop N, and competition between the LM legume and crop N uptake difficult to predict. Success of the LM system will likely require a coordinated effort among soil, crop, and climatological scientists to develop reliable soil, crop, and environmental parameters to optimize N fertility of the LM cover crop system.

CONCLUSIONS

The data demonstrate that N availability was lowest in the LM system, leading to reduced N uptake, growth, and corn grain yields than the CC and CR systems. However, despite only receiving 56 kg N ha^{-1} as supplemental fertilizer, the LM system had yields that were only 22 and 20% lower than the CC and CR systems, respectively. The IUE of N was similar among the cover crop systems, though larger PNB and PFP values in the LM system indicates that N is supplied mainly by the white clover, which is a main goal of LM systems. Encouraging grain yields in the LM system provides enticing opportunities to supply N to row crops and minimize needs for mineral N use, but lack of consistency of the response over years may impede adoption and implementation of the LM technology. Variation of grain yield among years is the result of complex interactions between soil N, cover crop mineralization, and climate. The traditional assessments of these parameters limit our capability of predicting supplemental N needs regardless of cover crop systems and improvement of our understanding of soil N, cover crop mineralization, and climate will be necessary to assist producers who are willing to adopt the LM system.

Despite the challenges of yearly yield variations in the LM cover crop system, the variation experienced within were the result of an unusual drought event. We believe the LM system has the opportunity to provide sustainable crop production options, especially when mineral N prices are high relative to crop commodity prices. The system is applicable to thermic soils commonly found in the southeastern United States.

REFERENCES

- Affeldt, R.P., K.A. Albrecht, C.M. Boerboom, and E.J. Bures. 2004. Integrating herbicide-resistant corn technology in a kura clover living mulch system. *Agron. J.* 96:247–251. doi:10.2134/agronj2004.0247
- Arya, L. 2002. Wind and hot-air methods. In: J.H. Dane and C.G. Topp, editors, *Methods of soil analysis. Part 4 Physical methods.* SSSA Book Ser. 5.4. SSSA, Madison, WI. p. 916–926.
- Baker, W., and T. Thompson. 1992. Determination of total nitrogen in plant samples by Kjeldahl. *Plant analysis reference procedures for the southern region of the United States.* South. Coop. Ser. Bull. 368:13–16.
- Beck, M.A., L.W. Zelazny, W.L. Daniels, and G.L. Mullins. 2004. Using the Mehlich-1 extract to estimate soil phosphorus saturation for environmental risk assessment. *Soil Sci. Soc. Am. J.* 68:1762–1771. doi:10.2136/sssaj2004.1762
- Campbell, C., Y. Jame, O. Akinremi, and H. Beckie. 1994. Evaluating potential nitrogen mineralization for predicting fertilizer nitrogen requirements of long-term field experiments. In: J.H. Havlin and J.S. Jacobsen, editors, *Soil testing: Prospects for improving nutrient recommendations.* SSSA Spec. Publ. 40. SSSA and ASA, Madison, WI. p. 81–100.
- Dharmakeerthi, R.S., B.D. Kay, and E.G. Beauchamp. 2005. Factors contributing to changes in plant available nitrogen across a variable landscape. *Soil Sci. Soc. Am. J.* 69:453–462. doi:10.2136/sssaj2005.0453
- Duda, G.P., J.G.M. Guerra, M.T. Monteiro, H. De-Polli, and M.G. Teixeira. 2003. Perennial herbaceous legumes as live soil mulches and their effects on C, N, and P of the microbial biomass. *Sci. Agric.* 60:139–147. doi:10.1590/S0103-90162003000100021
- Echtenkamp, G.W., and R.S. Moomaw. 1989. No-till corn production in a living mulch system. *Weed Technol.* 3:261–266. doi:10.1017/S0890037X00031778
- Fageria, N.K., and V.C. Baligar. 2005. Enhancing nitrogen use efficiency in crop plants. *Adv. Agron.* 88:97–185. doi:10.1016/S0065-2113(05)88004-6
- Fageria, N.K., V.C. Baligar, and B.A. Bailey. 2005. Role of cover crops in improving soil and row crop productivity. *Commun. Soil Sci. Plant Anal.* 36:2733–2757. doi:10.1080/00103620500303939
- Fixen, P., F. Brentrup, T. Bruulsema, F. Garcia, R. Norton, and S. Zingore. 2015. Nutrient/fertilizer use efficiency: Measurement, current situation and trends. In: P. Drechsel, P. Heffer, H. Magen, R. Mikkelsen, and D. Wichelns, editors, *Managing Water and fertilizer for sustainable agricultural intensification.* International Fertilizer Industry Association, International Water Management Institute, International Plant Nutrition Institute, and International Potash Institute. Paris, France p. 8–38.
- Hartwig, N.L., and H.U. Ammon. 2002. Cover crops and living mulches. *Weed Sci.* 50:688–699. doi:10.1614/0043-1745(2002)050[0688:AIACCA]2.0.CO;2
- Kramberger, B., A. Gselman, M. Janzekovic, M. Kaligarić, and B. Bracko. 2009. Effects of cover crops on soil mineral nitrogen and on the yield and nitrogen content of maize. *Eur. J. Agron.* 31:103–109. doi:10.1016/j.eja.2009.05.006
- Kurtz, T., S.W. Melsted, and R.H. Bray. 1952. The importance of nitrogen and water in reducing competition between intercrops and corn. *Agron. J.* 44:13–17. doi:10.2134/agronj1952.0002196200440001005x
- Langdale, G.W., L.T. West, R.R. Bruce, W.P. Miller, and A.W. Thomas. 1992. Restoration of eroded soil with conservation tillage. *Soil Technol.* 5:81–90. doi:10.1016/0933-3630(92)90009-P
- Lee, R.D., G.H. Harris, K. Harrison, W. Porter, E. Prostko, D. Buntin, B. Kemerait, P. Sumner, N. Smith, and A. Smith. 2015. *A guide to corn production in Georgia 2015.* Spec. Publ. CSS 01-2016. Dep. of Crop and Soil Sci., Univ. of Georgia, Athens.
- Lloveras, J., and I. Iglesias. 2001. Morphological development and forage quality changes in crimson clover (*Trifolium incarnatum* L.). *Grass Forage Sci.* 56:395–404. doi:10.1046/j.1365-2494.2001.00289.x
- Myers, R., K. Weier, and C. Campbell. 1982. Quantitative relationship between net nitrogen mineralization and moisture content of soils. *Can. J. Soil Sci.* 62:111–124. doi:10.4141/cjss82-013
- Nakamoto, T., and M. Tsukamoto. 2006. Abundance and activity of soil organisms in fields of maize grown with a white clover living mulch. *Agric. Ecosyst. Environ.* 115:34–42. doi:10.1080/00380768.2012.699881
- Paine, L.K., and H. Harrison. 1993. The historical roots of living mulch and related practices. *Hort Technol.* 3:137–143.
- Quemada, M., and M.L. Cabrera. 1997. Temperature and moisture effects on C and N mineralization from surface applied clover residue. *Plant Soil* 189:127–137. doi:10.1023/A:1004281804058
- Rasse, D.P., A.J.M. Smucker, and O. Schabenberger. 1999. Modifications of soil nitrogen pools in response to alfalfa root systems and shoot mulch. *Agron. J.* 91:471–477. doi:10.2134/agronj1999.00021962009100030019x
- Raun, W.R., and G.V. Johnson. 1999. Improving nitrogen use efficiency for cereal production. *Agron. J.* 91:357–363. doi:10.2134/agronj1999.00021962009100030001x
- Sanders, Z.P., J.S. Andrews, U.K. Saha, W. Vencill, R.D. Lee, and N.S. Hill. 2017. Optimizing agronomic practices for clover persistence and corn yield in a white clover–corn living mulch system. *Agron. J.* 109:2025–2032. doi:10.2134/agronj2017.02.0106
- Scharf, P.C. 2001. Soil and plant tests to predict optimum nitrogen rates for corn. *J. Plant Nutr.* 24:805–826. doi:10.1081/PLN-100103775
- Scharf, P.C., N.R. Kitchen, K.A. Sudduth, J.G. Davis, V.C. Hubbard, and J.A. Lory. 2005. Field-scale variability in optimal nitrogen fertilizer rate for corn. *Agron. J.* 97:452–461. doi:10.2134/agronj2005.0452
- Scharf, P.C., W.J. Wiebold, and J.A. Lory. 2002. Corn yield response to nitrogen fertilizer timing and deficiency level. *Agron. J.* 94:435–441. doi:10.2134/agronj2002.4350
- Schomberg, H.H., D.M. Endale, A. Calegari, R. Peixoto, M. Miyazawa, and M.L. Cabrera. 2006. Influence of cover crops on potential nitrogen availability to succeeding crops in a Southern Piedmont soil. *Biol. Fertil. Soils* 42:299–307. doi:10.1007/s00374-005-0027-8
- Scott, T.W., J. Mt. Pleasant, R.F. Burt, and D.J. Otis. 1987. Contributions of ground cover, dry mater, and nitrogen from intercrops and cover crops in a corn polyculture system. *Agron. J.* 79:792–798. doi:10.2134/agronj1987.00021962007900050007x
- Smil, V. 1997. Global population and the nitrogen cycle. *Sci. Am.* 277:76–81. doi:10.1038/scientificamerican0797-76
- Snapp, S.S., S.M. Swinton, R. Labarta, D. Mutch, J.R. Black, R. Leep, and K. O’Neil. 2005. Evaluating cover crops for benefits, costs and performance within cropping system niches. *Agron. J.* 97:322–332.
- St. Luce, M.S., J.K. Whalen, N. Ziadi, and B.J. Zebarth. 2011. Nitrogen dynamics and indices to predict soil nitrogen supply in humid temperate soils. *Adv. Agron.* 112:55–102. doi:10.1016/B978-0-12-385538-1.00002-0
- Stanford, G., and E. Epstein. 1974. Nitrogen mineralization-water relations in soils. *Soil Sci. Soc. Am. J.* 38:103–107. doi:10.2136/sssaj1974.03615995003800010032x
- Suleiman, A.A., and G. Hoogenboom. 2007. Comparison of Priestley-Taylor and FAO-56 Penman-Monteith for daily reference evapotranspiration estimation in Georgia. *J. Irrig. Drain. Eng.* 133:175–182. doi:10.1061/(ASCE)0733-9437(2007)133:2(175)

- Svenning, M., and J. MacDuff. 1996. Low root temperature retardation of the mineral nitrogen induced decline in N₂ fixation by a northern ecotype of white clover. *Ann. Bot. (Lond.)* 77:615–621. doi:10.1093/aob/77.6.615
- Tonitto, C., M.B. David, and L.E. Drinkwater. 2006. Replacing bare fallows with cover crops in fertilizer-intensive cropping systems: A meta-analysis of crop yield and N dynamics. *Agric. Ecosyst. Environ.* 112:58–72. doi:10.1016/j.agee.2005.07.003
- Uhart, S.A., and F.H. Andrade. 1995. Nitrogen deficiency in maize: I. Effects on crop growth, development, dry matter partitioning, and kernel set. *Crop Sci.* 35:1376–1383. doi:10.2135/cropsci1995.0011183X003500050020x
- University of Georgia. 2017a. Cover crop nitrogen availability calculator. Univ. of Georgia, Athens. <http://aesl.ces.uga.edu/mineralization/> (accessed 2 May 2018).
- University of Georgia. 2017b. Weather network. Univ. of Georgia, Athens. <http://weather.uga.edu/index.php> (accessed 2 May 2018).
- USDA-NRCS. 2015. USDA-NRCS Georgia cover crop (Code 340) standard. USDA, Washington, DC. <https://efotg.sc.egov.usda.gov/references/Public/GA/> (accessed 15 Jan. 2018).
- van Genuchten, M.T. 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Sci. Soc. Am. J.* 44:892–898. doi:10.2136/sssaj1980.03615995004400050002x
- Young-Mathews, A. 2013. Plant guide for crimson clover (*Trifolium incarnatum*). USDA-NRCS, Plant Materials Center, Corvallis, OR.
- Zemenchik, R.A., K.A. Albrecht, C.M. Boerboom, and J.G. Lauer. 2000. Corn production with kura clover as a living mulch. *Agron. J.* 92:698–705. doi:10.2134/agronj2000.924698x