

Establishing the relationship of soil nitrogen immobilization to cereal rye residues in a mulched system

Alwyn Williams · M. Scott Wells · David A. Dickey · Shuijin Hu · Jude Maul · Daniel T. Raskin · S. Chris Reberg-Horton · Steven B. Mirsky

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Abstract

Background and aims Soil nitrogen (N) immobilization from cover crop residues may help suppress weeds. We established a gradient of cereal rye shoot biomass to determine the extent that soil N can be immobilized and its effect on redroot pigweed (*Amaranthus retroflexus* L.). **Methods** A microplot study was conducted in no-till cereal rye (*Secale cereale* L.)—soybean (*Glycine max* L. (Merr.)) systems at two sites in eastern USA. Microplots received 0, 2000, 5000, 8000, 12,000 or

15,000 kg ha⁻¹ of cereal rye shoot biomass, and were injected with two mg ¹⁵N kg⁻¹ soil 5 cm below the soil surface. Pigweeds were sown and allowed to germinate. **Results** Maximum rates of cereal rye shoot decomposition were observed at ≥5000 kg ha⁻¹. Although cereal rye shoot N declined, shoots became enriched with ¹⁵N, indicating fungal transfer of soil N to shoots. Soil inorganic N declined by an average of 5 kg N ha⁻¹. Pigweed tissue N and biomass were reduced in the presence of cereal rye. The magnitude of pigweed N reduction was similar across all shoot application rates.

Conclusions We found weak evidence for a cereal rye shoot-based N immobilization mechanism of weed suppression. Our results indicate N immobilization may be primarily due to root residues.

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A. Williams
School of Agriculture and Food Sciences, The University of Queensland, QLD, Gatton 4343, Australia

M. Scott Wells (✉) · D. T. Raskin
Department of Agronomy and Plant Genetics, University of Minnesota, St. Paul, MN 55108, USA
e-mail: mswells@umn.edu

D. A. Dickey
Department of Statistics, North Carolina State University, Raleigh, NC 27695, USA

S. Hu
Department of Plant Pathology, North Carolina State University, Raleigh, NC 27695, USA

J. Maul · S. B. Mirsky
Sustainable Agriculture Systems Laboratory, USDA-ARS, Beltsville, MD 20705, USA

S. Chris Reberg-Horton
Department of Crop Science, North Carolina State University, Raleigh, NC 27695, USA

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Introduction

Demand for organic soybean (*Glycine max* L. (Merr.)) for both feedstock and human consumption has grown continuously over the past decade. Increased demand has driven commodity prices to near record highs, and in many cases organic soybean sells for twice that of conventional soybean (McBride et al. 2015). However, organic soybean production incurs considerably higher operational costs than conventional soybean production, arising primarily from higher fuel costs for weed

management (McBride and Greene 2009). These higher operational costs have the potential to reduce the economic and environmental sustainability of organic soybean production systems, pointing to the need to develop alternative methods of organic weed control.

Weeds in organic soybean systems are typically managed through frequent and intensive cultivation events. While effective for weed control, excessive soil cultivation can lead to compaction of the sub-soil layer, increase the risk of water and wind erosion, and stimulate mineralization of soil organic carbon (C) (Håkansson and Reeder 1994; Grandy and Robertson 2007; Montgomery 2007). Increased disturbance also contributes to the degradation of soil aggregates and loss of C storage capacity (Beare et al. 1997; Six et al. 2006). Moreover, frequent tillage entails elevated energy consumption and higher labor costs (Bernstein et al. 2011; Mirsky et al. 2012).

Weed suppressive cover crop mulches are underutilized in organic soybean production systems, yet have the potential to increase the sustainability of these systems. Several studies have demonstrated the effectiveness of cover crop mulches, produced via a roller-crimper, for weed control in organic systems (Reberg-Horton et al. 2012; Wells et al. 2013; Mirsky et al. 2013). A roller-crimper is a ground-driven implement that physically terminates near-mature cover crops before no-till cash crop planting, leaving a surface mulch of cover crop shoot residues as well as intact belowground root residues (Ashford and Reeves 2003; Reberg-Horton et al. 2012; Wells et al. 2013). Used for many years in Brazil (Derpsch et al. 1991), roller-crimping cover crops in annual row-crop systems increased in popularity in the US following improvements in roller-crimper design (Kornecki et al. 2009).

The primary mechanisms behind the weed suppressive attributes of roller-crimped (roll-crimped) cover crops are both physical and chemical in nature. Physically, cover crop residues provide a restrictive barrier that alters the soil surface microclimate (i.e., soil moisture and light), thus inhibiting weed seed germination (Teasdale and Mohler 2000; Webster et al. 2016). This mechanism requires sufficient cover crop biomass production to achieve optimum weed suppression. In the case of organic soybean production, 8000–9000 kg ha⁻¹ rye dry matter biomass has been reported as being the minimum threshold for acceptable weed control in the eastern US (Reberg-Horton et al. 2012; Mirsky et al. 2013). Chemically, cover crop residues suppress weeds

through the release of phytotoxic allelopathic chemicals (Reberg-Horton et al. 2005).

Recent research suggests that a third control mechanism of nitrogen (N) limitation may also play an important role in weed suppression (Kumar et al. 2008, 2011). Reduced plant-available nitrogen and subsequent N stress in summer annual broadleaf weeds (*Amaranthus retroflexus* L.), was reported in organic soybean systems that utilized roll-crimped cover crops (Wells et al. 2013). Lower plant-available N in high cover crop residue systems may contribute to and enhance overall weed suppression in these systems. While cover crop residue-induced N immobilization can limit N uptake by cash crops as well as weeds, leguminous cash crops such as soybean do not rely solely on plant-available soil N for growth, and consequently may not be impaired by N immobilization.

To our knowledge, weed suppression by N limitation due to cover crop root and shoot residues has not been investigated. There is, however, a sizable body of literature describing the effects of incorporating high C:N ratio residues into the soil system and subsequent increases in N immobilization (Schomberg et al. 1994; Recous et al. 1995; Burgess et al. 2002; Jin et al. 2008). In forestry systems, N transfer from soil to surface residues accounted for total N-immobilization in the forest litter layer during the first year of decomposition (Hart and Firestone 1991). Analogous N-immobilization effects were reported when wheat straw residues (ranging from 40 to 80:1 C:N) were applied to soil surfaces (Holland and Coleman 1987; Schwendener et al. 2005), and fungal translocation of soil N to the surface residues was confirmed as one of the modes of N-transfer (Frey et al. 2000). However, the concept of N limitation associated with high C:N ratio cover crop residues is not fully characterized in an agricultural setting. The absence of such characterization limits opportunity to manage cover crops and microbial processes for enhanced weed suppression, and thus constrains potential improvements in agricultural sustainability.

Recent research on N dynamics associated with high biomass cover crop residues has confirmed N-transfer from soil to aboveground residues, and provides partial confirmation of the hypothesized fungal translocation mechanisms (Frey et al. 2000; Wells et al. 2017). However, Wells et al. (2017) did not establish the optimal rate of cereal rye residue biomass for N immobilization, nor determine if the N immobilization event had a measurable

response on escaped weeds in the system. We hypothesize that increased cereal rye biomass levels will result in greater immobilization of soil N into surface residues, thereby limiting plant-available N throughout the soil profile and increasing N stress in summer annual broadleaf weeds. The objective of this study was to characterize the magnitude of N immobilization from increasing rates of cereal rye shoot residue biomass, and the subsequent effect on soybean and pigweed biomass and N content.

Methods

Study locations

In 2011, a two site-year experiment was conducted at the Center for Environmental Farming Systems in Goldsboro (GOLD), North Carolina (35.38291° N, -78.035846° W), and the USDA-ARS Beltsville Agricultural Research Center (BARC) in Beltsville, Maryland (39.03269° N, -76.928143° W). The soil type in GOLD was Wickham loamy sand (fine-loamy, mixed, semiactive, thermic Typic Hapludults) with 2 to 6% slope; at BARC the soil types were Codorus and Hatboro (mica bearing loamy alluvium), with 0 to 2% slope. Climate conditions over the experimental period are shown in Table 1.

Experimental design

Treatments consisted of six cereal rye shoot biomass application rates crossed with seven two-week destructive harvests (no replication) for a total of 42 treatment combinations including experimental controls. We prioritized establishing a response surface, where many factor levels of each treatment were considered more important for modeling purposes than replication of treatment combinations. The time factor is not a repeated measure in this study since each plot was randomly assigned a time at which it would be sampled and each experimental unit was sampled only once.

Prior to fall drilling of cereal rye (*Secale cereale* ‘Wheeler’), the entire field, at both locations, was disked and field cultivated to remove any existing vegetation from the prior maize and clover hay crops at BARC and GOLD, respectively. Lime, phosphorus (P), and potassium (K) were applied according to soil test before cereal rye planting. Cereal rye was drilled at a rate of 134 kg seed ha⁻¹ on a 13 cm row spacing during mid-October for all treatments. Plots were fertilized in the fall with 30 kg N ha⁻¹ as urea ammonium nitrate (UAN) to ensure adequate N availability for early growth of the cereal rye cover crop.

The microplots consisted of 42 steel box frames that were 0.58 m² (no boxes were assigned to the time = 0 plots; Fig. 1). Before microplots were installed, the cereal

Table 1 Monthly precipitation and maximum, minimum and mean air temperature from May to October, 2011 in Beltsville, MD and Goldsboro, NC. 30-year mean values (1980–2010) are shown in parentheses

Location	Month	Precip. (mm)	Monthly air temperature (°C)		
			Maximum	Minimum	Mean
Beltsville, MD	May	64 (110)	24.7 (23.6)	14.1 (11.3)	19.4 (17.4)
	June	70 (94)	29.8 (28.7)	18.4 (16.8)	24.1 (22.7)
	July	70 (100)	32.7 (30.9)	21.1 (19.4)	26.9 (25.2)
	August	316 (83)	29.8 (30.1)	19.3 (18.6)	24.5 (24.3)
	September	248 (104)	25.5 (26.1)	17.0 (14.3)	21.3 (20.2)
	October	113 (93)	18.7 (19.8)	8.5 (7.3)	13.6 (13.6)
	Mean	294 (97)	26.9 (26.5)	16.4 (14.6)	21.6 (20.6)
	Goldsboro, NC	May	27 (96)	27.5 (27.3)	14.9 (14.7)
Goldsboro, NC	June	23 (98)	33.2 (30.9)	20.1 (19.7)	26.7 (25.3)
	July	147 (141)	34.3 (32.2)	22.4 (21.7)	28.3 (27.0)
	August	420 (149)	31.8 (31.3)	21.1 (20.8)	26.5 (26.1)
	September	55 (152)	28.3 (28.2)	18.3 (17.3)	23.3 (22.8)
	October	51 (76)	22.1 (23.2)	8.9 (11.1)	15.5 (17.1)
	Mean	121 (119)	29.5 (28.9)	17.6 (17.6)	23.6 (23.2)

rye cover crop was terminated in early June (Zadoks 85) via a mower conditioner haybine. Average aboveground field biomass across both sites was $9400 \text{ kg DM ha}^{-1}$, with C:N ratios of 68:1 and 48:1 for Beltsville and Goldsboro, respectively. Belowground cereal rye biomass was estimated to be 20% of total (aboveground and belowground) cereal rye biomass at termination, i.e., $2350 \text{ kg DM ha}^{-1}$ (Sheng and Hunt 1991; Bolinder et al. 2007; Patel et al. 2015). Haybined cereal rye shoots were removed from the experimental area and air-dried for one-week. Following cereal rye shoot removal, 42 microplot boxes were installed directly into the cereal rye cover crop stubble to a depth of 40 cm. Soybean (Maturity Group VI) was hand-sown at a rate of $370,650 \text{ seeds ha}^{-1}$ with 76 cm row spacing. In addition, redroot pigweed (*Amaranthus retroflexus* L.) was sown on both sides of the soybean row. A one-time application of ^{15}N -enriched $(\text{NH}_4)_2\text{SO}_4$ solution (99.7 at.%), at a rate of $3.31 \text{ kg N ha}^{-1}$, was uniformly injected using large gauge needles approximately 5 cm below the soil surface at soybean planting (i.e., zero days after planting, DAP). This low rate of N addition was used to provide an effective N label that

would not perturb natural N dynamics. Following injection of ^{15}N , cereal rye shoot residues were applied to each microplot according to the prescribed rate.

Cereal rye shoot application rates consisted of 0, 2000, 5000, 8000, 12,000, and 15,000 kg ha^{-1} of aboveground DM. For the 0 kg ha^{-1} shoot rate treatment, no residues were applied, creating a ‘roots only’ control that was intended to quantify N dynamics in the absence of surface residue but with root residues included (Fig. 1). An additional control treatment was created where neither cereal rye roots nor shoots were present, i.e., a fallow ‘bare-ground’ check. Bare-ground checks were maintained in a fallow state using herbicides beginning several months prior to soybean planting. Sampling events occurred 0, 14, 30, 44, 58, 72 and 86 days after planting (Fig. 1).

To assess ^{15}N contamination to cereal rye shoots at injection, shoots from the 0 DAP microplot were applied and then removed after two to four hours; the collected material was evaluated for percent enrichment of ^{15}N . Cereal rye shoots were arranged away from regions where soybean and pigweed rows were seeded,

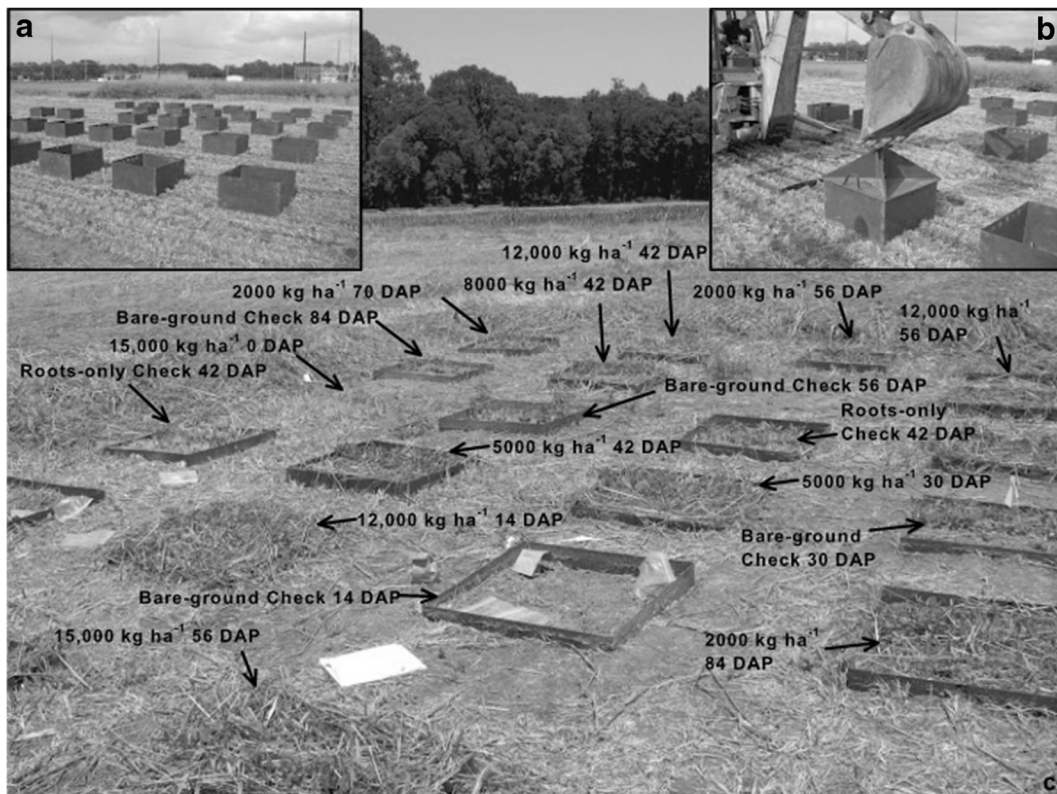


Fig. 1 Treatment assignment and layout corresponding with cereal rye residue rates and times associated with harvest (c). Top panels (a and b) show micro-plot boxes prior to installation and during installation. Goldsboro, North Carolina

and were pinned down using landscape staples. This was done to prevent the cereal rye shoots from influencing light transmittance at the soil surface, as the focus of this project was to isolate the effects of N availability from physical effects (light, temperature, and physical occlusion). After emergence, pigweed was thinned to eight plants per microplot and all other emerged weeds were removed by clipping them at the soil surface with scissors. Microplots were irrigated weekly during the first five weeks of the trial at a rate simulating 1.3 cm rainfall per week (equivalent to 7.4 L H₂O microplot⁻¹ week⁻¹); afterwards, irrigation was administered at the same rate on an as-needed basis based on perceived plant moisture stress.

Parameter assessments

For each sampling event, the following soil and crop parameters were measured: cereal rye shoot biomass, soybean plant tissue N, pigweed tissue N, and soil extractable inorganic N (0–10 cm depth). Cereal rye shoots, as well as soybean and pigweed tissue, were collected from entire microplots and air-dried at 60 °C for 72 h. Dried plant tissue was weighed, finely milled (i.e., ball-ground), and analyzed for total N by a PerkinElmer (Norwalk, CT) Model 2400 CHN elemental analyzer (Tu et al. 2006; Wells et al. 2013). Ball-ground plant tissue was also packed into 9 × 5 mm tin capsules and sent to the Stable Isotope Facility at University of California, Davis to be analyzed for N isotope ratios using a PDZ Europa ANCA-GSL elemental analyzer interfaced to a PDZ Europa 20–20 isotope ratio mass spectrometer (Sercon Ltd., Cheshire, UK).

Soil inorganic N was monitored by collecting 16 × 7.6 cm diameter cores (0–10 cm depth), arranged in a grid within each microplot. Bulk density and soil moisture were also assessed at each sampling interval. Soil samples were homogenized, wet-sieved (2 mm) to remove any plant material and rocks, and placed in cold (4 °C) storage for transport. Soil inorganic N was extracted from 20 g of field moist sieved soil in 50 mL of 0.5 M K₂SO₄ shaken for 30 min on an orbital shaker (Hart et al. 1994; Frey et al. 2000). After samples had been shaken, the soil suspension was filtered with filter papers that had been preleached with 100 mL of 0.5 M K₂SO₄ (Fisher Scientific Filter Paper Grade Q2); subsamples were analyzed for ammonium and nitrate on a Quick Chem 8000 Lachat (Keeney and Nelson 1982).

Statistical analysis

Data were first assessed by ANOVA to determine the presence of any significant site effects. Given the absence of statistically significant site effects, data from BARC and GOLD were pooled to improve robustness of our model fits. Model fitting was conducted utilizing exponential growth and decay equations in R 3.3.2 (R Core Team 2016; Pinheiro et al. 2016). Cereal rye shoot decomposition and N loss were modeled for each biomass application rate with the following exponential decay equation:

$$P_t = P_0 \cdot e^{(-\lambda \cdot DAP)} \quad (1)$$

Where P_t = cereal rye shoot biomass or N content at time t , P_0 = cereal rye shoot biomass or N content zero days after soybean planting, λ = decay constant, and DAP = days after soybean planting. The decay constant, λ , was estimated for each cereal rye shoot application rate using nonlinear least squares.

Soybean and pigweed biomass N uptake were modeled across all cereal rye shoot application rates with the following exponential growth equation:

$$Y_t = P_r \cdot e^{(\lambda \cdot DAP)} \quad (2)$$

Where Y_t = soybean or pigweed biomass N at time t , P_r = cereal rye shoot biomass plus estimated below-ground biomass zero days after soybean planting (fallow rate = 0 kg ha⁻¹).

Cereal rye shoot ¹⁵N and soil extractable inorganic N were modeled using the following response surface quadratic function:

$$Y_t = \beta_0 + \beta_1 \cdot DAP + \beta_2 \cdot P + \beta_3 \cdot DAP \cdot P + \beta_4 \cdot DAP^2 + \beta_5 \cdot P^2 \quad (3)$$

Where Y_t = cereal rye shoot ¹⁵N or soil extractable inorganic N, β_0 = intercept, β_{1-5} = regression coefficients, $P = P_0$ (for cereal rye shoot ¹⁵N accumulation; P_0 from Eq. 1) or $P = P_r$ (for extractable soil N; P_r from Eq. 2). All model terms were retained regardless of statistical significance. For all modeled parameters, the effects of shoot application rates were assessed using ordinary least squares regression.

Results

Cereal rye shoot biomass decomposition kinetics

Applied cereal rye shoots decomposed steadily over the 86 days of the experiment, with 55% decomposition of shoot biomass occurring for each application rate (Fig. 2). While total decomposition levels were comparable, the rate of decomposition differed significantly ($F_{4,60} = 17.00$, $P < 0.001$) between application rates (Fig. 2). At 2000 kg ha⁻¹ of shoot biomass, decomposition was slower compared with the 5000–15,000 kg ha⁻¹ application rates, which did not differ statistically from one another. The decay constant, λ , increased from 0.008 for the 2000 kg ha⁻¹ rate to a maximum of 0.011 for the 5000 kg ha⁻¹ rate (Table 2).

Cereal rye shoot nitrogen dynamics

Cereal rye shoot N content declined over time across all shoot application rates, losing approximately 45% of initial N content by 86 days after soybean planting (Fig. 3). Decomposition rates and estimated decay constants did not differ across the different shoot application rates.

There was detectable enrichment of cereal rye shoots with ¹⁵N in all shoot application rates throughout the duration of the study, with ¹⁵N content averaging 0.031 kg ha⁻¹ by 86 DAP across all shoot application rates (Fig. 4). Translocation of ¹⁵N from the soil surface to shoots increased with shoot application rate ($t_{1,64} = 1.90$, $P = 0.06$). At 86 DAP, ¹⁵N content in the 2000 kg

rate was 0.022 kg ha⁻¹ while ¹⁵N content in the 15,000 kg rate was 0.035 kg ha⁻¹ (Fig. 4).

The majority of the ¹⁵N applied was recovered in aboveground soybean tissues (Fig. 5). The proportion of ¹⁵N recovered in soybean tissues showed an increasing trend with the rate of cereal rye shoots applied, while ¹⁵N in pigweed showed a declining trend (Fig. 5). The recovery of ¹⁵N in soybean and pigweed at the highest shoot application rate appears anomalous relative to the overall trend, and exclusion of the highest rate shows the difference between soybean and pigweed trendlines to be significant ($t_{1,18} = 2.11$, $P = 0.05$; Fig. 5). The proportion of ¹⁵N recovered in cereal rye shoots did not differ statistically across shoot application rates.

Extractable soil inorganic nitrogen and plant responses

Extractable soil inorganic N content declined over time by approximately 78% of initial soil N content by 86 DAP across all shoot application rates (Fig. 6). While soil inorganic N declined with increasing shoot biomass ($t_{1,64} = 2.49$, $P = 0.01$), the magnitude of the differences across shoot application rates was small (Fig. 6).

The rate of pigweed N uptake and biomass accumulation over the course of the experiment did not differ between any of the microplots containing cereal rye residues (Figs. 7 and 8). However, pigweed had greater rates of N uptake and biomass accumulation in the absence of cereal rye roots and shoots (pigweed tissue N: $F_{1,72} = 17.36$, $P < 0.001$; pigweed biomass: $F_{1,58} = 10.75$, $P = 0.002$). By 86 DAP, pigweed N in the bare-

Fig. 2 Exponential decomposition of cereal rye shoot biomass for each shoot application rate (kg ha⁻¹). Points for each sampled day after planting are offset to reduce overlap

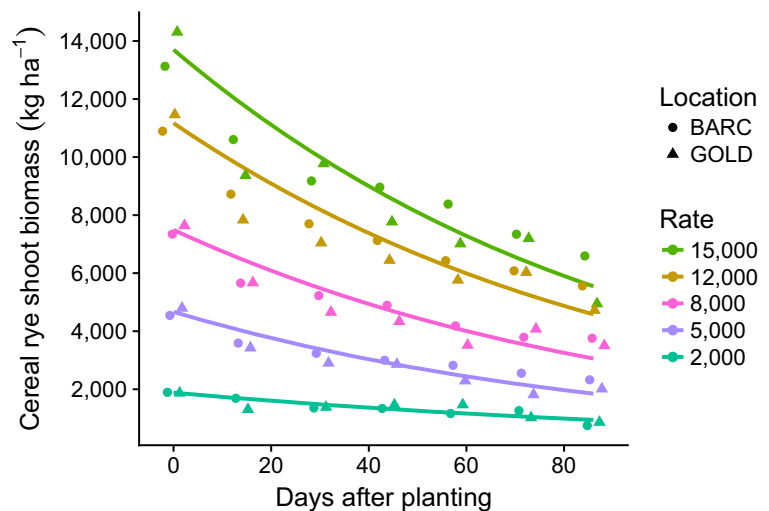
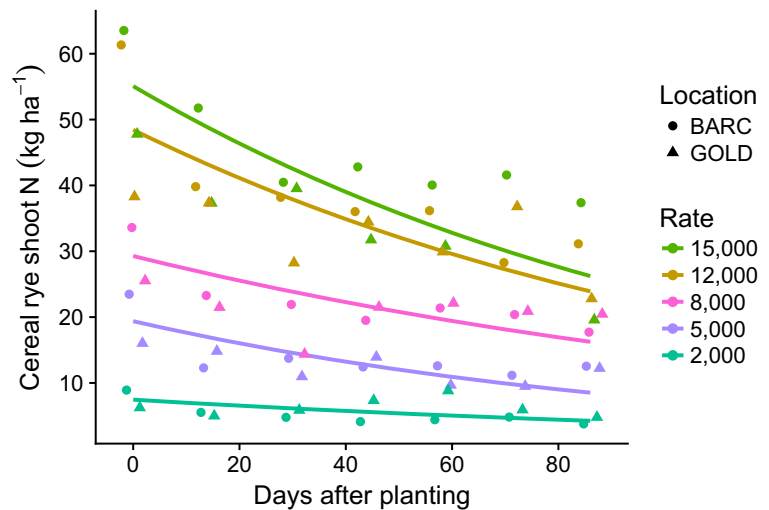


Fig. 3 Exponential loss of cereal rye shoot N for each shoot application rate (kg ha^{-1}). Points for each sampled day after planting are offset to reduce overlap



ground check increased to an average of 19 kg N ha^{-1} , compared to 3 kg N ha^{-1} averaged across all cereal rye treatments (Fig. 7), and pigweed biomass reached 3505 kg ha^{-1} in the bare-ground check compared with 583 kg ha^{-1} averaged across all cereal rye treatments (Fig. 8). In contrast, soybean biomass (Fig. 9) and N uptake (data not shown) were not affected by the presence of cereal rye residues. By 86 DAP, soybean biomass averaged 9253 kg ha^{-1} , and N uptake averaged 83 kg ha^{-1} across all treatments and controls.

Discussion

Contrary to our initial hypothesis, cereal rye shoot biomass rates did not drive system N dynamics in this study. Cereal rye shoot biomass decomposition was significantly affected by shoot application rate, but had limited impacts on soil N immobilization

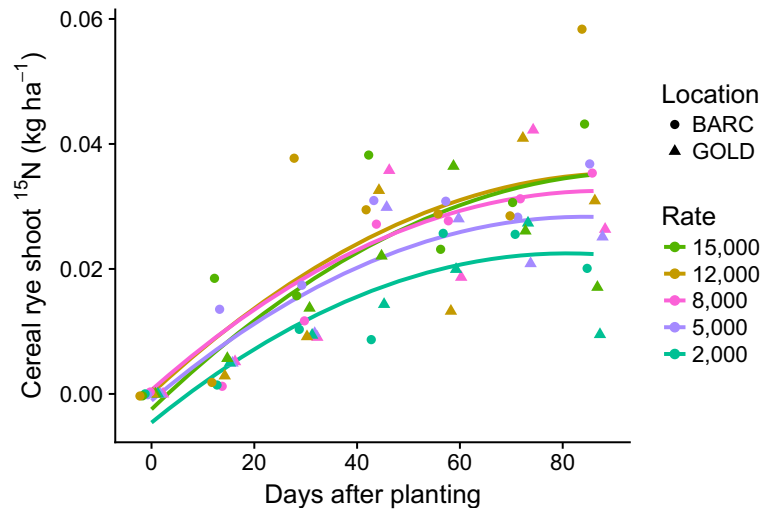
and pigweed N uptake over the duration of the study. While the accumulation of ^{15}N into cereal rye shoots was confirmed, the magnitude of translocation of N from the soil was small, and was not a driving mechanism for either N immobilization or weed suppression.

Shoot biomass decomposition rates differed as a function of shoot application rate, with more rapid decomposition and N loss occurring with shoot application rates $\geq 5000 \text{ kg ha}^{-1}$ as compared to the 2000 kg ha^{-1} rate. Cereal rye shoot biomass decomposition is a spatially differentiated process. Higher rates of decomposition occur at the soil surface, where spatial proximity and microclimate support residue colonization by soil microorganisms and arthropods, while upper residue layers remain protected from biological decomposition (Thorburn et al. 2001). Surface residues moderate soil temperature and increase soil water storage (Rathore et al. 1998; Cook et al. 2006). Available soil moisture exerts significant controls on decomposition rates (Fraser and Hockin 2013), and several studies have reported moisture, not temperature, as the dominant climatic control on decomposition (Murphy et al. 1998; Torres et al. 2005; Bontti et al. 2009). Soil moisture can also have effects on soil micro-arthropod communities (Wickings and Grandy 2013), which are influential during early stages of residue decomposition (Frouz et al. 2015; Soong and Nielsen 2016). Micro-arthropods can significantly increase decomposition rates by increasing detritus surface area through fragmentation, which fosters greater microbial colonization (Londoño-R et al. 2013).

Table 2 Estimated cereal rye shoot biomass decay constants (λ) for each shoot application rate

Cereal rye residue application rate (kg ha^{-1})	Estimated decay constant (λ) (day^{-1})
2000	0.00805
5000	0.01072
8000	0.01042
12,000	0.01036
15,000	0.01053

Fig. 4 ^{15}N in cereal rye shoot biomass for each shoot application rate (kg ha^{-1}). Points for each sampled day after planting are offset to reduce overlap



That said, it is also important to note that our experimental design controlled aspects of the soil environment that could have potentially differed if the quantities of aboveground biomass assigned to each microplot had actually been grown rather than applied as a residue treatment. For example, had $15,000 \text{ kg ha}^{-1}$ of cereal rye biomass been grown, the microplot soil environment would likely have been much drier upon cover crop termination compared with a microplot that grew $2,000 \text{ kg ha}^{-1}$ of cereal rye biomass, due to differences in evapotranspiration. This may have impacted the

observed rates of biomass decomposition across the different residue treatments.

The positive relationship between cover crop shoot biomass application rate and decomposition contrasts with results of previous studies that demonstrated a negative relationship between these factors (Parr and Papendick 1978; Stroo et al. 1989; Stott et al. 1990; Steiner et al. 1999; Thorburn et al. 2001). There are two potential reasons for this discrepancy: 1) differing experimental conditions; and 2) possible relationships between residue biomass and soil microenvironment.

Fig. 5 Proportional recovery of ^{15}N in soybean and pigweed aboveground tissues and in cereal rye shoots for each shoot application rate

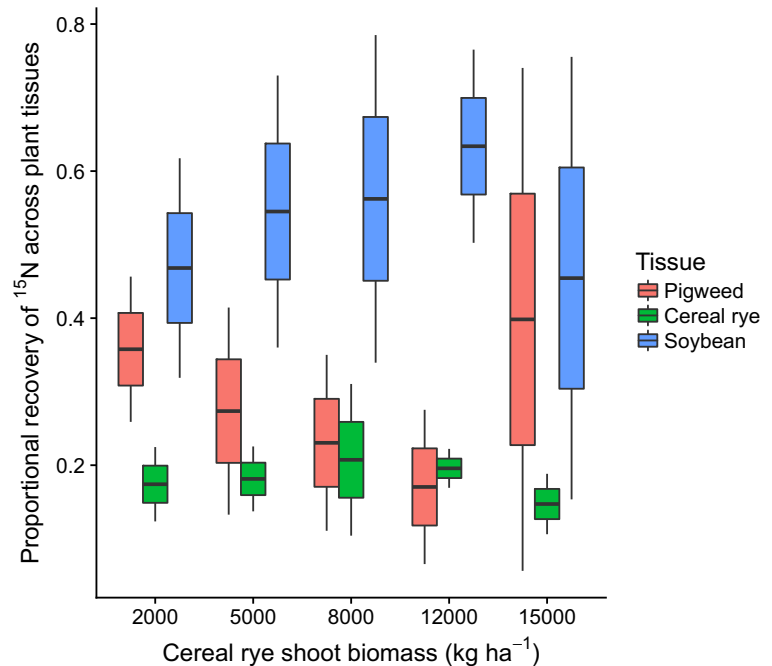
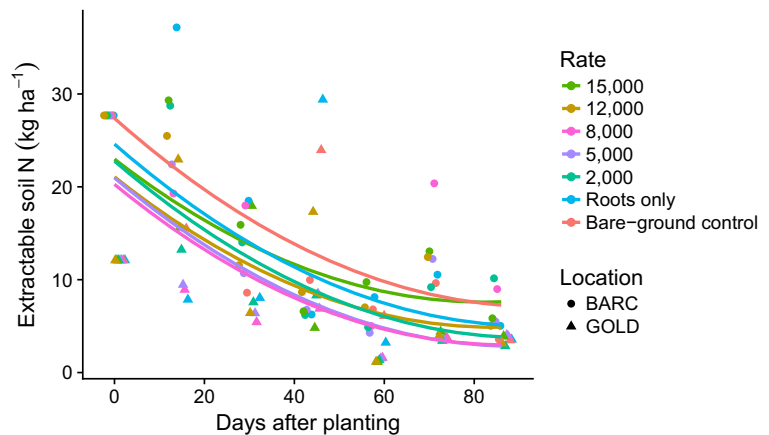


Fig. 6 Extractable soil inorganic N across six cereal rye shoot biomass rates including a ‘roots only’ rate and ‘bare-ground’ check (kg ha^{-1}). Points for each sampled day after planting are offset to reduce overlap



Other than Thorburn et al. (2001), none of the listed studies characterized decomposition rates of initial biomass applications greater than 8400 kg ha^{-1} , and all were conducted under dryland conditions. Thus, to the best of our knowledge, our experiment explores residue decomposition dynamics of biomass quantities orders of magnitude greater than most previous studies, and at levels considered necessary for effective weed suppression (Reberg-Horton et al. 2012; Mirsky et al. 2013). While Thorburn et al. (2001) modeled decomposition of high biomass rates ($10,000\text{--}20,000 \text{ kg ha}^{-1}$) of sugar cane residue under varied climatic conditions, they did not account for the impact of initial residue mass on the size and properties of the actively decomposing, soil-contact residue layer.

Residue biomass rates can increase soil water storage (Cook et al. 2006; Mulumba and Lal 2008). Mulumba and Lal (2008) reported that wheat biomass rates ranging from 0 to 16 Mg ha^{-1} had logarithmic effects on field capacity moisture, where no gain in soil moisture retention was observed above 10 Mg ha^{-1} . Greater

biomass rates can limit soil water recharge due to higher rates of precipitation interception and subsequent evaporation (Cook et al. 2006). Thus, the effect of shoot biomass on soil surface microclimate and residue decomposition may depend on precipitation.

In the present study, microplots were hand-irrigated, and water was introduced directly to the soil surface and decomposition layer, rather than being intercepted by the residue layer. It is possible that the observed increase in decomposition rate for the 8000, 12,000, and $15,000 \text{ kg ha}^{-1}$ shoot application rates was a result of differential desiccation of the surface residue after irrigation events. Microclimate conditions conducive for decomposition could have remained optimal for an increased period in the 12,000 and $15,000 \text{ kg ha}^{-1}$ shoot application rates, whereas rates less than or equal to 8000 kg ha^{-1} may have experienced hastened declines in soil moisture (i.e., logarithmic decline), thereby diminishing the time frame for decomposition.

Cereal rye shoot N release coincided with the accumulation of ^{15}N from surface soil into cereal rye shoots

Fig. 7 Pigweed tissue N across six cereal rye shoot biomass rates including a ‘roots only’ rate and ‘bare-ground’ check (kg ha^{-1}). Points for each sampled day after planting are offset to reduce overlap

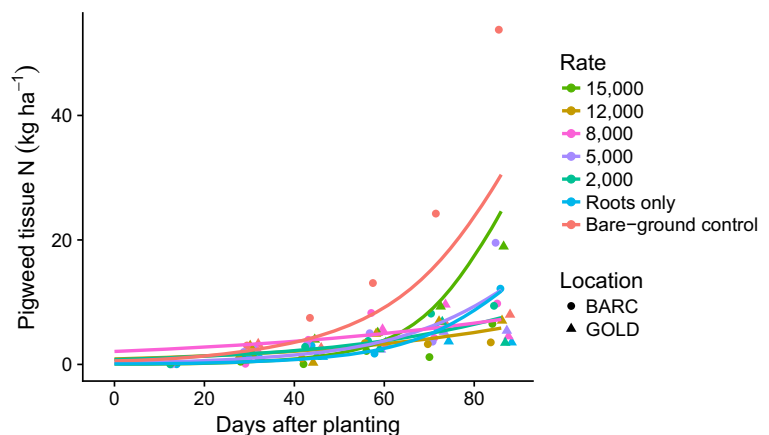
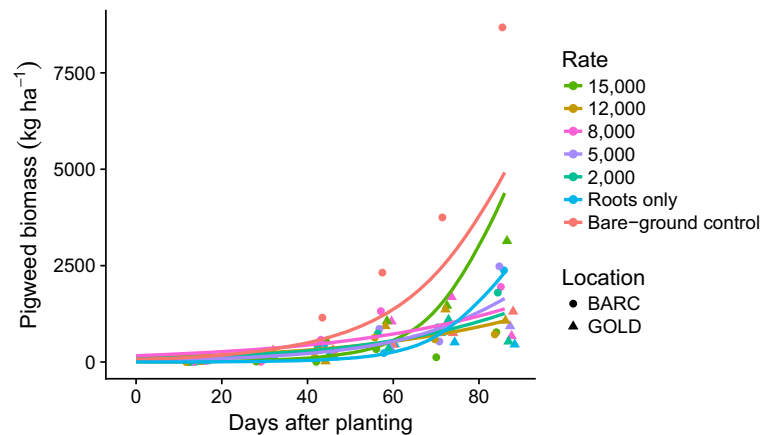


Fig. 8 Pigweed biomass across six cereal rye shoot biomass rates including a ‘roots only’ rate and ‘bare-ground’ check (kg ha^{-1}). Points for each sampled day after planting are offset to reduce overlap



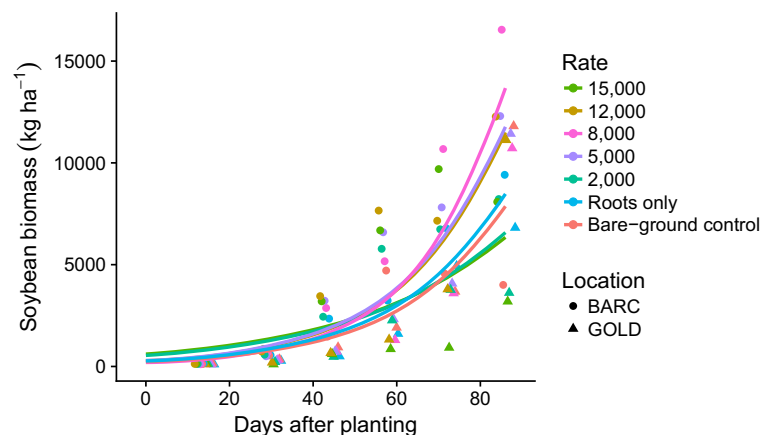
throughout the duration of the study, indicating a bi-directional movement of N between soil and surface residues. Similar quantities of ^{15}N enrichment of cereal rye shoots were reported by Wells et al. (2017) under similar experimental conditions. Such movement has been characterized as evidence of direct translocation of soil N by fungal hyphae (Frey et al. 2000; Wells et al. 2017). In the present study, the quantity of ^{15}N in cereal rye shoots at 86 DAP was lowest at the 2000 kg ha^{-1} shoot application rate. This corresponds to the observed relationship between shoot application rate and decomposition, suggesting a decreased rate of fungal colonization, and a corresponding decrease in N translocation.

Despite evidence of N transfer into surface residues, the primary direction of N movement over time was from residues to soil. Cereal rye shoot N loss ranged from 5 to 30 kg N ha^{-1} , resulting in approximately 45% loss of residue N by 86 DAP, a finding consistent with other studies (Poffenbarger et al. 2015; Pantoja et al. 2016). Most studies examining decomposition of cover

crop surface residues have considered the effects of residue quality rather than residue quantity on net N mineralization (Reberg-Horton et al. 2012; Lawson et al. 2012; Wells et al. 2013; Parr et al. 2014; Poffenbarger et al. 2015). Net N immobilization occurs when soil N availability poses limitations on microbial C acquisition. Net N immobilization is often expected when residue C:N ratios are greater than 25 (Reberg-Horton et al. 2012). The C:N ratio of the shoots applied in the present study was 47. Thus, it was anticipated that higher shoot application rates would encourage greater microbial demand for available N, stimulating more net immobilization during decomposition. However, soil extractable N decreased similarly over time across all shoot application rates and bare-ground checks.

Residue-induced soil N immobilization was expected to suppress pigweed biomass and N uptake. Pigweed can be sensitive to N limitations (Shibley and Keddy 1988), and observed decreases in soil inorganic N from $19.3 \text{ kg N ha}^{-1}$ at 0 DAP to 4.9 kg N ha^{-1} at 86 DAP, averaged across

Fig. 9 Soybean biomass across six cereal rye shoot biomass rates including a ‘roots only’ rate and ‘bare-ground’ check (kg ha^{-1}). Points for each sampled day after planting are offset to reduce overlap



residue rates, was within the range of N limitation known to negatively influence summer annual broadleaf species such as pigweed (Wells et al. 2013). Pigweed biomass accumulation and N uptake were similar across all treatments containing cereal rye residue. However, greater pigweed N uptake and biomass accumulation values in bare-ground checks indicate that the presence of cereal rye roots prior to soybean planting had a suppressive effect on pigweed regardless of shoot application rate.

Roots are increasingly recognized as a primary source of soil C in agroecosystems, due largely to the preferential metabolism of root C by soil microorganisms (Rasse et al. 2005; Kätterer et al. 2011; Cates et al. 2016). The role of roots is amplified in no-till systems where shoots are not incorporated and decomposition is slowed due to lower oxygen levels. Under these conditions, roots are likely the primary sink for soil N in no-till systems (Gale and Cambardella 2000; Dinnes et al. 2002; Martinez-Feria et al. 2016). In contrast to the effects of cereal rye root and shoot biomass on pigweed growth and development, soybean biomass and N uptake were unaffected. This limited effect of cereal rye residue on soybean biomass and tissue N is attributed to the ability of soybean to fix N.

Conclusion

This study provides some evidence for residue-induced N immobilization as a weed suppression mechanism in mulched no-till systems, with pigweed biomass and N uptake reduced in the presence of cereal rye roots and shoots. While N immobilization likely occurred via fungal N transportation to applied cereal rye shoots, soybean uptake was a stronger sink for soil inorganic N. Soybean growth and development was unaffected by soil N availability. The positive relationship between shoot application rate and decomposition was unexpected. Greater shoot application rates may have created favorable microclimates for microbial and micro-arthropod activity, thereby increasing decomposition by improving the microclimates throughout the shoot residue layer and detritosphere. Further research is needed to directly quantify the mechanisms by which cover crop driven N immobilization limits weed growth. While shoot biomass quantity did not impact weed suppression via N immobilization, cover crop species, tillage, and soil type may influence the magnitude of a nutritive mechanism for weed suppression and requires further investigation. This is important not only for developing more cost-effective weed control methods in organic

farming systems, but also for developing integrated approaches to confronting the increasing prevalence of herbicide resistant weeds stemming from over-use of herbicides in conventional systems (Mortensen et al. 2012).

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