



## Enhanced nitrogen mineralization in mowed or glyphosate treated cover crops compared to direct incorporation

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### Abstract

Information on how management by mowing and herbicide alter residue quality and nitrogen (N) inputs would be valuable to improve prediction of N availability. Mowing and glyphosate application are widely used by growers to limit cover crop growth and facilitate incorporation. A mixture of cover crops, hairy vetch (*Vicia villosa* L.), oriental mustard (*Brassica juncea* L.) and cereal rye (*Secale cereale* L.), was investigated as a means to improve soil quality and optimize N availability. There is limited information on how mowing or glyphosate application influence cover crop decomposition and N mineralization from these heterogeneous residues. A rye cover crop was grown in the field over the winter and transferred to containers as an intact soil profile to conduct a greenhouse study. Management treatments (mowing and glyphosate) were imposed eight days before incorporation. Plant and soil N dynamics were monitored. The experiment was repeated with the addition of a tri-mixture cover crop. Inorganic  $\text{NO}_3^-$  in bare soil ranged from 6 to 10  $\mu\text{g N g soil}^{-1}$  over 39 days. Similar or lower levels of soil  $\text{NO}_3^-$  were observed after rye residue incorporation, from 2 to 6  $\mu\text{g N g}^{-1}$ ; consistent with N-immobilization. Application of untreated, mixed cover crop residues generally was associated with higher levels of soil inorganic  $\text{NO}_3^-$ , from 3 to 11  $\mu\text{g N g}^{-1}$ . For both rye and mixed residues, management by mowing or glyphosate enhanced N mineralization by 10 to 100%, compared to untreated residues. At the same time, application of mowing or glyphosate 8 days before cover crop incorporation seemed to reduce the amount of residues by about half compared to untreated controls. Belowground biomass was reduced more than aboveground, although recovery of senescent roots may have been incomplete. Management by glyphosate or mowing enhanced soil inorganic N availability in the short-term while simultaneously reducing carbon and N inputs.

### Introduction

Predicting the effect of management on residue nitrogen (N) mineralization could enhance synchronization of N supply and crop demand. Environmental conditions, crop and soil management all influence the rate of N mineralization from indigenous soil N and added organic sources. Residue quality is known to play a key role in controlling rate of N release (Swift et al., 1979). Residues with high carbon to N ratios are generally associated with relatively slow N release rates, due to N immobilization and limited soluble carbon

(C) to support microbial activity (Trinsoutrot et al., 2000). Mechanical and chemical management could alter the quality and quantity of residue incorporated, which will influence N inputs and mineralization.

Research has frequently focused on species differences in residue quality without taking into account management of the plant (Biederbeck et al., 1996; Rosecrance et al., 2000). Information on management effects would be valuable to improve prediction of N availability, as mowing and herbicide applications are widely used to check cover crop growth and facilitate incorporation. A survey of Michigan potato growers indicated that the most common cover crop management practice was to spray glyphosate about one week

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before incorporation (Snapp et al., 2001). Cereal rye (*Secale cereale* L.) is widely grown as a winter cover crop, and 55% of potato growers use tillage or mowing combined with glyphosate application to check rapid spring growth of rye. In a comparison of organic and conventional systems mowing and tillage intensity enhanced N mineralization in hairy vetch (Drinkwater et al., 2000). Chemical control by glyphosate will cause root senescence and desiccation of tissues (Carlson and Donald, 1988), which is expected to influence N mineralization.

Forage research has shown that although biomass quantity is reduced, tissue quality is enhanced by frequent mowing, as the younger tissues associated with regrowth have higher N content (Harris and Hesterman, 1990). Similarly, mowing can markedly increase root turnover, as shown in alfalfa (Goins and Russelle, 1996). Defoliation will generally stimulate regrowth of young, low C:N tissue that is higher quality than mature tissues. This could enhance short-term N release while reducing long-term N inputs in mowed cover crops, compared to a directly incorporated cover crop. Further research is required as this hypothesis was not supported by a study of *Lolium perenne* (L.), where defoliation reduced N concentration in tissues rather than increased it (Mackie-Dawson, 1999).

Mixed cover crop systems that combine variable quality residues are being recommended to farmers, to enhance inputs of soluble C and N content (Clark et al., 1994; Mutch and Snapp, 2003). These higher quality residue could release N more rapidly, but prediction has remained challenging. Highly variable soil inorganic N was observed after hairy vetch (*Vicia villosa* Roth)-rye mixtures were incorporated (Rosencrance et al., 2000).

Modeling of residue N mineralization generally involves assumptions about homogeneous tissues (Thorup-Kristensen and Nielsen, 1998). Laboratory incubations can in some cases predict the maximum N mineralization potential (Cabrera et al., 1994; Honeycutt, 1999), although underestimation also occurs compared to N mineralization observed in the field (Sanchez et al., 2002). To improve model and assay prediction capacity, information is needed on level and timing of N mineralization from mixed cover crop residues that are subjected to chemical and mechanical management.

Our objectives were to: (1) evaluate the effect of cover crop management by mowing or glyphosate application on residue quality and quantity of biomass and N inputs; (2) determine the consequences for in-

organic soil N and (3) compare an aerobic laboratory N mineralization potential assay with N mineralization measured in a container study.

## Materials and methods

The same general protocol was used in both experiments. Cover crop plants were grown over the winter in the field so that the plants were subject to realistic environmental stress and produced tissues with appropriate quality characteristics. Crop-soil profiles were extracted intact and transferred to containers in a greenhouse to allow uniform environmental conditions during cover crop treatment, incorporation and subsequent monitoring.

A representative alfisol soil from Montcalm county was chosen, a Montcalm loamy sand from the Montcalm Research Farm located near Stanton, MI (43° 20' N; 85° 01' W). This is the largest potato production area in Michigan, where winter cover crops are widely grown (Snapp et al., 2001). Initial soil characteristics were measured at 5 randomly chosen locations within a 50 m square site, 20 composite samples per location taken on May 4, 2001 from the 0–19 cm depth with a 1 cm diameter core sampler. Soil was dried and ground to pass a 2-mm sieve and processed by A&L Laboratories (Fort Wayne, Indiana) where particle size analysis was conducted by the hydrometer method after dispersing soil in 1% sodium hexametaphosphate. Organic carbon was measured by a modified Walkley-Black procedure (Snapp, 1998). Soil texture ranged from a sand content of 76–85% (average 80%) and a silt content of 8 to 14% (average 11%). Organic carbon levels varied across the site from 0.4 to 1.0% (average 0.6%).

### Experimental design

In experiment 1, three management treatments were imposed: no treatment, mowing and glyphosate applied to a cereal rye (*Secale cereale* L. var. Wheeler) cover crop 8 days before residue incorporation. Experimental design was a randomized complete block with 8 replications per treatment: 2 replications at destructive harvest at time –8 (when management treatments were imposed) and 2 replications at destructive harvest 8 days later, at time 0, when residues were incorporated. The remainder 4 replications per treatment were used to monitor soil after incorporation of cover crops. In addition, four bare soil containers that had no cover

crops were maintained under the same conditions and monitored to evaluate indigenous soil N mineralization, thus 3 cover crop treatments  $\times$  8 replications plus 4 bare soil = 28 containers.

In experiment 2, two cover crops (a trimixture [25% (*Vicia villosa* L.), 25% oriental mustard (*Brassica juncea* L.) and 50% rye] and rye) were evaluated in a complete factorial with the three management treatments used in experiment 1. Three replications  $\times$  2 cover crops were harvested at time -8d, 3 replications  $\times$  2 cover crops  $\times$  3 management systems were harvested at time 0, and 4 replications  $\times$  6 treatments were monitored after incorporation in addition to 4 bare soil containers =  $6+18+24+4 = 52$  containers.

#### *Experiment 1 – Collection of cover crop-soil profiles*

On May 4, 2001 soil profiles were collected intact from a field of winter cover crop cereal rye. Flat-sided shovels were used to delineate a 19 cm deep section of soil with the length by width dimensions of 41 by 27 cm. The profiles were transferred to 17 L plastic tubs with the same dimensions as the soil profile that were used as large pots with drilled drainage holes. The soil bulk density of the containers was  $1.05 \text{ gm cm}^3$ . The rye cover crop was counted and thinned to a plant population density of  $290 \text{ m}^2$ , being careful to remove the shallow roots, crown and shoot of thinned plants with minimal disturbance. Very few plants had to be thinned (0 to 3 per container), which minimized the impact of any roots that remained behind from thinned plants.

The containers were transferred to a greenhouse at East Lansing, MI and allowed to equilibrate for four days before cover crop management treatments were imposed. Greenhouse temperature was set to  $25 \text{ }^\circ\text{C}$  during the day and  $20 \text{ }^\circ\text{C}$  at night; a cooling and heating system kept the temperature within  $\pm 2 \text{ }^\circ\text{C}$  of the set temperature. Irrigation was used to keep plants and bare soil treatments to approximately 20–30% of soil water depletion from field capacity level, where soil water potential was monitored through tensiometers placed at a 15 cm depth.

*Cover crop management and monitoring.* Three types of cover crop management were imposed on May 8<sup>th</sup>, 2001: (1) a mowing operation where all plants were cut within 1 cm of the soil surface; (2) a spray with commercial grade glyphosate [recommended dose of 0.35 mg a.i. per plant] and (3) no treatment. Eight days later, plants were incorporated

completely to 19 cm, using a weeding implement to mimic the effects of a chisel plough.

Above and below ground biomass was quantified at the time of treatment (d -8) and at the time of cover crop incorporation (d 0) by conducting destructive measurements of the replicate containers. Senescent and living tissue was included in the harvested and incorporated materials. Shoots were cut from the root at the soil surface and fresh weights determined before drying in an oven at  $60 \text{ }^\circ\text{C}$ . Dry weights were determined after residues came to a constant weight. Root systems were rinsed off the sandy growth media using a 13 mm screen to recover the major portions of roots, and then passing the soil in the container through a wet-sieve system using deionized water and tweezers to recover roots (separating roots from organic debris) off a #16 seed sieve (Snapp et al., 1995). Roots were carefully rinsed and patted dry with paper towels to remove excess water, then all root material was weighed. Dry weight of the root system was determined after drying at  $60 \text{ }^\circ\text{C}$ , as described for shoots. To measure root length density at treatment and at incorporation, two 1-cm diameter soil cores were taken to an 18 cm depth in each container, soils were wet-sieved as described for destructive harvest soils. A sub-sample of roots recovered was used for N determination and the remainder of the root sample was stored in 5% ethanol solution to preserve the root structure. The fresh weight ratio of sub-samples and total samples were used to estimate the total weight and root length of the sample. The roots were imaged and length analysed through the use of a scanner and the WinRhizo<sup>®</sup> program.

Nitrogen analysis was conducted after grinding dried root and shoot material to pass a 1 mm mesh sieve. Sample N concentration was determined using the total Kjeldahl N digestion procedure (Bremner and Mulvaney, 1982), where N content was calculated from tissue N concentration and dry weight.

*N mineralization potential incubations.* Soil samples were taken at 0, 5, 10 and 20 days after treatments were applied, two cores per container on each sampling date (1-cm diameter cores by 18-cm depth) were composited into one and stored in plastic bags at  $4 \text{ }^\circ\text{C}$ . Samples were processed within 48 h. Soil inorganic N ( $\text{NH}_4^+$  and  $\text{NO}_3^-$ ) was extracted at each time point with 1N KCl (Keeney and Nelson, 1982). Samples were shaken at 180 rpm for 30 min and sieved through #1 Whatman filter paper (moistened first with 1 N KCl to remove possible nitrate contamination). Inorganic N

( $\text{NH}_4^+$ ,  $\text{NO}_3^-$ ) was determined in extracts by colorimetric methods using an autoanalyzer (Lachat Instruments Inc., Milwaukee, WI), as described by Keeney and Nelson (1982). Three time periods for N mineralization potential (NMP) aerobic assays were conducted for sub-samples of soil (10 g) incubated at 70% water holding capacity at 25 °C for 30, 70 or 110 days (Klute, 1986). Net N mineralization was calculated using the difference between inorganic N content at day 0 of the incubation and at the end of the incubation period or the final sampling in the container.

#### *Experiment 2*

A second greenhouse experiment was conducted starting April 20, 2002 to test the impact of management on a trimixture of cover crops [25% hairy vetch (*Vicia villosa* L.), 25% oriental mustard (*Brassica juncea* L.) and 50% rye] compared to a monoculture of cereal rye. These two cover crop systems will be referred to as 'mixture' and 'rye'. A randomized complete block experimental design was used to compare the three management treatments (no treatment, mowing and glyphosate) for two cover crops, the mixture and rye. Treatments were applied as in experiment 1, eight days before biomass was incorporated. Replications for the two destructive harvests (one at the treatment time –8 days and the other at incorporation, time zero) were increased from 2 containers per treatment to 3 containers, as described under experimental design.

Soil collection involved slightly larger containers than those in experiment 1, 40 × 32 × 19 cm depth (17.9 L). After crop-soil profiles were transferred to containers, cover crops were thinned to a plant population density of 290 m<sup>2</sup>. In the trimixture the final plant population density was 50% rye: 25% hairy vetch and 25% oriental mustard. Biomass accumulation over the eight days from treatment until incorporation was calculated by subtracting initial biomass at treatment from the final biomass at incorporation. Soil sampling was conducted as in experiment 1, with the addition of a soil collection time at 39 days after residue incorporation.

#### *Statistical analysis*

A one-way analysis of variance was conducted in experiment 1 to evaluate cover crop management effects on biomass and N content at incorporation. A two-way analysis of variance was conducted in experiment 2 to evaluate cover crop type (rye *versus* mixed) and management effects on biomass and N content changes

between treatment and incorporation, as well as biomass and N content at incorporation. Treatment means with standard deviations were calculated as well. A repeated measures analysis of variance was used to evaluate treatment effect on inorganic N levels in soil over time, and changes in NMP over time.

## **Results**

### *Cover crop biomass and nitrogen*

Rapid accumulation of biomass occurred in untreated control cover crops over the eight day period between application of management treatments and incorporation. Dry weight of rye (root plus shoot) at the time treatment was applied was 270 g m<sup>-2</sup> in 2001 and 350 g m<sup>-2</sup> in 2002, whereas dry weight of the mixed cover crop in 2002 was 370 g m<sup>-2</sup>. Biomass increased to 520–630 g m<sup>-2</sup> in controls over 8 days, where a similar pattern of root and shoot biomass accumulation occurred both years (Figure 1). Incomplete recovery of senescent root and shoot tissues in treated cover crops may have contributed to apparent reduction in biomass of treated cover crops compared to biomass at time 0, when the treatment was applied. Thus the large difference at incorporation between biomass of untreated controls and biomass of mowing or glyphosate treatments may be overestimated, given the difficulty of fully recovering senescent root biomass in particular. For the measurable biomass, there was a highly significant reduction associated with glyphosate and mowing treatment, compared to untreated cover crops (Figure 1; *P*-value = 0.001).

Shoot biomass was lowest in glyphosate-treated rye cover crops, 80 g m<sup>-2</sup> compared to 200 g m<sup>-2</sup> in untreated rye (Figure 1A and B). Root biomass of glyphosate-treated plants was decreased markedly as well, 115 g m<sup>-2</sup> compared to 320 g m<sup>-2</sup> in control plants. Mowing had an intermediate effect on biomass accumulation in both cover crops. In a parallel manner to the effect of glyphosate, mowing consistently reduced root growth (Figure 1C). This was reflected in reductions in total root dry weight. Further, there were marked reductions in the root length density at incorporation of mowed rye and mixed cover crops (1.4 cm cm<sup>-3</sup>; 1.6 cm cm<sup>-3</sup>, respectively), which was significantly lower (*P*-value 0.04) than root length density of control rye and mixed cover crops (1.8 cm cm<sup>-3</sup>; 1.9 cm cm<sup>-3</sup>, respectively). Note that root length density methodology recovers primarily

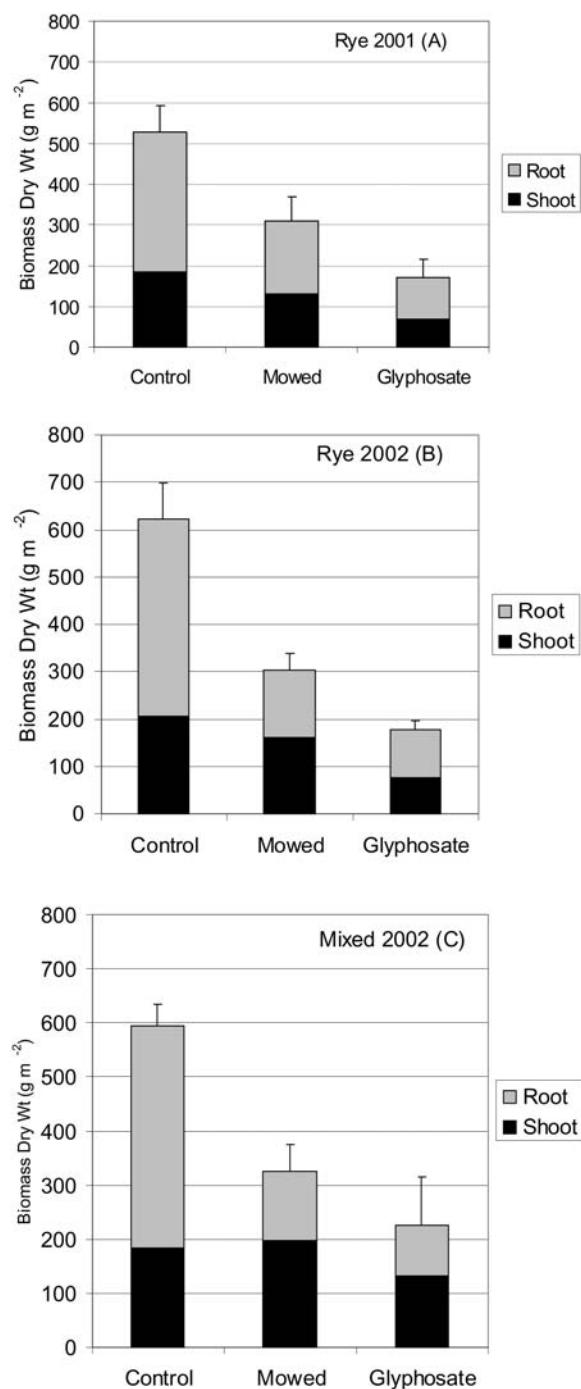


Figure 1. Root and shoot biomass of cover crops at incorporation, eight days after treatment (control = untreated; mowed; glyphosate), bar represents standard deviation of total biomass. A) Rye biomass in experiment 1; B) Rye biomass in experiment 2; C) Mixed cover crop (Rye-Hairy vetch-Oriental mustard) biomass in experiment 2.

live roots, thus this measurement may underestimate N inputs from senescent tissue.

Nitrogen inputs generally reflected the biomass accumulated in each treatment, although not closely for mowed treatments (Table 1). Data from experiment 1 was highly variable, but followed similar patterns to experiment 2 (data not shown). As expected from the presence of legumes, higher N levels were associated with the mixed cover crop compared to monoculture rye (Table 1). The residues of mowed, mixed cover crops included young, new tissues as well as more mature and senescent tissues at incorporation, with a slightly higher N concentration overall compared to untreated mixed cover crop tissues (Table 1).

#### Soil N dynamics

Soil nitrate levels increased gradually over time, whereas the soil ammonium-N pool size stayed constant (Figure 2). This is shown for experiment 1. The same pattern was seen in experiment 2, so ammonium and nitrate data were combined as inorganic N, to simplify presentation (Figure 3). Nitrogen mineralization at 20 days was higher in experiment 1 compared to experiment 2, possibly due to slightly younger plant material and higher N content of rye tissue in experiment 1. Overall the response to cover crop management treatment was similar in both experiments, where N mineralization was higher for rye managed by glyphosate or mowing compared to untreated rye.

A consistent pattern was observed across different management treatments for rye residues: inorganic N levels were highest about 3 weeks after residue incorporation (Figures 2A and 3A). Inorganic N levels increased more rapidly for the mixed cover crop, reaching close to maximum levels by day 10 (Figure 3B). This was similar to the pattern seen with bare soil inorganic N, although absolute levels were almost 50% higher with mixed cover residues.

Amendment with untreated rye residues was generally associated with lower soil inorganic N levels than bare soil at most observation points, indicating that N immobilization occurred (Figure 3A). Net N mineralization as indicated by soil inorganic N levels and N mineralization potential was higher after day 5 in soil amended with a mixed cover crop compared to soil amended with a rye cover crop (Figure 3; Figure 4). This may be due to the higher N concentration of residues in the mixed cover compared to the rye cover (Table 1). It is also possible that soluble C levels were higher in the mixed cover crop residues, provid-

*Table 1.* Cover crop nitrogen content at incorporation. Average N concentration and content of root and shoot tissue in experiment 2 at incorporation (standard deviation in parentheses). Cover crops are rye and a mixed cover (Rye-Hairy vetch-Oriental mustard), management treatments are control, mowing and glyphosate applied eight days before incorporation

		N concentration (%)	Root and shoot N content at incorporation (g m <sup>-2</sup> )	Total N input at incorporation
<b>Control</b>				
Rye	Shoot	1.7 (0.3)	3.48 (0.6)	5.15
	Root	0.4 (0.1)	1.67 (0.3)	
Mix	Shoot	2.3 (0.2)	4.23 (0.4)	9.15
	Root	1.2 (0.6)	4.92 (1.5)	
<b>Mowing</b>				
Rye	Shoot	2.4* (0.7)	4.01 (1.1)	4.72
	Root	0.5 (0.1)	0.71 (0.1)	
Mix	Shoot	2.9* (0.9)	5.90 (1.6)	7.57
	Root	1.3 (0.4)	1.67 (0.5)	
<b>Glyphosate</b>				
Rye	Shoot	1.6 (0.3)	1.21 (0.2)	1.62
	Root	0.4 (0.1)	0.41 (0.1)	
Mix	Shoot	2.3 (0.3)	3.05 (0.7)	4.08
	Root	1.1 (0.3)	1.03 (0.4)	

\*Weighted average of %N in 8-day-old surface residues remaining from mowing operation and %N in new growth.

ing an energy source to support faster decomposition, but this was not tested.

At 20 days after incorporation, nitrate-N was two-fold higher in soil amended with glyphosate-treated residues compared to bare soil, in Experiment 1 (Figure 2A). A similar trend was observed in experiment II, although both glyphosate and mowing treatments were associated with higher soil inorganic N levels, in the range of 10–14  $\mu\text{g N g}^{-1}$  (Figure 3A). This is compared to 6–10  $\mu\text{g N g}^{-1}$  in soil that was not amended or that was amended with an untreated cover crop.

Total N mineralised in a 70 day aerobic incubation is presented as an estimate of what would be available over the growing season (Figure 4). In general, cover crop treatments that enhanced the soil inorganic N pool had a comparable effect on soil NMP. The trends were similar for 100, 70 and 30 day assays of NMP. Across all management treatments, average NMP-30 day was 30  $\mu\text{g N g}^{-1}$  for soil amended with mixed covers, with the highest NMP-30 day (36  $\mu\text{g N g}^{-1}$ ) observed for mowed covers (significantly higher than untreated control,  $P$ -value = 0.03). The average NMP-30 day was 23  $\mu\text{g N g}^{-1}$  for soil amended with rye.

The higher NMP observed for soil treated with mixed cover crop residues may be due to higher N tissue concentration, or to ~50% higher organic-N inputs from roots and shoots of mixed cover compared to rye (Figure 4).

## Discussion

### *Cover crop biomass and N*

In the control, rapid growth of cover crops occurred over the 8 days between treatment and incorporation. High rates of biomass and N accumulation have been observed previously at similar temperatures, where shoot biomass doubled over two weeks in cowpea (Franzluebbers et al., 1994). Mowing greatly reduced biomass, though there was moderate vegetative regrowth in the mowed treatment (Figure 1). Application of glyphosate induced senescence and markedly reduced biomass. This is consistent with grower practice: mowing and glyphosate are used by growers to reduce the amount of residue biomass and facilitate incorporation (Snapp et al., 2001). As has

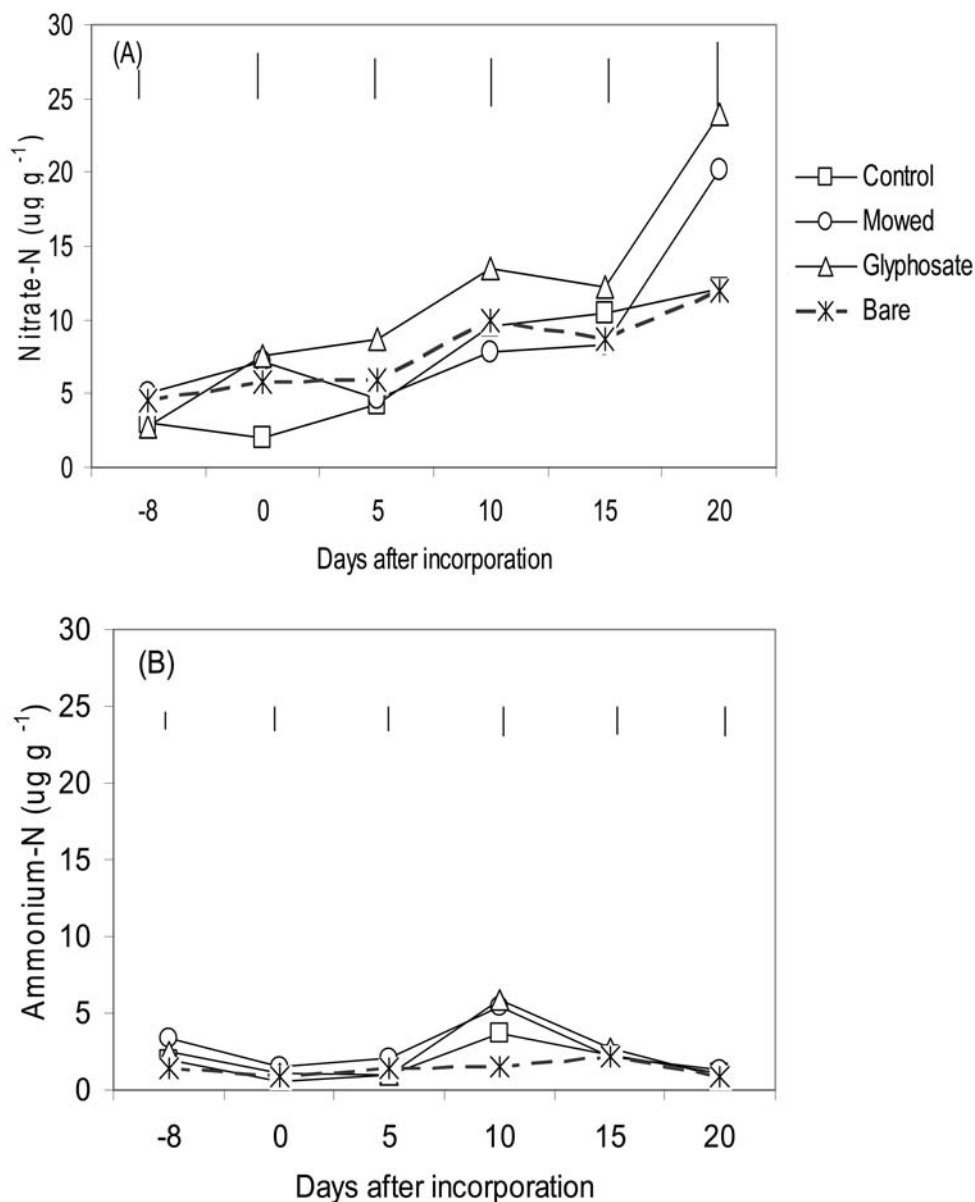


Figure 2. Soil inorganic N ( $\mu\text{g g}^{-1}$  soil) over time in experiment 1 containers, bars represent  $\text{LSD}_{0.05}$ . A) Nitrate-N before and after incorporation with control (untreated), mowed and glyphosate-treated cover crops, compared to bare soil. B) Ammonium-N reported, treatments as described in A.

been found previously, rye senescence was rapid with glyphosate whereas growth inhibition of the rye:hairy vetch:mustard mixed cover crop was more moderate (Figure 1C), reflecting species difference in tolerance to glyphosate (Vaughan and Evanylo, 1998). Hairy vetch is a species somewhat tolerant to glyphosate injury and frequently growth is not completely inhibited (Clark et al., 1994); accumulation of biomass reflected this.

The primary effect of management treatments on N inputs appeared to be through the inhibition of growth, either through a temporary reduction associated with mowing, or a permanent cessation of growth with glyphosate applied to rye. Overall, glyphosate-treated rye had the lowest amount of N inputs from roots and shoots at  $1.6 \text{ g m}^{-2}$ , twenty percent of the N incorporated with control rye (Table 1). This may be under-representative of the N inputs, as senescent tis-

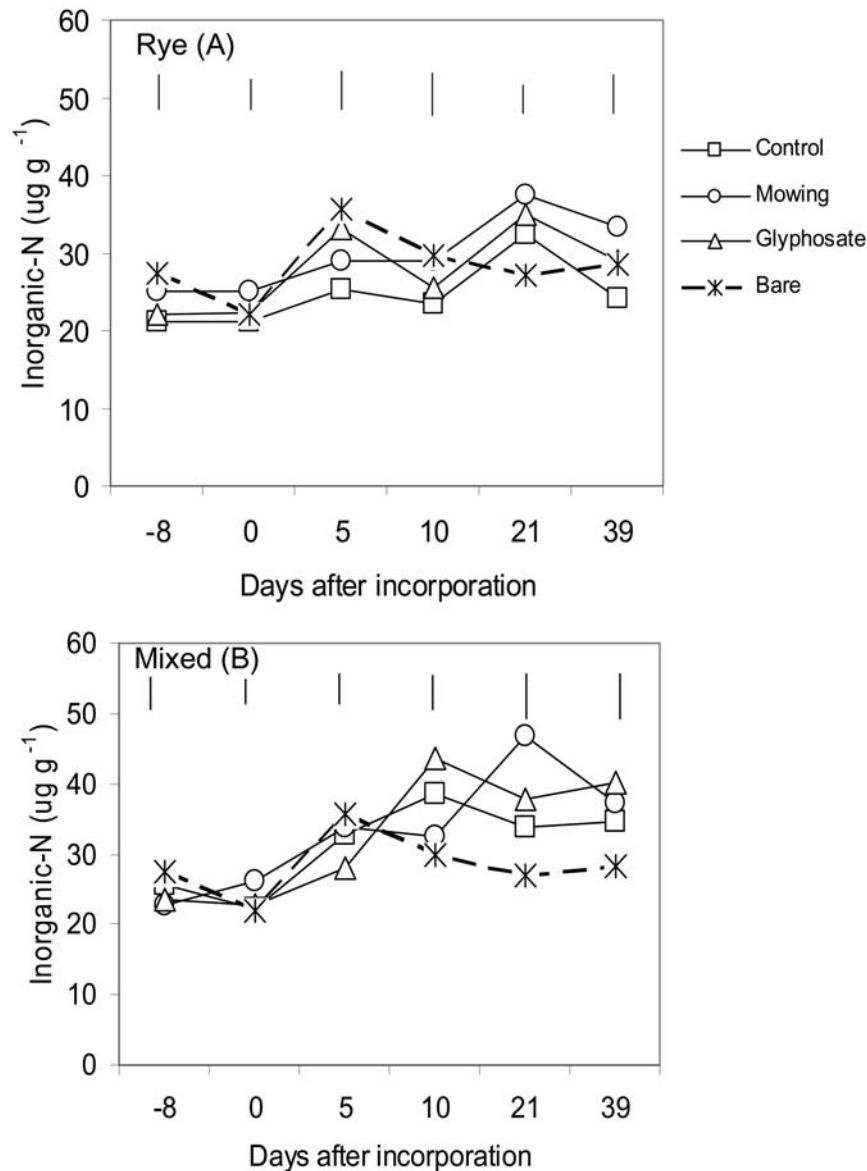


Figure 3. Soil inorganic N ( $\mu\text{g g}^{-1}$  soil) over time in experiment 2 containers, bars represent  $\text{LSD}_{0.05}$ . A) Inorganic N ( $\text{NH}_4^+$  and  $\text{NO}_3^-$ ) before and after incorporation with control (untreated), mowed and glyphosate-treated rye cover crop, compared to bare soil. B) Treatments as described in A, for a mixed cover crop (Rye-Hairy vetch-Oriental mustard).

sues of glyphosate-treated cover crops were difficult to completely recover. Most of the reduction of N inputs associated with management treatments in the mixed cover crop was a result of reduced root biomass.

We found that root growth was dramatically reduced by glyphosate compared to shoot growth (Figure 1), both in terms of biomass accumulated below-ground and root length density. This is presumably related to the mode of action of glyphosate through inhibition of root enzymatic activity and growth (Carl-

son and Donald, 1988). Interestingly, mowing was also associated with a significant reduction in root biomass. This may be due to feedback from shoot removal that induces root senescence. Mowing has been shown previously to reduce root biomass by sixty-five to forty percent in sweetclover; the extent depending on the height of the remaining shoot (Schmidt et al., 2001). Root biomass was dramatically reduced in defoliated *Lolium* as well (Makie-Dawson, 1999). It should be noted that root growth of untreated controls

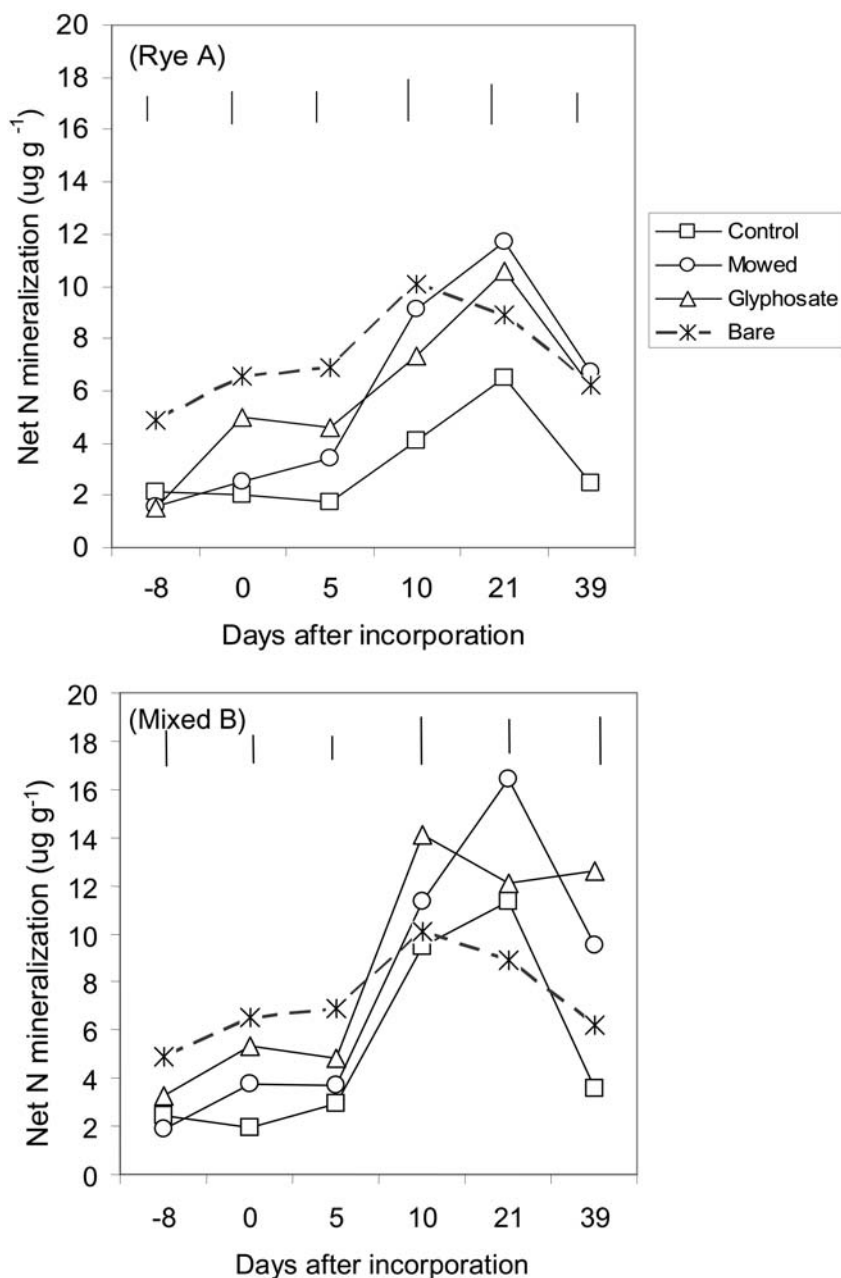


Figure 4. Net soil inorganic N ( $\mu\text{g g}^{-1}$  soil) mineralization 70 day aerobic incubation of soil sampled over time in experiment 2 containers, bars represent  $\text{LSD}_{0.05}$ . A) Rye cover crop treatments are control (untreated), mowed and glyphosate, compared to bare soil. B) Treatments as described in A, for a mixed cover crop (Rye-Hairy vetch-Oriental mustard).

was rapid, which may have been induced in part by the warm ( $\sim 25$  °C) temperature in the greenhouse. Root growth is generally enhanced by warm soil temperatures (McMichael and Burke, 1996); however, all of the cover crop treatments were subjected to the same soil temperature environment.

Investigating root response to cover crop management is important to understanding long-term effects of management practices on soil organic matter. Recent field studies that trace labelled N and C from alfalfa and hairy vetch indicate that root systems are major contributors to soil C and N pools, to a greater

extent than shoot biomass (Puget and Drinkwater, 2001; Rasse et al., 1999). The marked reductions in cover crop root biomass we observed with mowing and glyphosate management treatments could have long term consequences for soil organic matter, as soil C pools are influenced by cover crop inputs.

Mowing treatment altered residue N content, presumably through stimulating re-growth of young tissue that was high in N. The C:N ratio of shoot residues was reduced from 26 in control rye to 19 in mowed rye residues that contained both senescent and vegetative tissues. This small change in tissue N content could alter N release dynamics as previous research has shown that a C:N ratio of 20 to 23 can be the approximate dividing line between N immobilization and release (Cabrera et al., 1994; Honeycutt, 1999). However, there are many other factors that influence N mineralization than C:N ratio, including biochemical tissue characteristics such as lignin content and physical accessibility of residues to soil microorganisms (Honeycutt, 1999; Trinsoutrot et al., 2000).

#### *Soil N dynamics*

Overall, the pattern of N mineralization observed here (Figures 2A and 3A) followed that of an oat and rye root decomposition study (Malpassi et al., 2000). Three weeks after residue incorporation, soil inorganic N status was at a maximum in both experiments. This was similar to the pattern observed by Malpassi and colleagues.

The C:N ratio of residues was generally related to N release rates in our experiments. No difference was found between soil inorganic N levels between bare soil and soil amended with untreated rye residues in experiment 1. However, soil inorganic N levels and N mineralization potential both indicated that N immobilization occurred with the incorporation of control rye in experiment 2 (Figures 2A and 3A). In untreated rye residues, shoot tissue had a C:N ratio of 26 and a root C:N ratio of 100; which is consistent with earlier observations of N immobilization following incorporation of tissue with a C:N ratio wider than 23 (Honeycutt, 1999). Similarly, in a soil core assay, rye tissue was associated with N immobilization whereas a rye-hairy vetch mixture was associated with moderately higher N mineralization of  $\sim 1 \text{ mg N day}^{-1}$  (Rosecrance et al., 2000). A mixture of red clover and corn residues was associated with 40 to 90% higher net N mineralization compared to corn residues (Sanchez et al., 2001). We observed 20 to 80% higher net N

mineralization at 21–30 d after incorporation of a rye-hairy vetch-mustard mixture compared to rye alone (Figure 3). Hairy vetch-rye bicultures have higher N mineralization compared to rye alone, even when hairy vetch residues contributed a relatively small amount of biomass to the total mixture (Clark et al., 1994; Vaughan and Evanylo, 1998).

Nitrogen mineralization was also influenced by management treatments. This was not surprising for the mowed treatment, as the C:N ratio of shoot residues 8 days after mowing was 19, compared to 26 in control rye. Desiccation of residues and root degradation induced by glyphosate treatments may have enhanced microbial access to residue constituents and thus increased the rate of N mineralization, compared to residues from untreated cover crops. In a field study that examined timing of glyphosate application rye residues that were desiccated weeks before incorporation were associated with greater N release compared to rye residues desiccated later (Vaughan and Evanylo, 1998).

Sanchez and colleagues (2001) evaluated N mineralization potential for a long-term cropping system trial in southern Michigan using the same aerobic incubation assay as in our study. A similar trend was observed here: the cover crop treatment with mixed quality residues was associated with approximately 30% higher N mineralization over a 70 d incubation compared to that associated with a monoculture cereal cover crop (Figure 4). However, total N mineralised after 70 and 100 days was approximately forty percent lower in our study compared to that observed by Sanchez et al. (2001). This could be due to differences in cover crop inputs, which were approximately 50% lower in our study. This is because we investigated 5-month winter season cover crops, compared to frost-seeded in March red clover which had 9 months to grow in the Sanchez study. Soil and environmental characteristics may also contribute to the differences observed, as soil organic C was 0.8% in our study and approximately 20% higher in the Sanchez study.

The NMP technique is widely used by researchers to predict N release (Sanchez et al., 2001; Stanford and Smith, 1972). Insight into the relationship of the incubation assay to soil nitrogen mineralized in the containers is thus of general interest. In the second experiment it is possible to use a similar time-frame and compare the 30 day aerobic NMP assay of soils sampled on day 10 after residue was incorporated (NMP-30<sup>10</sup>) to N mineralization measured on day 39 of the container study (Table 2). The NMP-30<sup>10</sup> as-

Table 2. Soil inorganic N from experiment two is presented for 39d after incorporation (Nmin39d), for a 30d aerobic assay of soil 10d after incorporation (NMP30<sup>10d</sup>) and for a 100d aerobic assay of soil 10d after incorporation (NMP-100<sup>10d</sup>). Means are presented and least significant difference (LSD<sub>0.05</sub>) for cover crop management treatment

	N min 39d	NMP30 <sup>10d</sup>	NMP-100 <sup>10d</sup>
Rye cover		$\mu\text{g g}^{-1}$	
Control	24	19	24
Mowed	33	27	33
Glyphosate	29	20	28
Bare	29	25	28
LSD <sub>0.05</sub>	3.9	1.5	1.7
Mixed Cover			
Control	34	29	34
Mowed	38	30	38
Glyphosate	39	33	40
Bare	29	25	28
LSD <sub>0.05</sub>	4.3	1.2	1.5

say was associated with the same relative treatment effects, showing its value in predicting treatment effects on N mineralization. However, the NMP-30<sup>10</sup> assay had an absolute lower level (16 to 27% less) of N mineralized compared that measured in the container on day 39 (Nmin 39d). Interestingly, the 100 day NMP assay of soil sampled day 10 was closely related to Nmin 39d in the container (Table 2). In our experiment, enhanced stimulation of N mineralization occurred in container soil compared to the incubation assay. This may have been due to the continuing presence of decomposing shoot and root tissues, compared to sieved soil used for NMP laboratory incubations.

In a study that compared N<sup>15</sup> mineralization from ground hairy vetch residues applied to field soil and to soil in a laboratory incubation, N mineralization was similar in both cases (Honeycutt, 1999). However, the vast majority of laboratory incubations are based on using sieved soils, which may remove decomposing residues. Similar to our findings, other field studies have found that relatively long laboratory NMP incubation times of 70 to 150 days may be required to predict field mineralization (Sanchez et al., 2001). Laboratory incubations are conducted under ideal environmental conditions for mineralization and are frequently assumed to represent the maximum possible mineralization rate (Stanford and Smith, 1972). Our experience indicates that laboratory assays may lack substrate, or due to other factors, under-represent

mineralization rates that are observed *in situ*. Recent research points to the critical role of rhizodeposition in enhancing the active C pool and as an energy source to support microbial activity; a source lacking in laboratory incubations (Sanchez et al., 2002).

## Conclusions

Treatment of rye through mowing or application with glyphosate before incorporation markedly enhanced N mineralization, while reducing the total amount of N incorporated compared to untreated cover crops. Reduced root biomass through growth inhibition or induced root death was largely responsible for lower N inputs from treated cover crops compared to untreated cover crops. Reduced root inputs could impact soil organic matter formation. Improving residue N content by planting a mixed cover crop in place of rye achieved substantially higher N mineralization and higher N input from residues, compared to rye grown alone. We also found that a NMP laboratory incubation assay did not appear to provide an optimal environment for mineralization, as it required a 100 day incubation period to predict 39 day *in situ* mineralization in the container.

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