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Conservation Agriculture Practices Increase Potentially Mineralizable Nitrogen: A Meta-Analysis

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Potentially mineralizable nitrogen (PMN) is considered an important indicator of soil health. Cropping systems management can affect PMN. However, the effect size and relationship with crop yield across specific management practices remain uncertain. We conducted a quantitative review to understand how conservation agriculture management practices affect PMN including N fertilizer application, cropping system diversity, and tillage system as well as the relationship of crop yield with PMN. Data were extracted from 43 studies published in peer-reviewed journals, providing 494 paired comparisons of PMN and 26 paired comparisons of PMN and yield across selected crop management practices. In our meta-analysis, the effect size for each management practice was expressed as a response ratio, calculated as PMN or yield for the fertilizer application, high crop diversity, and no-till system to the no-fertilizer, less diverse crop system, and tillage system. On average, N-fertilized cropping systems had greater PMN: compared to no N fertilizer, inorganic N fertilizer had 22%, and manure had 34% higher PMN. Diverse cropping systems also had greater PMN: three or more different crops in rotation had 44% greater PMN than continuous cropping systems; cropping systems with a leguminous cover crop had 211% greater PMN than systems without cover crops. Compared to till systems, no-till systems had 13% higher PMN. Overall, conservation practices consistently increased both PMN and yield; however, the increase in PMN and yield were not correlated. Consistent with the use of PMN as a soil health indicator, this synthesis demonstrates that practices benefiting PMN also benefit yield.

Keywords

Potentially mineralizable nitrogen, Conservation agriculture, No-till, Fertilizer, Crop diversity

Disciplines

Agriculture | Agronomy and Crop Sciences | Soil Science

Comments

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Conservation agriculture practices increase potentially mineralizable nitrogen: a meta-analysis.

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Abstract

Potentially mineralizable nitrogen (PMN) is considered an important indicator of soil health. Cropping systems management can affect PMN. However, the effect size and relationship with crop yield across specific management practices remain uncertain. We conducted a quantitative review to understand how conservation agriculture management practices affect PMN including N fertilizer application, cropping system diversity, and tillage system as well as the relationship of crop yield with PMN. Data were extracted from 43 studies published in peer-reviewed journals, providing 494 paired comparisons of PMN and 26 paired comparisons of PMN and yield across selected crop management practices. In our meta-analysis, the effect size for each management practice was expressed as a response ratio, calculated as PMN or yield for the fertilizer application, high crop diversity, and no-till system to the no-fertilizer, less diverse crop system, and tillage system. On average, N-fertilized cropping systems had greater PMN: compared to no N fertilizer, inorganic N fertilizer had 22%, and manure had 34% higher PMN. Diverse cropping systems also had greater PMN: three or more different crops in rotation had 44% greater PMN than continuous cropping systems; cropping systems with a leguminous cover crop had 211% greater PMN than systems without cover crops. Compared to till systems, no-till systems had 13% higher PMN. Overall, conservation practices consistently increased both PMN and yield; however, the increase in PMN and yield were not correlated. Consistent with the use of PMN as a soil health indicator, this synthesis demonstrates that practices benefiting PMN also benefit yield.

Keywords: *Potentially mineralizable nitrogen; Conservation agriculture; No-till, Fertilizer; Crop diversity*

Highlights

- Conservation agriculture practices benefit PMN
- Optimum N fertilizer inputs benefit PMN, but low and excessive N fertilizer does not
- Legume cover crops benefit PMN, but non-legume cover crops do not
- Crop rotations with ≥3 crops benefit PMN, but simpler rotations do not
- No-till has greater PMN than chisel and moldboard plow
- Conservation practices consistently increased both PMN and yield; but the increase in PMN and yield were not correlated.

1. Introduction

In fertile soils with high soil organic matter (SOM) content, the mineralization of SOM nitrogen (SOM-N) is a major source of N for crop uptake and has been positively associated with crop yield (Stevens et al., 2005; Gardner and Drinkwater, 2009). As a result, researchers have suggested that knowledge about the fraction of SOM-N susceptible to mineralization may help to optimize N fertilizer management (Franzluebbers, 2016). This fraction of SOM-N, commonly referred to as potentially mineralizable nitrogen (PMN), is defined as SOM-N that is converted to plant-available inorganic forms under laboratory incubations that control temperature, moisture, aeration and time. Because PMN measures the release of plant-available N, it has been proposed as an indicator of soil quality and is included in contemporary assessments of soil health (Gregorich et al., 1994; Moebius-Clune et al., 2016). However, cropping system management strategies that can improve soil quality may not have consistent effects on PMN.

In agricultural systems, PMN is indirectly managed through cropping system management practices such as fertilizer application, cropping system diversity, and tillage. The rational application of these practices, often referred to as conservation agriculture, aims to maximize sustainable production of agricultural systems. Although several studies have evaluated the effects of individual crop management practices on PMN, general patterns of the response have not been examined or connected to crop yield. Information about the response of PMN to conservation agriculture practices could aid research that aims to link PMN with crop yield, N fertilizer demand, and soil health (Franzluebbers, 2016).

At present, the effect of N fertilizer application on PMN and SOM is actively debated (Poffenbarger et al. 2017). Fertilizer application affects the amount and quality of crop residue production, which is mostly incorporated into the soil and therefore affects PMN. Nitrogen fertilization almost always increases the amount and quality of crop residue (Brown et al. 2014; Poffenbarger et al. 2017), which can build SOM thereby increasing PMN. However, N fertilizer may also increase SOM mineralization by relieving microbial N limitation, which can decrease SOM thereby decreasing PMN (Pikul et al. 2001; Mack et al. 2004; Russell et al. 2009).

Crop diversity, which can be increased with the number of cash crops in rotation or the inclusion of non-cash crops (e.g., cover crops) may affect PMN through a number of processes. An increase in the number of crops in rotation is typically accompanied by changes in soil management strategies and crop growth habits (Davis et al., 2012). In general, cropping systems with greater rotational diversity include more organic fertility sources such as manures and legumes as well as more crops with high root inputs such as small grains and alfalfa (Campbell et al., 1991; Davis et al. 2012). In addition to crop rotation diversity, cover crops, grown between cash crops when the field would otherwise be fallow, can also increase cropping systems diversity (Thorup-Kristensen et al., 2003). Well-grown cover crops produce large amounts of residue and retain or add nutrients by scavenging inorganic N, reducing erosion, and fixing atmospheric N (Tonitto et al., 2006; Hoorman et al., 2009; Liu et al., 2015). Combinations of legume and non-legume cover crops are particularly effective because they combine the benefits of N fixation with N scavenging and biomass production (Sainju et al., 2005).

Tillage systems can affect PMN due to impacts on crop growth, residue incorporation, and SOM decomposition. No-till soil management can reduce erosion of nutrient-rich surface soils and increase surface SOM by accumulating crop residue on the soil surface, altering root growth, and reducing mechanical disruption of soil aggregates (Angers and Eriksen-Hamel 2008; Paustian et al., 1997; Six et al., 1999; Baker et al., 2007). In contrast, moldboard plowing fully inverts the tillage layer, moving aboveground residue downwards and belowground residue upwards while chisel plowing loosens surface soils, increasing soil-residue contact. The effects of tillage systems on SOM decomposition vary with the duration of no-till and depth of analysis, potentially resulting in contradictory reports about tillage effects on SOM dynamics (e.g., Six et al. 2004; Baker et al. 2007).

Maintenance or improvement of SOM is considered to be a critical response to the implementation of these conservation agriculture management strategies (Reicosky, 2003; Franzluebbers, 2016) and PMN is positively associated with SOM because covalent bonds among organic C and N inseparably link C and N mineralization (Ros et al., 2011; Drinkwater et al., 1996). Nevertheless, the overall response of PMN to conservation agriculture practices has not been determined or linked to yield. Our objectives were to: 1) examine the effect of various conservation agriculture practices on soil PMN, and 2) determine if these practices had consistent effects on PMN and crop yield. We hypothesized that conservation agriculture practices increase PMN and crop yield.

2. Materials and Methods

2.1 Comparisons using meta-analysis: In our analysis, we prioritized three crop management practices: i) organic and inorganic N fertilizer addition, ii) cropping system diversity (crop rotation and cover crops), and iii) no-till systems. These were compared with suitable controls which were part of the experimental design and were established with treatments at the time of experiment set up (i.e., treatments and controls were established in the same year). The controls changed depending on the selected crop management practices and were defined as no fertilizer addition, continuous cropping system, no cover crops, and tillage systems (chisel and moldboard plow). Potentially mineralizable N data were extracted from the studies in which a treatment group could be compared with a control group with all other factors unchanged. If studies included subfactors within the management practices, such as N fertilizer rate or the number of crops in the rotation, we compared these treatments against the control as well.

2.2 Database sources and treatment: An extensive literature search was performed using Web of Science with the search terms "soil N mineralization OR Potentially Mineralizable Nitrogen NOT forest NOT tree" which resulted in 6,665 studies published before the cut-off date of 1st July 2014. However, many of these studies were not relevant (described above) in the context of this paper or were not found to include sufficient information regarding soil, crop management or crops. A search was also performed using Google Scholar, but no additional studies were found relevant to our analysis. From those studies, conference abstracts and studies not providing quantitative results were rejected. Finally, 43 studies were considered relevant to include in the meta-analysis. These studies provided 494 observations for selected crop management practice effects on PMN and 26 observations for PMN and yield relationship.

Relevant data were extracted from each study including crop type, fertilizer type and rate, cover crop, tillage system, and duration of the experiment in years. Additional information recorded was incubation method, soil sampling time, soil sampling depth, soil type (texture), pH, bulk density, SOM, soil organic carbon (SOC), soil total nitrogen, nitrate, and ammonium concentrations, mean annual temperature and precipitation, crop yield, and state and country where the study was conducted. In instances where relevant information was not given, soil information was taken from the Web Soil Survey (Soil survey staff, 2015) and efforts were made to contact the lead authors for additional data. When data was only provided in graphic format, DataThief III (Tummers, 2006) was used to extract relevant data points. In a meta-analysis, the individual variance for a study is required for weighting the means and including the uncertainty from individual studies in the uncertainty of weighted means. In most of the studies, standard error or standard deviation were not provided, therefore, field experimental design and number of replications were extracted from the study to calculate the weightage factor (see equation [3] in Data Analysis section).

The PMN results were converted, when necessary, to mg N per kg of dry soil. Bulk density and soil depth were used to convert the units from mass of N per unit of ground area to mass of N per unit mass of soil for studies related to tillage systems. For fertilizer application rate comparisons, the recommended fertilizer rate for that particular cropping system was considered the "optimum". All rates lower than the optimum were considered "low", and all higher rates were considered "high". For soil depth comparisons, the average depth of soil cores was calculated and was recorded as "average soil depth" for each observation. This was considered to be the preferred way to obtain the soil depth effect on PMN for all tillage system studies. To avoid over- or under-representation of certain studies, only the growing season data were used from studies where sampling was conducted throughout the year at the same site. A summary of the studies can be found in the supplementary section (Supplemental Table S1).

2.3 Analysis of data quality: All the data included in the database were extracted from peer-reviewed journal articles and one thesis (Lazicki, 2011, subsequently published as a peer-reviewed article (Lazicki et al. 2016)). In the articles, net N mineralization data were derived from aerobic or anaerobic laboratory incubations where standard methods were used for designing and conducting the experiments. Experimental designs were 33% randomized complete block design, 24% split plot, 16% split-split plot or block and 9% completely randomized design. Eighteen percent of the studies did not report the experimental design.

2.4 Data analysis: The effect size was expressed as a ratio between the PMN or yield with the defined treatment to PMN or yield of the defined control of that management practice (Hedges et al., 1999):

$$\mathrm{RR} = \frac{\text{treatment}}{\text{control}} \qquad [1]$$

The response ratio (RR) for each study was natural log transformed for normality.

$$\mathrm{LRR} = ln\ (\mathrm{RR}) \qquad [2]$$

Since most studies did not provide enough data to extract a standard deviation for each mean, we applied weights by following the method used by Pittelkow et al. (2015), using the reported number of replications.

$$w = \frac{NC\ *\ NT}{NC +\ NT} \qquad [3]$$

where NC is the replications of the control and NT is the replication of the treatment.

The homogeneity among LRR values from all the studies was analyzed. The data were analyzed for outliers by plotting each observation against the natural log of the response ratio and a box plot (Figure 1).

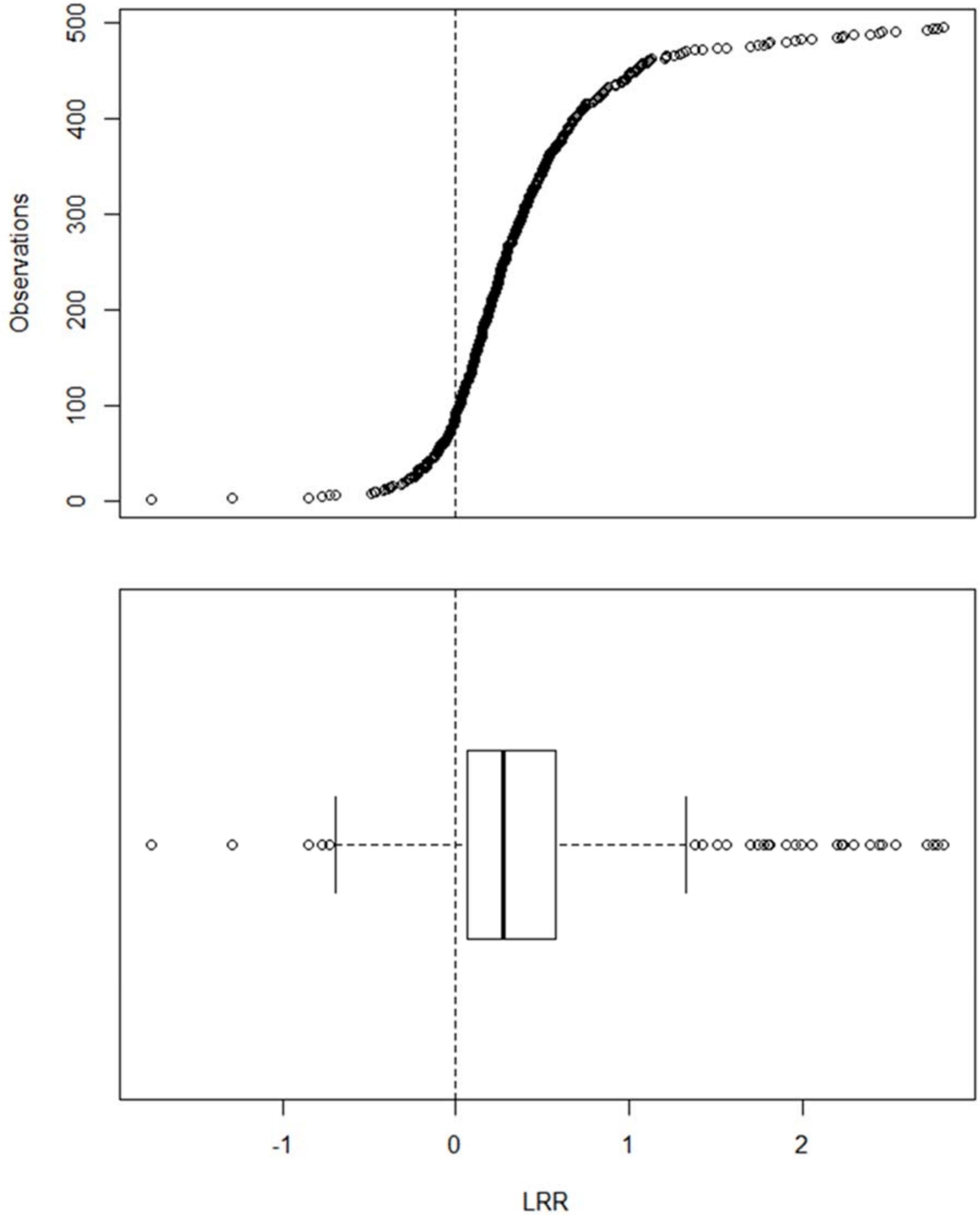

Figure 1. Natural logarithm of the potentially mineralizable nitrogen response ratio [ln(PMN of treatment/PMN of control)] (LRRi) for each observation included in the meta-analysis.

The variable weights were forced to add up to 1:

$$W_i * = \frac{W_i}{Sum(W_i)} \quad [4]$$

Weighted analysis of variance was used to compare mean response ratio for different management practices and treatments. The statistical model used for crop management practices was:

$$L_{ij} = \mu + s_i + M_j + e_{ij} \quad [5]$$

where L_{ij} is the natural log of the response ratio of the i^{th} study with j^{th} level of crop management practices, μ is the overall mean, s_i is the random effect due to the i^{th} level of study, M_j is the fixed effect of j^{th} level of crop management practices, and e_{ij} is the residual error. Next, a second series of analyses of variance was performed for the categorical variables within each crop management practice using the statistical model:

$$L_{ijk} = \mu + s_i + M_j + C_k + MC_{jk} + e_{ijk} \quad [6]$$

where L_{ijk} is the natural log of the response ratio of the i^{th} study with j^{th} level of crop management practices, μ is the overall mean, s_i is the random effect due to the i^{th} level of study, M_j is the effect of j^{th} level of crop management practices, C_k is the effect of k^{th} level of sub factor (categorical variable within j^{th} level of crop management practices), MC_{jk} is the interaction effect of j^{th} level of crop management practices with k^{th} level of sub factor, and e_{ijk} is the residual error.

A meta-regression analysis was performed to analyze data for the effect of continuous variables such as the duration of the management practice and the soil depth. The statistical model used for regression analysis was:

$$L_{ijk} = \beta_o + s_i + M_j + \beta_1 R_k + \beta_2 MR_{jk} + b_i R_k + e_{ijk} \quad [7]$$

where L_{ijk} is the natural log of the response ratio of the i^{th} study with j^{th} level of crop management practices, β_o is the overall intercept across all studies, s_i is the random effect due to the i^{th} level of study, M_j is the effect of j^{th} level of crop management practices, R_k is the effect of k^{th} level of sub factor (continuous variable within j^{th} level of crop management practices), β_1 is the regression coefficient for continuous variable R_k, MR_{jk} is the interaction effect of j^{th} level of crop management practices with k^{th} level of sub factor, β_2 is the regression coefficient for the interaction $M_j \times R_k$, b_i is the random effect due to the i^{th} level of study on regression coefficient β_1 and e_{ijk} is the residual error.

The relationship between PMN and crop yield was determined by using the following linear regression model:

$$YRR_i = \beta_o + s_i + \beta_1 RR_i + e_i \quad [8]$$

where YRR_i is the response ratio of crop yield of the i^{th} study, β_o is the overall intercept across all studies, s_i is the random effect due to the i^{th} level of study, β_1 is the regression coefficient for PMN response ratio of i^{th} study (RR_i), RR_i is the response ratio of PMN, and e_i is the residual error.

All statistical analyses were conducted with R (version 3.4.2). Significant difference between treatments was considered if p values < 0.05. Bootstrapping procedures were used to generate 95% confidence intervals for weighted mean effect sizes using 500 iterations. Results were considered significant for the effect of the treatment compared with the control, if the confidence intervals did not overlap with zero log response ratio (or, response ratio =1). For ease of interpretation, all results were back transformed to response ratio of treatment to control. Percent difference between treatment and control was calculated by subtracting 1 from response ratio and multiplying the result by 100.

3. Results

Potentially mineralizable N responded positively to all conservation agriculture practices. On average, systems with N fertilizer application had 44% greater PMN than systems with no N fertilizer application. An increase in crop rotation diversity from one to two or two to three or more cash crops was associated with 46% higher PMN. However, the addition of cover crops had a greater impact; PMN was 104% higher in cropping systems with a cover crop in comparison to cropping systems without a cover crop (although the positive effect was limited to legume cover crops). In contrast, tillage system had relatively little effect on PMN; no-till had 13% higher PMN as compared to the cropping systems with tillage (Figure 2).

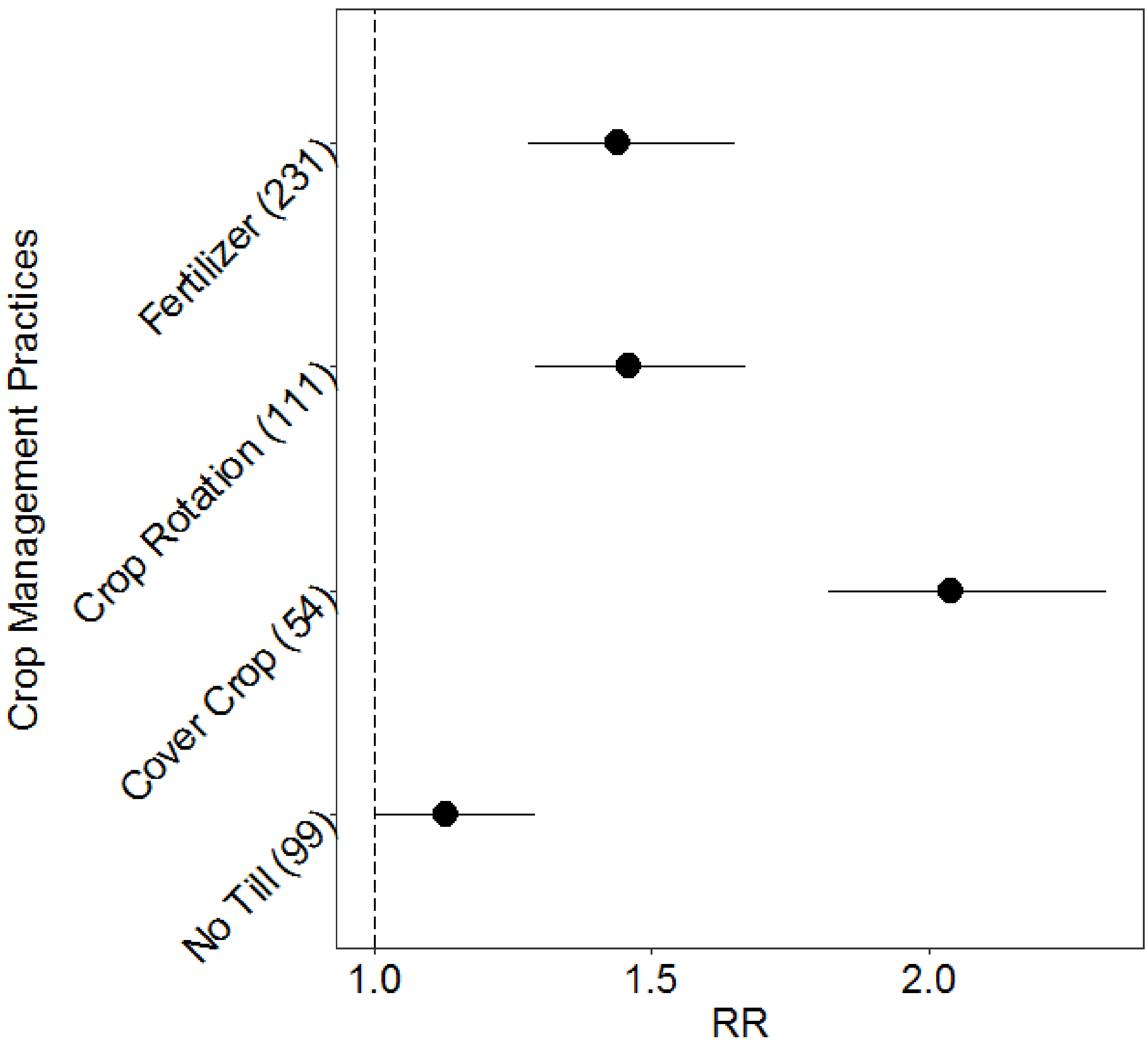

Figure 2. Mean response ratio (RR) [PMN of treatment/PMN of control (without treatment)] and 95% confidence interval (horizontal bars) for four different crop management practices. The number of observations is displayed in parentheses.

A very limited number of studies provided PMN and crop yield data: two tillage studies, three fertilizer, three crop rotation and one cover crop study. Together, these nine studies included 26 comparisons. No significant differences were found among the effect size of crop management practices on crop yield (p= 0.13). However, within each crop management practice, cropping systems with N fertilizer had 37% higher crop yield than cropping systems with no N fertilizer. Crop rotation and no-till had no effect on crop yield when high diversity cropping systems were compared to less diverse systems and no-till systems were compared to systems with tillage. In this dataset, just one cover crop study reported PMN and crop yield results (three observations), and it showed 48% higher crop yield with cover crop compared with no cover crop (Table 1).

Table 1. Mean response ratio (Yield RR) [crop yield with treatment/crop yield with control] and 95% confidence interval (LL - lower limit and UL - upper limit) for crop management practices effect on crop yield. In parentheses is the number of comparisons used for each practice.

Crop Management Practices	Yield RR	LL	UL
No-Tillage (2)	1.17	0.94	1.46
Nitrogen Fertilizer (12)	1.37	1.16	1.61
Crop Rotation (9)	1.07	0.88	1.35
Cover Crop (3)	1.48	1.35	1.63

3.1 Nitrogen Fertilizer: Potentially mineralizable N was greater in cropping systems that received N fertilizer (Figure 2). However, the effect differed with N fertilizer source. Compared to cropping systems without N fertilizer, PMN was 78% higher in systems receiving manure N, 72% higher in systems receiving a combination of manure and inorganic N fertilizer, and 52% higher in systems receiving compost N (Figure 3). Cropping systems with inorganic N fertilizer had 19% higher PMN, but the effect was not significant. There was no interaction between fertilizer type and rate (low, optimum and excessive N fertilizer rate); however, fertilizer type had a significant effect ($p = 0.02$). Compared to systems without N fertilizer, systems with inorganic N fertilizer applied at optimum rates had 22% higher PMN. However, when inorganic N fertilizer was applied at low and excessive rates, PMN was not different from systems receiving no N fertilizer. For the manure application rates compared to no manure, the effect was higher with low application rates than that for the optimum rates. The systems with excessive rates had 85% higher PMN than no manure systems, but was not significantly different from systems with low and optimum rates (Table 2).

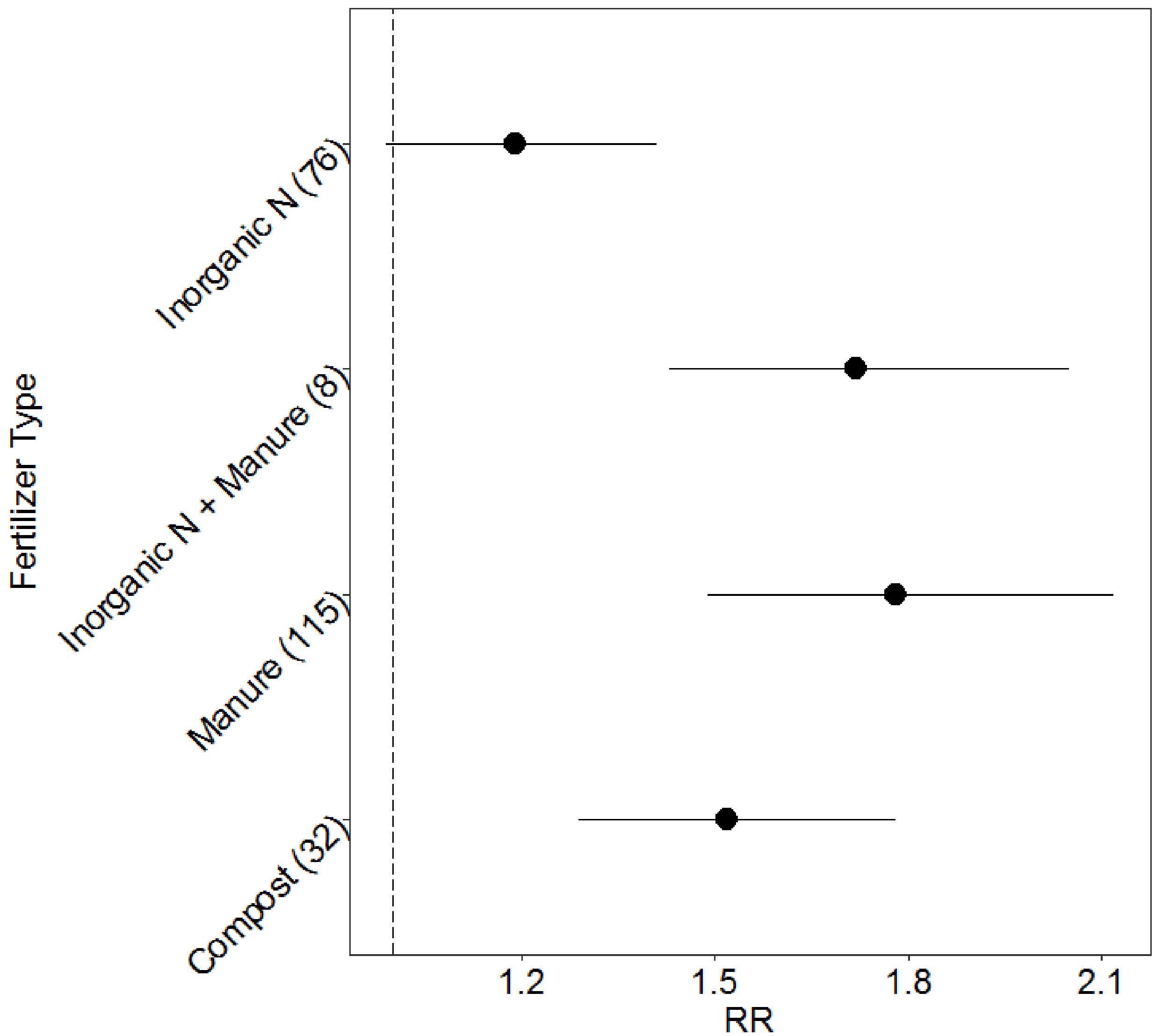

Figure 3. Mean response ratio (RR) [PMN of fertilizer type/ PMN of no fertilizer addition] and 95% confidence interval (horizontal bars) for four fertilizer types. The number of observations is displayed in parentheses.

Table 2. Mean response ratio (RR) and 95% confidence interval (LL - lower limit and UL - upper limit) for two fertilizer types and nitrogen application rates effect on PMN.

Fertilizer Type	N Rate	RR	LL	UL
Inorganic	Low	1.17	0.98	1.42
Inorganic	Optimum	1.22	1.02	1.47
Inorganic	High	1.19	0.99	1.44
Manure	Low	2.12	1.76	2.59
Manure	Optimum	1.34	1.11	1.63
Manure	High	1.85	1.54	2.23

3.2 Cropping system diversity: An increase from a single crop system (i.e., continuous cropping system) to a two-crop rotation did not affect PMN (Figure 4, Supplemental Table S2). Moreover, no effect was observed when specifically comparing PMN in corn-soybean systems to continuous corn systems. The positive effect of crop rotation was limited to the comparisons of three different crops in rotation versus continuous crop systems. PMN was 44% higher in the three-crop than in the single-crop systems. The duration of the experiment, or the number of years the crop rotation had been in practice, had no significant effect on PMN (Figure 4). The positive effect of cover crops on PMN was limited to legumes and mixed plantings including legumes (Figure 5). Compared to no cover crop, non-legume cover crops had no effect on PMN, legume/non-legume cover crop mixtures had 77% higher PMN, and legume cover crops had 211% higher PMN.

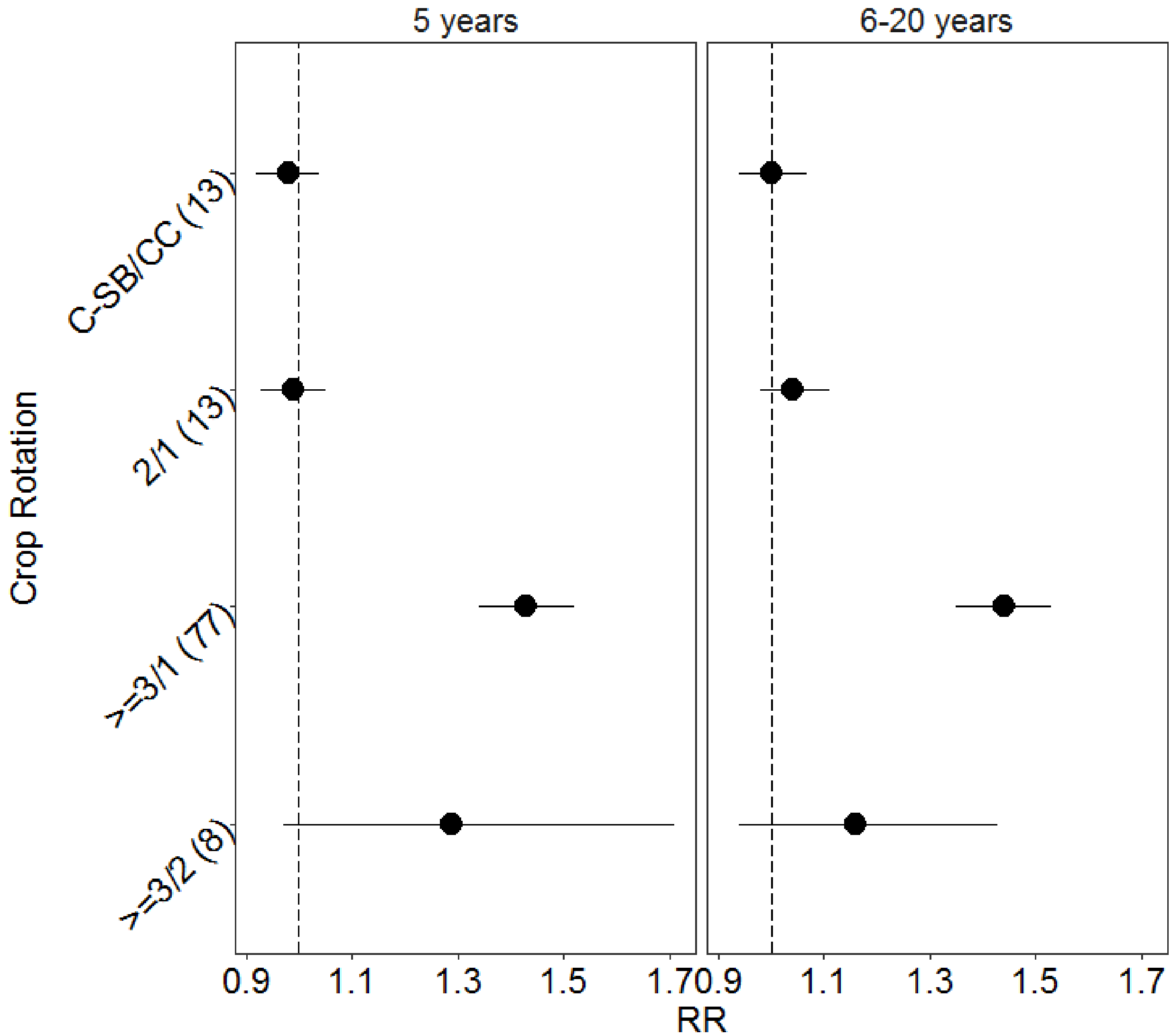

Figure 4. Mean response ratio (RR) [PMN of high diversity cropping systems/ PMN of less diverse cropping systems] of crop rotation type for 5 and 6- 20 years. Horizontal bars represent 95% confidence interval. 2/1 represents two crops in rotation versus continuous crop system, C-SB/CC represents corn-soybean rotation versus continuous corn system, >=3/1 represent three or more crops in rotation versus continuous crop system, and >=3/2 represent three or more crops in rotation versus two crops in rotation. The number of observations is displayed in parentheses.

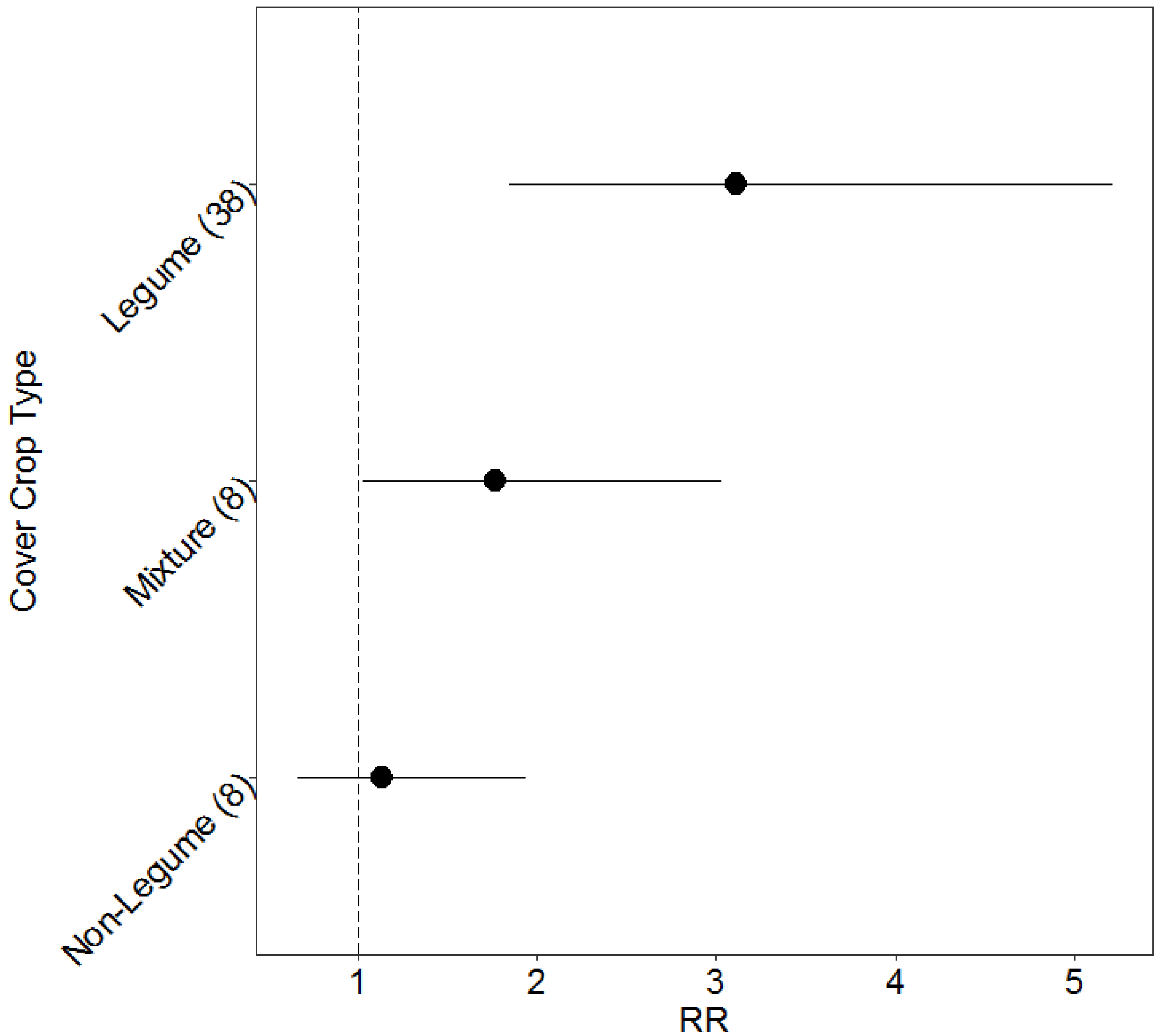

Figure 5. Mean response ratio (RR) [PMN for system with cover crop/ PMN for system without cover crop] for three cover crop types and 95% confidence interval (horizontal bars). The number of observations is displayed in parentheses.

3.3 Tillage: Overall, tillage systems differed in PMN; no-till systems had 13% higher PMN than systems with tillage (Figure 2). However, tillage types did not differ across soil depth (p = 0.99; no-till systems had on average 23% higher PMN than chisel and moldboard plow tillage systems, to an average 15 cm soil depth (Figure 6). Also, there was no effect of depth or interaction of depth with tillage type (Supplemental Table S3).

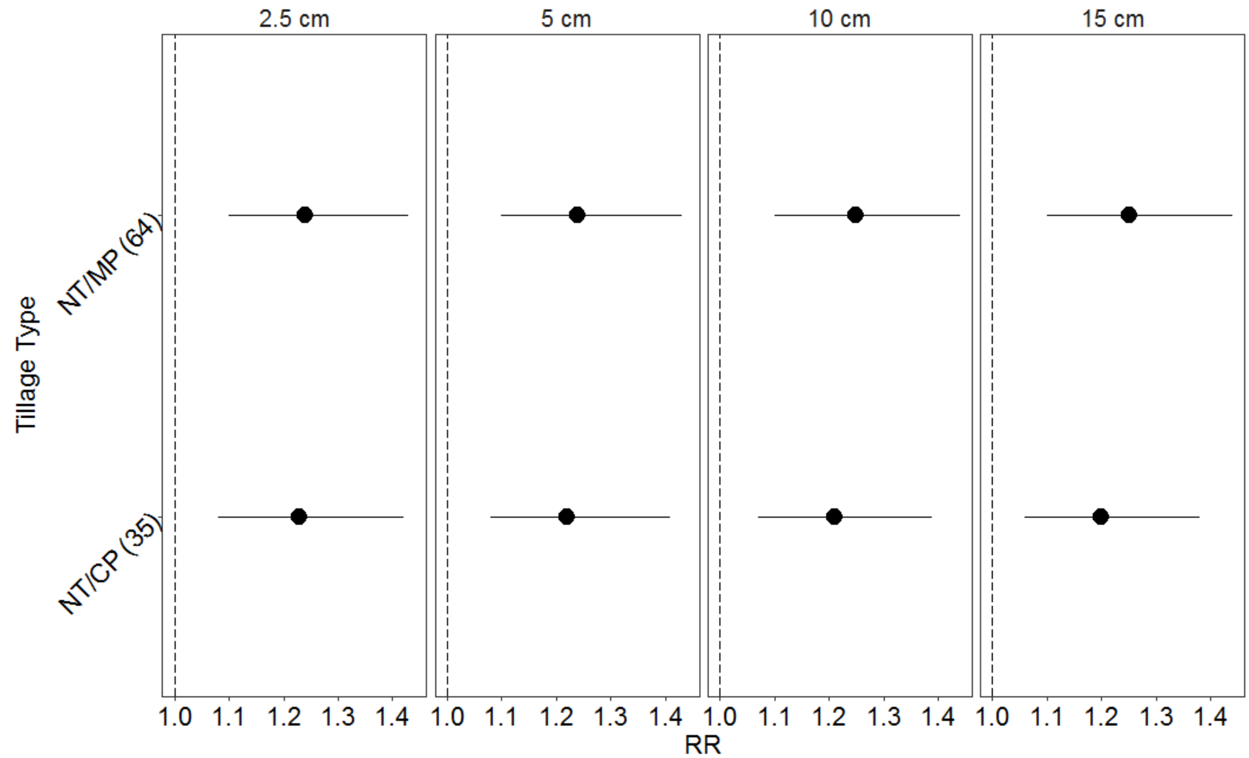

Figure 6. Mean response ratio (RR) [PMN of no-till systems/PMN of systems with tillage (chisel or moldboard plow)] of two tillage types for four depth increments. Horizontal bars represent 95% confidence interval. NT/MP represents no-till versus moldboard plow, and NT/CP represents no-till versus chisel plow. The number of observations is displayed in parentheses.

Study duration had no significant effect on the response of PMN to no-till compared with chisel and moldboard plow tillage (Figure 7). In relatively short-term 5-year comparisons, PMN was 35% higher in no-till systems than in chisel and moldboard plow tillage systems. However, in relatively long-term 15-year comparisons, PMN in no-till systems was 25% higher than in the systems with moldboard plow tillage but was not significantly different from systems with chisel plow tillage (Figure 7). In addition, there was no significant interaction between tillage type, soil depth and study duration ($p = 0.44$).

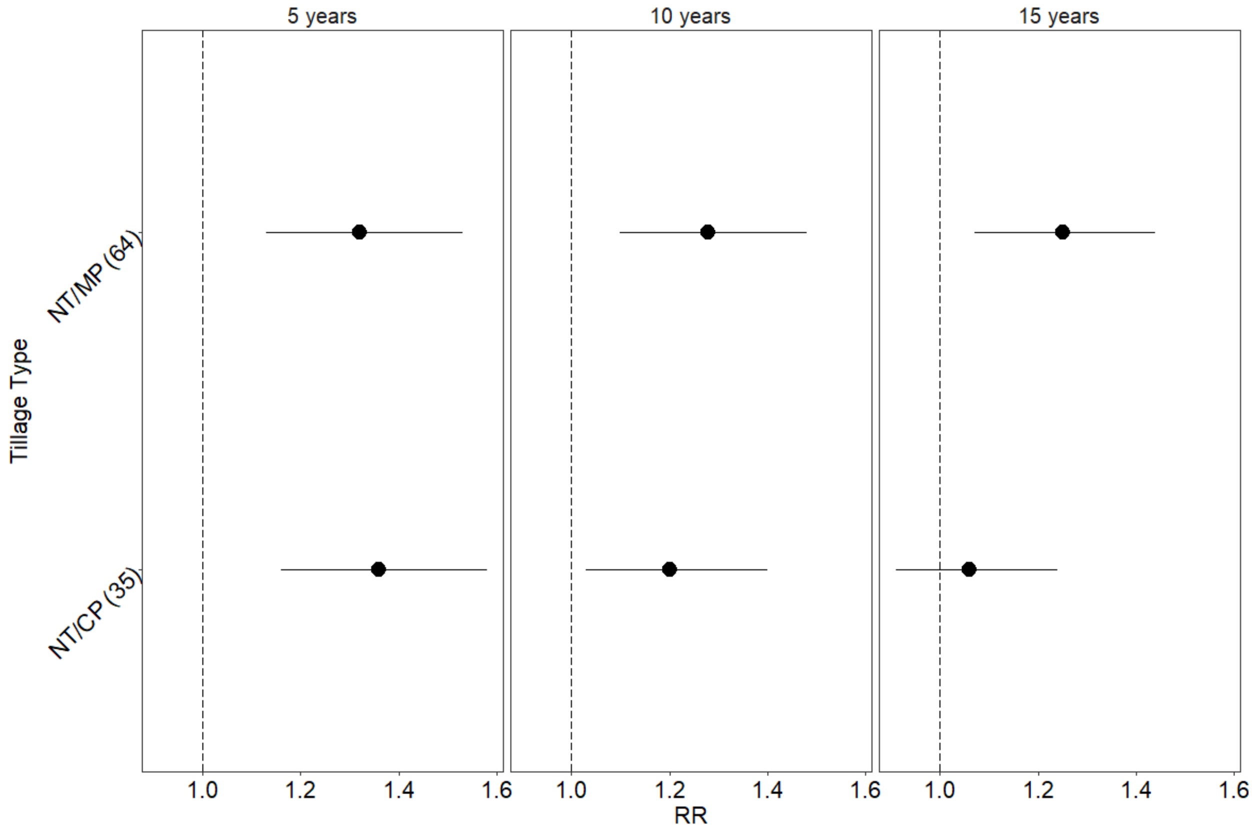

Figure 7. Mean response ratio (RR) [PMN of no-till systems/PMN of systems with tillage] of tillage types for 5, 10 and 15 years. Horizontal bars represent 95% confidence interval. NT/MP represents no-till versus moldboard plow, and NT/CP represents no-till versus chisel plow. The number of observations is displayed in parentheses.

3.4 Crop yield and PMN relationship: The crop yield response ratio and PMN response ratio were positively associated; treatments with PMN response ratio greater than 1 also had crop yield response ratio greater than 1. The only exception to this association was one data point which was related to excessive fertilizer application rate compared to no fertilizer (Figure 8). Although PMN and crop yield were associated, they were not correlated (p = 0.22, R^2 = 0.008).

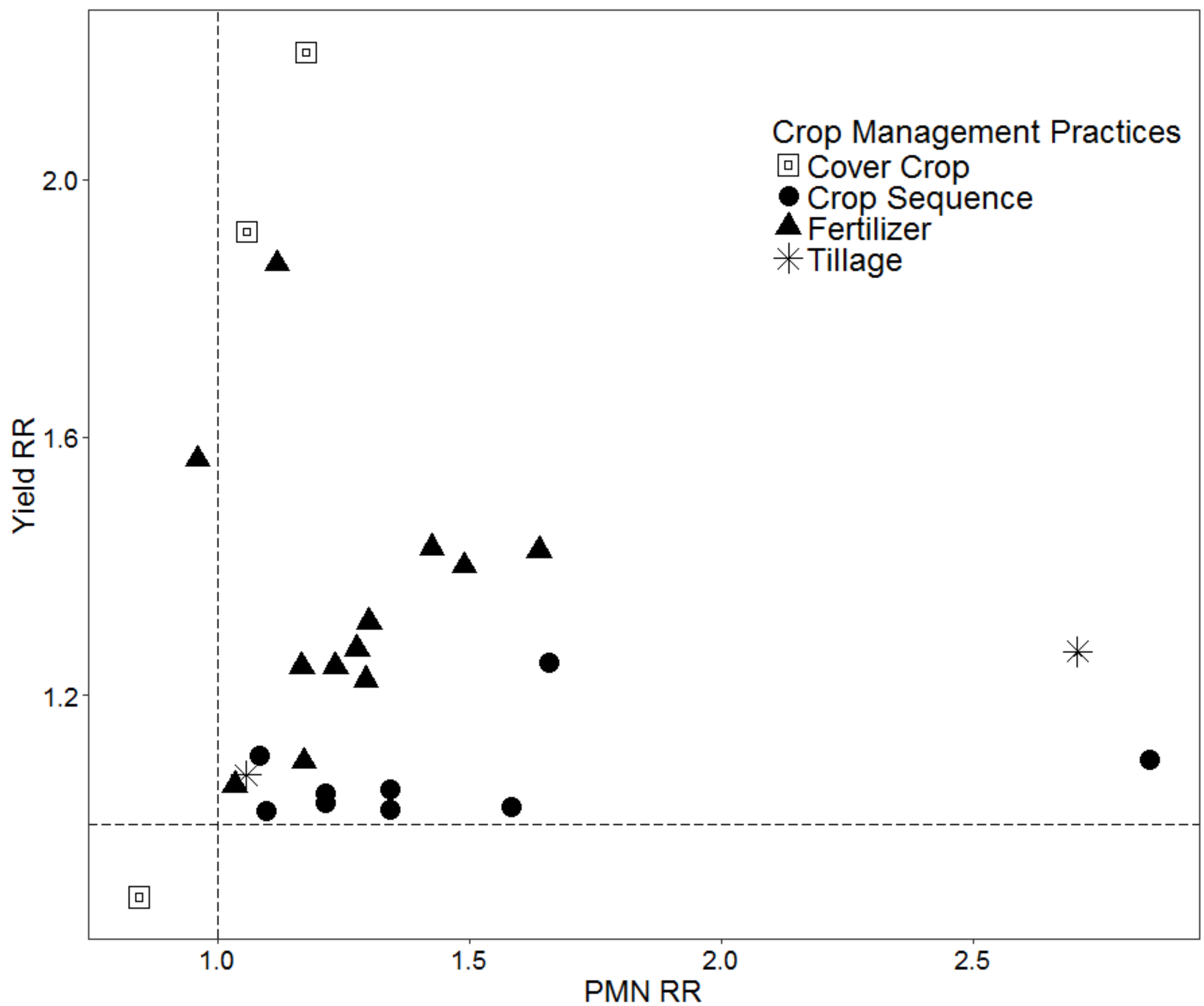

Figure 8. Yield response ratio (Yield RR) [Yield of treatment/Yield of Control] vs. potentially mineralizable nitrogen response ratio (PMN RR) [PMN of treatment/ PMN of control].

4. Discussion

Our results are consistent with the concept that PMN is an important indicator of soil quality that positively impacts crop yield (Drinkwater, 1996; Idowu et al., 2008). Although PMN and yield were not significantly correlated, conservation agriculture practices consistently increased both. Therefore, increased N supply in the conservation agriculture treatments may be one reason for the boost in crop yield. It is not surprising that the increases in yield and PMN were not correlated because PMN characterizes the potential N mineralization; in the field, weather and management control the actual rates of N mineralization (Drinkwater et al., 1996).

4.1 Nitrogen Fertilizer: The positive impact of N fertilizer application on PMN is likely due to the positive response of plant growth and crop residue input to fertilizer application (Mitchell et al., 1991; Russell et al., 2009; Ladha et al., 2011; Brown et al., 2014). However, the magnitude of the positive effect of N fertilizer on PMN varied depending on type and rate of fertilizer application (Table 2). Manure application may have a greater effect on PMN than inorganic N because manure-N input is a direct addition to the pool of PMN while fertilizer N indirectly increase the pool of PMN by increasing crop residue inputs.. The response of PMN across the range of insufficient to optimum and excessive inorganic N fertilizer input (Table 2) is consistent with the response of crop residue input and SOM across the same range of N input (Poffenbarger et al. 2017).

4.2 Crop diversity: Overall, an increase in PMN occurred with an increase in crop diversity either by increasing the number of crops in the rotation or including cover crops into the system. An increase in crop diversity typically alters crop management practices and adds different quality and quantity of crop residue to the soil. This impacts the physical, chemical and biological properties of the soil (Bennett et al., 2012). Cropping system diversification can also lead to greater total soil N and microbial biomass N as compared to continuous cropping systems (McDaniel et al., 2014). However, our meta-analysis shows that for crop rotation, a positive effect was observed only when three or more crops were compared with a continuous crop system.

There was no difference in PMN between continuous corn systems and corn-soybean rotation systems. This result supports evidence that soybeans are not net contributors of N to the soil even though N recommended for corn following corn is generally higher than that for corn following soybeans (e.g., Poffenbarger et al., 2017). The difference in corn N fertilizer requirement among these crop systems may be best viewed as a 'continuous corn penalty' (Gentry et al., 2013). Lower N fertilizer requirements in corn following soybeans likely results from lower crop residue on the soil surface and lower C:N of soybean residue, which promotes SOM mineralization (Gentry et al., 2001). Indeed, crop residue harvest in corn following corn reduces optimum N fertilizer input by enhancing SOM mineralization (Pantoja et al., 2015).

Consistent with these results, Russell et al., (2009) found that SOC accumulation is higher for systems with three crops in rotation, and the continuous corn and corn-soybean systems have similar and lower amounts of SOC than more diverse cropping systems. McDaniel et al. (2014) found the same pattern for microbial biomass. In addition, SOC accumulation was better correlated with the belowground organic matter input (from roots) as compared to aboveground residue input. Roots are in close proximity with soil microbes and minerals; therefore disproportionately impacting SOM accumulation (Rasse et al., 2005). When a third crop is added to the rotation, it is often a crop with a larger rooting system than corn or soybeans (e.g., Davis et al., 2012; Ball et al., 2005).

The lack of time since study initiation (i.e., duration) and crop rotation interaction suggests that crop rotation is a rapid approach to enhance PMN. Diversified cropping systems have a wide variety of organic inputs, which promote a diverse suite of decomposer organisms that contribute to greater soil biological activity (McDaniel et al., 2014; Tiemann et al., 2015). The greatest effect of diversity was found when we compared systems with three or more crops in rotation to continuous cropping systems because the difference between the size and diversity of the microbial community may be more pronounced for this comparison than other comparisons of crop diversity (Campbell et al., 1991; Moore et al., 2000).

The addition of legume cover crops into the cropping system had the greatest impact on PMN as compared to all other management practices. Legume and legume/non-legume cover crop mixtures can affect PMN in a number of ways. McDaniel et al., (2014) observed an increase in total soil C and N for systems with cover crops compared to no-cover crop systems. Cover crops extend the primary productivity period, which reduces the N losses from the system and provides additional residue input, which can increase SOM and PMN (Tonitto et al., 2006; Moore et al., 2014). The non-legume cover crops retain N in the system, whereas legume cover crops retain N in the system and add N to the system from atmospheric fixation. Moreover, legumes produce crop residues that rapidly mineralize (Tonitto et al., 2006; Kramberger et al., 2014).

4.3 Tillage: No-till systems can build or maintain SOM in the surface soil by increasing the residue cover, altering the energy balance, and reducing erosion losses (Baker et al., 2007). In contrast, chisel and moldboard plows loosen surface soil and promote SOM mineralization, which can reduce SOM content. Unfortunately, soil sampling in the moldboard plow tillage system studies included in our meta-analysis was limited to the plow layer (0- 30 cm); whereas tillage system can affect the distribution of SOM by altering soil compaction and root distribution to a much deeper depth. In addition, shallow sampling could underestimate the soil N supplying capacity due to transportation and accumulation of soil N below the plow layer (Angers and Eriksen-Hamel, 2008 and Baker et al., 2007).

4.4 Crop yield and PMN: It is notable that 24 of 26 observations fall in the positive quadrant (1st quadrant), which means that the conservation practices increased PMN and yield (Figure 8). However, the lack of a statistical correlation between increase in PMN and yield may be due to the fact that yield depends on the actual mineralization that takes place in the field instead of PMN which is a laboratory potential. Soils with similar amounts of PMN can have very different N mineralization depending on the specific environmental conditions (Drinkwater et al., 1996). The PMN is a laboratory estimation of the fraction of soil N that could be mineralized, but soil moisture and temperature control actual N mineralization during the growing season. Potentially mineralizable N is necessarily different from the actual N mineralized in the field or plant available N, which correlates with the crop yield but not with soil total N or PMN (Drinkwater et al., 1996).

5. Conclusions

Consistent with the use of PMN as a soil health indicator, this meta-analysis provides a sound basis for the potential of conservation agriculture practices to benefit both the PMN and crop yield. Our meta-analysis shows that conservation practices have the potential to increase PMN in the surface soil. However, it also indicated that not all the conservation practices provided similar benefits to PMN. Non-leguminous cover crop systems when compared to systems with no cover crop, and no-till system as compared to chisel plow tillage systems in the long-term provided no clear benefit to PMN. In addition, this analysis showed that PMN and crop yield were not correlated, although they were positively associated. A limitation of this analysis was that only 16% of the studies reported crop yields and therefore we were not able to relate PMN with crop yield for individual crop management practices. In the future, additional analyses that report both PMN and crop yield will be required to directly link laboratory measurements of PMN to crop production.

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Supplemental Material

Supplemental Table S1 Summary of studies included in the meta-analysis. Supplemental Table S2 Analysis of variance and mean response ratio for crop diversity effect on PMN. (2/1 – two crops in rotation versus continuous cropping system, >=3/1 – three or more crops in rotation versus continuous cropping system and >=3/2 – three or more crops in rotation versus two crops in rotation). Supplemental Table S3 *F* and *P* values for tillage type and soil depth effect on PMN in a mixed model regression analysis (NT/MP - no-till versus moldboard plow and NT/CP - no-till versus chisel plow). Mean response ratio for tillage type and soil depth effect on PMN.

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Supplementary Information

Conservation agriculture practices increase potentially mineralizable nitrogen: a meta-analysis.

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Table S1. Summary of studies included in the meta-analysis.

Management Practice	Publication	Year	Location	Methods
Tillage	Doran	1980	Kentucky, Minnesota, W. Virginia, Nebraska, Oregon	Air dried soil, aerobic incubation and leaching
	El-Haris et al.	1983	Washington	Air dried soil, aerobic incubation, leaching, non-linear regression
	Wood and Edwards	1992	Alabama	Field moist soil, aerobic incubation, Net N mineralized
	Franzluebbers et al.	1995	Texas	Aerobic incubation and leaching
	Sanlinas-Garcia et al.	1997	Texas	Air dried soil, unfumigated soil
	Wienhold and Halvorson	1999	North Dakota	Field moist soil, aerobic incubation and leaching
	Eghball et al.	2000	Nebraska	Field moist soil, non-linear regression
	Drinkwater et al.	2000	Pennsylvania	Field moist soil, anaerobic incubation
	Wright et al.	2005	Texas	Air dried soil, aerobic incubation, Net N mineralized
	Mikha et al.	2006	Kansas	Field moist soil, aerobic incubation and leaching, first order exponential model
	Sharifi et al.	2008	Canada	Air dried soil, aerobic incubation, first order kinetic model
	Watts et al.	2010	Alabama	Field moist soil, anaerobic incubation, Net N mineralized
	Spargo et al.	2011	Maryland	Field moist soil, aerobic incubation, first order kinetic model
	Sainju et al.	2012	Montana	Air dried soil, aerobic incubation

Fertilizer	El-Haris et al.	1983	Washington	Air dried soil, aerobic incubation, leaching, non-linear regression
	Chae and Tabatabai	1986	Iowa	Field moist soil, aerobic incubation and leaching, non-linear regression
	Franzaluebbers et al.	1995	Texas	Aerobic incubation and leaching
	Kingery et al.	1996	Alabama	Field moist soil, aerobic incubation
	Dou et al.	1996	Pennysylvania	Air dried soil, aerobic incubation and leaching
	Wienhold and Halvorson	1999	North Dakota	Field moist soil, aerobic incubation and leaching
	Eghball	2000	Nebraska	Field moist soil, non-linear regression
	Deng and Tabatabai	2000	Iowa	Field moist soil, aerobic incubation and leaching, first order kinetic model
	Sanchez et al.	2001	Michigan	Field moist soil, aerobic incubation, Net N mineralized
	Sainju et al.	2003	Georgia	Field moist soil, non-fumigated incubation, Net N mineralized
	Senwo and Tabatabai	2005	Iowa	Field moist soil, aerobic incubation and leaching, non-linear regression
	Russell et al.	2006	Iowa	Field moist soil, Net N mineralized
	Mikha et al.	2006	Kansas	Field moist soil, aerobic incubation and leaching, first order exponential model
	Burger and Vanterea	2008	Minnesota	Air dried soil, aerobic incubation, Net N mineralized
	Balkom et al.	2009	Iowa	Field moist soil, anaerobic incubation, Net N mineralized
	Sainju et al.	2010	Alabama	Air dried soil, aerobic incubation, Net N mineralized
	Sanchez and Mylavarapu	2011	Florida	Air dried soil, aerobic incubation, Net N mineralized
	Wild et al.	2011	California	Anaerobic incubation, Net N mineralized
	Mohanty et al.	2011	India	Air dried soil, aerobic incubation, first order kinetic model
	Aita et al.	2012	Brazil	Aerobic incubation, Net N mineralization
	Dempster et al.	2012	Australia	Field moist soil, aerobic incubation, Net N mineralized
	Nira and Hamaguchi	2012	Japan	Field moist soil, aerobic incubation, zero order reaction
	Johnson et al.	2012	Wisconsin	Air dried soil, aerobic incubation, Net N mineralized

	Mohanty et al.	2013	India	Air dried soil, aerobic incubation, first order kinetic model
	Habibur-Rahman et al.	2013	Bangladesh	Air dried soil, aerobic incubation, first order kinetic model
Crop Rotation	El-Haris et al.	1983	Washington	Air dried soil, aerobic incubation, leaching, non-linear regression
	Wood et al.	1990	Colorado	Field moist soil
	Wood and Edwards	1992	Alabama	Field moist soil, aerobic incubation, Net N mineralized
	Franzluebbers et al.	1995	Texas	Aerobic incubation and leaching
	Christenson and Butt	1997	Michigan	Air dried soil, aerobic incubation, kinetic models
	Weinhold and Halvorson	1999	North Dakota	Field moist soil, aerobic incubation and leaching
	Deng and Tabatabai	2000	Iowa	Field moist soil, aerobic incubation and leaching, first order kinetic model
	Sanchez et al.	2001	Michigan	Field moist soil, aerobic incubation, Net N mineralized
	Liebig et al.	2002	Nebraska	Field moist soil, anaerobic incubation
	Senwo and Tabatabai	2005	Iowa	Field moist soil, aerobic incubation and leaching, non-linear regression
	Russell et al.	2006	Iowa	Field moist soil, Net N mineralized
	Spargo et al.	2011	Maryland	Field moist soil, aerobic incubation, first order kinetic model
	Sainju and Lenssen	2011	Montana	Air dried soil, aerobic incubation, Net N mineralized
	Sainju et al.	2012	Montana	Air dried soil, aerobic incubation
	Culman et al.	2013	Michigan	Field moist soil, anaerobic incubation, Net N mineralized
	Lazicki	2011	Iowa	Air dried soil, anaerobic incubation
Cover Crops	Kuo et al.	1996	Washington	Air dried soil, aerobic incubation, non-linear regression
	Dou et al.	1996	Pennsylvania	Air dried soil, aerobic incubation and leaching
	Kuo and Sainju	1998	Washington	Air dried soil, aerobic incubation, first order kinetic model
	Sanchez et al.	2001	Michigan	Field moist soil, aerobic incubation, Net N mineralized
	Sainju et al.	2003	Georgia	Field moist soil, non-fumigated incubation, Net N mineralized
	Rao and Li	2003	Florida	Aerobic incubation

	Mohanty et al.	2011	India	Air dried soil, aerobic incubation, first order kinetic model
	Habibur-Rahman et al.	2013	Bangladesh	Air dried soil, aerobic incubation, first order kinetic model

Table S2. Analysis of variance and mean response ratio for crop diversity effect on PMN. (2/1 – two crops in rotation versus continuous cropping system, >=3/1 – three or more crops in rotation versus continuous cropping system and >=3/2 – three or more crops in rotation versus two crops in rotation).

Source	F Value	Pr >F
Crop Rotation	8.01	<.0001

Crop Rotation	RR	LL	UL
2/1	1.02	0.95	1.09
C-SB/Cont. Corn	1.04	0.96	1.11
>=3/1	1.44	1.35	1.53
>=3/2	1.12	0.91	1.39

Table S3. *F* and *P* values for tillage type and soil depth effect on PMN in a mixed model regression analysis (NT/MP - no-till versus moldboard plow and NT/CP - no-till versus chisel plow).

Source	F Value	Pr >F
Tillage Type	0.00	0.9856
Depth	0.01	0.9266
Tillage Type * Depth	0.03	0.8584

Tillage Type	Depth	RR	LL	UL
NT/CP	2.50	1.23	1.07	1.41
NT/MP	2.50	1.24	1.07	1.42
NT/CP	5.00	1.22	1.06	1.40
NT/MP	5.00	1.24	1.08	1.43
NT/CP	10.00	1.21	1.05	1.38
NT/MP	10.00	1.25	1.08	1.43
NT/CP	15.00	1.20	1.04	1.37
NT/MP	15.00	1.25	1.09	1.43