Available online at www.sciencedirect.com
SCIENCE DIRECT®
Agriculture, Ecosystems and Environment 112 (2006) 58–72
Agriculture Ecosystems & Environment
www.elsevier.com/locate/agee

Replacing bare fallows with cover crops in fertilizer-intensive cropping systems: A meta-analysis of crop yield and N dynamics

C. Tonitto [a], M.B. David [b], L.E. Drinkwater [a,*]

[a] Department of Horticulture, Cornell University, Ithaca, NY 14853, USA
[b] Department of Natural Resources and Environmental Sciences, University of Illinois, Urbana, IL 61801, USA

Received 20 May 2004; received in revised form 16 June 2005; accepted 28 July 2005
Available online 30 September 2005

Abstract

The availability of Haber-Bosch nitrogen (N) has permitted agricultural intensification and increased the productive capacity of agroecosystems; however, approximately 50% of this applied fertilizer N is lost from agricultural landscapes. Extensive efforts have been devoted to improving the N use efficiency of these systems. Diversified crop rotations using cover crops to provide a variety of ecosystem functions, including biological N fixation (BNF), could maintain yields while reducing N losses. Although leguminous plants used as green manures are capable of fixing N in quantities which exceed cash crop demand, the prospect of replacing significant quantities of Haber-Bosch N with BNF is widely viewed as impractical due to yield reductions. Likewise, the practice of replacing bare fallows with non-leguminous cover crops in systems receiving Haber-Bosch N is generally deemed not economically viable. We conducted a quantitative assessment of cash crop yields and N retention in rotations that implemented these practices. We performed a meta-analysis on experiments comparing crop yield, nitrate leaching, or soil nitrate between conventional (receiving inorganic fertilizer with a winter bare fallow) and diversified systems managed using either a non-legume over-wintering cover crop (amended with inorganic fertilizer) or a legume over-wintering cover crop (no additional N fertilizer). Only studies with rotations designed to produce a cash crop every year were included in our analysis. Many yield comparisons were found in the literature, but only a limited number of nitrate leaching or soil inorganic N studies met the criteria for inclusion in a meta-analysis. Long-term studies were also uncommon, with most data coming from experiments lasting 2–3 years. Yields under non-legume cover crop management were not significantly different from those in the conventional, bare fallow systems, while leaching was reduced by 70% on average. Relative to yields following conventional N-fertilization, the legume-fertilized crops averaged 10% lower yields. However, yields under green manure fertilization were not significantly different relative to conventional systems when legume biomass provided $\geq$110 kg N ha^{-1}. On average, nitrate leaching was reduced by 40% in legume-based systems relative to conventional fertilizer-based systems. Post-harvest soil nitrate status, a measure of potential N loss, was similar in conventional and green manure systems suggesting that reductions in leaching losses were largely due to avoidance of bare fallow periods. These results demonstrate the potential for diversified rotations using N- and non-N-fixing cover crops to maintain crop yields while reducing the anthropogenic contributions to reactive N fluxes.

Keywords: Legumes; Green manure; Cover crops; Meta-analysis; Reactive N; Nitrate leaching; Agroecosystems; Alternative agriculture; Corn; Sorghum; Yield

1. Introduction

The uncoupling of carbon (C) and nitrogen (N) cycles is a defining trait of human-dominated ecosystems, and is most extensive in agroecosystems (Woodmansee, 1984). Prior to the widespread application of Haber-Bosch N, N additions to ecosystems resulted from biological N-fixation, and therefore co-occurred with C fixation. Current estimates suggest human activities have doubled the global N fluxes of biologically active N (NH_3, NH_4^+, NO_3^-, NO_x and N_2O) (Vitousek et al., 1997), with agriculture accounting for 75%

* Corresponding author. Tel.: +1 607 255 9408; fax: +1 607 255 0599.
E-mail address: led24@cornell.edu (L.E. Drinkwater).

0167-8809/$ – see front matter © 2005 Published by Elsevier B.V.
doi:10.1016/j.agee.2005.07.003

of the anthropogenic N forcing (Galloway and Cowling, 2002). Humans introduce 170 Tg of reactive N into agroecosystems annually, with inorganic fertilizer additions to agroecosystems accounting for approximately 80 Tg N year^{-1} (Smil, 1999). Of the reactive N entering agroecosystems, recovery in crop biomass averages 45–55% globally (Smil, 1999; Galloway and Cowling, 2002). The remaining N surplus is lost from agricultural landscapes through denitrification, leaching, and erosion. Denitrification is estimated to account for 26–60 Tg N year^{-1}, and leaching and erosion are attributed with 32–45 Tg N year^{-1} of N losses from agroecosystems (Smil, 1999). The inefficiency of N fertilization is a problem that must be addressed to significantly reduce anthropogenic forcing of the global N cycle.

Agricultural systems require surplus N additions in order to produce desired yields because current management practices tend to disengage energy flows and nutrient cycles in space and time (Drinkwater, 2004). For example, simplified rotations, made possible by the availability of synthetic fertilizers and chemical weed controls (Auclair, 1976), have resulted in the preferential removal of winter annuals from large expanses of intensively managed agricultural lands in North America, thereby increasing the prevalence of bare fallows (Mitsch et al., 2001). The adoption of this industrial agricultural model in China, Brazil, and India is expected to significantly increase global N fertilizer use (Tilman, 1999).

Dependence on N fertilizer results in a reduction in the duration of living plant cover accompanied by a reduction in C-fixation and N assimilation, increased soil erosion, and depletion of soil organic matter (SOM) stocks (Matson et al., 1997). Replacing bare fallow periods with cover crops is a tool that can be broadly applied to increase retention of post-harvest surplus inorganic soil N (McCracken et al., 1994; Drinkwater and Snapp, 2005). Cover cropping has been successfully applied in extensive systems, including diverse cash grain rotations of Northern Europe, wheat-hay rotations in arid regions of Australia, and low-input grain systems in Africa. Further improvements in global N management require large-scale implementation of cover crop management in intensified production systems (Thorup-Kristensen et al., 2003; Drinkwater and Snapp, 2005).

Mechanistic studies suggest that diversified rotations including leguminous and non-leguminous cover crops exhibit desirable biogeochemical properties, such as increased SOM, increased N mineralization potential, and reduced nitrate leaching (Drinkwater et al., 1998; Wyland et al., 1996; Sanchez et al., 2001; Reganold et al., 1987). The dominant cover crop species in temperate grain systems are cold-tolerant, non-leguminous species, such as cereal rye or rye grass. However, leguminous, N-fixing species, such as red clover, crimson clover, and hairy vetch, have been successfully managed as winter cover crops in cold temperate climates. The potential for leguminous cover crops which are managed as N sources (green manures) to supplement, or possibly replace, inorganic N fertilizer has been broadly discussed in the agricultural literature (Thorup-Kristensen et al., 2003; Peoples et al., 1995; Hendrix et al., 1992; Yadvinder-Singh et al., 1992; LaRue and Patterson, 1981). N-fixation measurements demonstrate that clover and vetch varieties commonly used as green manures in annual cropping systems can supply 50–370 kg N ha^{-1} (LaRue and Patterson, 1981; Peoples et al., 1995).

While measured rates of N-fixation documented for common leguminous green manure species indicate these species have the theoretical potential to replace inorganic fertilizer, the prospect of replacing significant quantities of Haber-Bosch N with biological N-fixation is widely viewed as impractical for a variety of reasons (Cassman et al., 2002, 2003). Though most accept legume-fertilization is possible in extensive systems, researchers who are skeptical of legume-fertilized systems frequently cite yield reduction as the most significant impediment to the widespread implementation of intensive, legume-fertilized systems (Smil, 2000, pp. 46–47; Sinclair and Cassman, 1999). There is a wide-spread perception that legume-fertilized systems would result in up to a 50% reduction in crop yields. The conviction that legume-based systems result in significant yield reductions stems from the following perceptions: (1) a legume green manure must be grown for a full year, thus halving the number of cash crop cycles, (2) legume management incurs regular 'opportunity costs' such as the inability to plant a cash crop due to the timing of green manure incorporation, (3) legumes can not provide adequate N for cash crop growth. Similar concerns have prevented the inclusion of non-leguminous cover cropping as a widespread nutrient management practice in North America. Adoption of cover crops has also been limited because agronomic indicators of nutrient use efficiency do not result in favorable assessments of these practices (Cassman et al., 2002; Smil, 2000). As a result, North American agronomic research aimed at improving fertilizer use efficiency continues to focus almost exclusively on refining the amount, timing, and placement of fertilizer application (Cassman, 1999; Balasubramanian et al., 2004).

A quantitative assessment of the literature comparing yield potential and N dynamics across diversified and input-intensive conventional systems has not previously been performed. We use meta-analysis to investigate the consequences of using non-legume and legume cover crops in intensively-managed agroecosystems with an annual cash crop. Meta-analysis is a tool for quantifying the impact of an experimental treatment relative to a control (Hedges and Olkin, 1985). Originally developed for application in the social and medical sciences, where experiments have large sample sizes in readily identifiable control versus treatment groups, recent work has adapted meta-analysis for application to ecological data sets available in the literature (Gurevitch and Hedges, 1999; Hedges et al., 1999; Osenberg et al., 1999; Johnson and Curtis, 2001). We use meta-analysis to ask the following questions: (1) How does the replacement of Haber-Bosch N with legume-derived N affect yield? (2) How does the management of a non-leguminous cover crop affect yield? (3) How do the N dynamics in conventional versus diversified agroecosystems differ? This quantitative assessment of yield and nitrate leaching across conventional and diversified systems is ultimately used to assess the viability of diversified systems as a management tool to reduce N loss from agroecosystems.

2. Methods

2.1. Systems compared using meta-analysis

The application of meta-analysis requires that each study compares a control to experimental treatments and that the control can be consistently defined across studies. Since we were interested in comparing the performance of conventional fertilizer-driven systems with alternatives, we defined the control treatment as a conventional system with an annual fertilized cash crop and winter bare fallow. We contrasted this control system to two categories of experimental treatments: (1) diversified systems with legume cover crops, and (2) diversified systems with non-legume cover crops. Studies compiled in our legume cover crop yield database had the following characteristics: (1) winter legume cover crop followed by an unfertilized cash crop compared to the control, (2) cash crop production every year, (3) no manure or other N additions applied during any phase of the diversified rotation, and (4) cover crop biomass incorporated into the soil or killed before crop planting, with no biomass removal. We excluded hundreds of studies because either the control or the experimental treatments did not meet these criteria. For example, we excluded hundreds of studies because legume treatments had excessive applications of inorganic N fertilizer or because the green manures were being compared to a zero N control. Studies included in the non-legume cover crop yield database had the following characteristics: (1) winter non-legume cover crop followed by a cash crop managed with inorganic N fertilization protocols equivalent to that in the conventional system, (2) cash crop production every year, and (3) cover crop biomass incorporated into the soil or killed before crop planting, with no biomass removal. For studies in our soil N status database, the same characteristics were needed, except that we looked for data on N leaching from the soil profile, or extractable inorganic N concentrations or pools in the soil profile following harvest (together these are termed soil N status). In addition, data included in our analysis were from studies in which (1) the land used had a cropping history typical of the production system under study, and (2) land management reflected the best (or typical) practice for a given climate or soil type.

2.2. Data sources, compiled information, and calculations

Data were compiled from the literature using field studies that compared crop yields, nitrate leaching, and soil inorganic N between N-intensive conventional systems and diversified cropping systems. We searched the literature by using electronic databases, including BIOSIS, Agricola, and Web of Science. The Science Citation Index was used to identify papers citing some of the key early papers that fit our parameters. Finally, citation lists from relevant, recent literature reviews were also used to obtain studies. For some studies, Data Thief® software was used to extract needed data from figures. When we came across studies that met our criteria, but did not report the values we needed in the paper, we contacted the author(s), and in some cases were able to obtain useful data.

As part of our data compilation and analysis we categorized the following factors in our database: cash crop species; cover crop species; cover crop phenology; soil order (USDA classification), soil texture, tillage (conventional, conservation, ridge-till, or no-till); climate (USDA hardiness zone); fertilizer rates; and legume N biomass. Fertilizer rates were further coded as recommended (amount that would be typically applied), low (rates below the recommended rate), and high (rates above the recommended rate). For some analyses, textures were grouped as heavy (clay + silty clay + silty clay loam), medium (loam + silt loam), and light (sandy loam + loamy sand + silty clay loam) groups.

Studies using corn (*Zea mays* L.) as the cash crop comprised the largest category of data fitting our constraints, with grain sorghum (*Sorghum biocolor* L. Moench) the second most common cash crop category. Data from vegetables crops meeting the meta-analysis constraints included broccoli (*Brassica oleracea* L.), sweet corn, potato (*Solanum tubersum* L.), and tomato (*Lycopersicon lycopersicum* L. Karsten). The cover crops cultivated in these studies included the legume species: hairy vetch (*Vicia villosa* Roth), bigflower vetch (*Vicia grandiflora* W. Koch), wooly-pod vetch (*Vicia dasycarpa* Ten.), arrowleaf clover (*Trifolium vesiculosum* Savi), berseem clover (*Trifolium alexandrinum* L.), red clover (*Trifolium pratense* L.), sweet clover (*Melilotus officinalis* Lamarck), crimson clover (*Trifolium incarnatum* L.), subterranean clover (*Trifolium subterraneum* L.), bell bean (*Vicia faba* L.), field pea (*Pisum sativum* L.), and alfalfa (*Medicago sativa* L.), and the non-legume species: cereal rye (*Secale cereale* L.), annual rye (*Lolium multiflorum* Lamarck), oat (*Avena sativa* L.), and oil seed radish (*Raphanus sativus* L.). Phenology was used to categorize species as perennials, indeterminate annuals, or determinant annuals.

We found a total of 31 studies that evaluated corn and sorghum yields from legume-fertilized relative to inorganic N-fertilized, conventional system, and four that compared yields in vegetable crops (Table 1); from these studies we obtained hundreds of individual yield comparisons. Yield

Table 1
Cash crop, soil order, soil texture, location, and reference for each study used for meta-analysis of yield data

Cash crop	Order	Texture	Location	Reference
Corn	Ultisol	Sandy loam	Georgia	Adams et al. (1970)
Corn/sorghum	Alfisol	Silt loam	Kentucky	Blevins et al. (1990)
Corn/sorghum	Mollisol/Alfisol/Inceptisol	Silty clay loam/silt loam	Illinois	Bollero and Bullock (1994)
Corn	Alfisol	Silt loam	Indiana	Bowen et al. (1991)
Broccoli	Mollisol	Silt loam	Oregon	Burket et al. (1997)
Corn	Ultisol	Sandy clay loam	Brazil	Burle et al. (1997)
Corn	Ultisol	Silt loam	Maryland	Clark et al. (1997)
Corn	Alfisol	Silt loam	Kentucky	Corak et al. (1991)
Corn	Ultisol	Silt loam/sandy loam	Maryland	Decker et al. (1994)
Corn	Alfisol	Silty clay loam	Pennsylvania	Drinkwater et al. (1998)
Corn	Inceptisol	Silty clay loam	Pennsylvania	Drinkwater et al. (2000)
Corn	Alfisol	Silt loam	Kentucky	Ebelhar et al. (1984)
Corn	Ultisol	Sandy loam	Georgia	Fleming et al. (1981)
Sorghum	Alfisol	Sandy loam	Georgia	Hargrove (1986)
Corn	Inceptisol	Silty clay	Michigan	Hesterman et al. (1992)
Corn	Ultisol	Silt loam	Maryland	Holderbaum et al. (1987)
Corn	Ultisol	Silt loam	Maryland	Holderbaum et al. (1990)
Corn	Mollisol	Clay loam	Minnesota	Iragavarapu et al. (1997)
Sorghum	Mollisol	Loam/silt loam	Kansas	Janke et al. (2002)
Corn	Mollisol	Silty clay loam	Nebraska	Koerner and Power (1987)
Corn	Inceptisol	Silt loam	Washington	Kuo and Jellum (2000)
Sorghum	Inceptisol	Silt loam	Texas	Lemon et al. (1990)
Corn	Entisol	Loamy sand	Delaware	Mitchell and Teel (1977)
Tomato	Aridsol	Loam	California	Mitchell et al. (2000)
Corn/sorghum	Ultisol	Sandy loam	Georgia	Neely et al. (1987)
Corn	Ultisol	Sandy loam/loamy sand	Alabama	Oyer and Touchton (1990)
Corn	Ultisol	Loamy sand	Delaware	Ritter et al. (1998)
Corn	Alfisol	Sandy loam/silt loam	Ontario	Samson et al. (1991)
Potato	Spodosol	Sandy loam	Prince Edward Island	Sanderson et al. (1999)
Corn	Alfisol	Loam/silt loam	New York	Sarrantonio and Scott (1988)
Tomato	Entisol	Sandy loam	California	Stivers and Shennan (1991)
Corn	Mollisol	Silt loam	Wisconsin	Stute and Posner (1995a,b)
Sorghum	Alfisol	Silt loam	Kansas	Sweeney and Moyer (1994)
Corn	Inceptisol	Loam	Michigan	Tiffin and Hesterman (1998)
Corn	Alfisol	Silt loam	Kentucky	Utomo et al. (1990)
Corn	Alfisol	Silt loam/sandy loam	Ontario	Vyn et al. (2000)

response to non-legume cover crop management was likewise extracted from these 31 studies, and is therefore not a comprehensive review of non-legume cover crop effect on yield. We limit our analysis of non-legume cover crop management to these 31 studies in order to evaluate non-legume cover crop effect under the same environmental conditions as the legume cover crop analysis. Our database is well-suited for this comparison.

Fourteen studies compared nitrate leaching between a bare fallow and cover crop rotation, with two of these studies including a leguminous cover crop (Table 2). Leaching data are reported annually in all legume-fertilized studies and in half of the non-legume cover crop studies. The remaining non-legume studies monitored leaching in the diversified system, relative to the conventional system, during the entire bare fallow period. Four studies reported difference in post-harvest soil inorganic N between legume-fertilized versus inorganically-fertilized systems (Table 2). Our intention was to quantify N losses in legume-based versus conventional inorganic N fertilizer-based agroecosystems. However, given the limited nitrate leaching data from green manure systems, our leaching analysis is dominated by comparisons of fertilized, bare fallow systems to fertilized, non-legume cover crop systems.

2.3. Meta-analysis

A meta-analysis was conducted to analyze the response of yield and soil N status in legume and non-legume cover crop systems compared with conventional systems, using MetaWin version 2.1 software (Rosenberg et al., 2000). Meta-analysis is a tool for quantifying trends across systems characterized by different summary statistics. This property of meta-analysis allows us to compare agroecosystem yield and soil N dynamics across broad climate, soil types and management protocols. To conduct the meta-analysis, an appropriate effect size estimator was calculated. An effect size estimator is an index which allows us to compare the experimental treatment mean to the control treatment mean (Osenberg et al., 1999). Ultimately, the effect size estimator

Table 2
Cash crop, soil order, texture, state, and reference for each study used for meta-analysis of soils data

Cash crop	Order	Texture	Location	Reference
Spring cereal		Sandy loam	Sweden	Aronsson and Torstensson (1998)
Corn	Alfisol	Loamy sand	Ontario	Ball-Coelho and Roy (1997)
Corn/broccoli	Mollisol	Loam	Oregon	Brandi-Dohrn et al. (1997)
Corn	Ultisol	Silt loam	Pennsylvania	Dou et al. (1995)
Corn	Alfisol	Silty clay loam	Pennsylvania	Drinkwater et al. (1998)
Corn	Alfisol	Silt loam	Kentucky	Ebelhar et al. (1984)
Barley		Sand/sandyloam	Denmark	Hansen and Djurhuus (1997)
Grain/potato		Silty sand	Germany	Herzog and Konrad (1992)
Corn	Inceptisol	Clay/sandy clay	Quebec	Isse et al. (1999)
Corn	Mollisol	Silty clay loam	Nebraska	Koerner and Power (1987)
Wheat/corn		Alluvial	France	Martinez and Guiraud (1990)
Corn	Alfisol	Silt loam	Kentucky	McCracken et al. (1994)
Corn	Mollisol	Sandy loam	Michigan	Rasse et al. (2000)
Corn	Entisol	Loamy sand	Delaware	Ritter et al. (1998)
Sugarbeet/potato		Loamy sand	UK	Shepherd (1999)
Corn	Mollisol	Silt loam	Wisconsin	Stute and Posner (1995a,b)
Barley		Sandy loam	Denmark	Thomsen and Christensen (1999)
Grain/potato		Sandy loam	Sweden	Torstensson and Aronsson (2000)

allows us to quantify the magnitude of a treatment effect. We calculate our effect size using the response ratio ($r = \overline{Xe}/\overline{Xc}$), which is the relative impact of the alternative management system compared with a conventional cropping system. In order to perform the meta-analysis on normally distributed data, we used a log transformation of the response ratio, $R = \ln(r) = \ln(\overline{Xe}) - \ln(\overline{Xc})$. For analyses where $\overline{Xc}$ is constrained to non-negative values and where $\overline{Xe}$ and $\overline{Xc}$ are normally distributed, such as the application presented here, R should be approximately normally distributed with a mean approximately equal to the true response ratio (Johnson and Curtis, 2001).

Most of the studies we used reported on several years of data, evaluated multiple cover crop species, and included many soil types. In some cases, more than one cash crop was studied. Therefore, we treated each unique pair of data as an independent observation (e.g., corn following red clover on a silt loam in 1992). Our yield database had a total of 635 observations; 206 observations represented crop yield after recommended fertilizer application compared to yield under legume-based management; 69 observations represented crop yield under recommended fertilizer application after bare fallow compared to non-legume cover crop management. Our soils database had 10 comparisons of soil inorganic N and 80 leaching comparisons for systems under recommended fertilization rates.

Because nearly all of the studies we used did not report any measure of variance or the number of replicates, we conducted an unweighted meta-analysis. Although a more rigorous weighted analysis is possible with known variance and replicates for each study, the statistical significance of our unweighted meta-analysis is enhanced by the calculation of confidence intervals (CI). After a mean effect size was calculated, a bias-corrected 95% confidence interval was generated by a bootstrapping procedure (5000 iterations) using the MetaWin software (Rosenberg et al., 2000).

Using meta-analysis, we explored the mean response ratio using categorical variables previously described (e.g., soil order, tillage, climate, or cover crop phenology) to examine their effect on yields. Means were considered to be significantly different from one another if their 95% CIs were non-overlapping, and were considered significantly different from zero if the 95% CI did not overlap zero (Gurevitch and Hedges, 1999; Johnson and Curtis, 2001).

3. Results

3.1. Characterization of published studies

Our initial literature searches revealed a wealth of agricultural research applying legumes in the full range of agroecosystems for a variety of functions. We identified three distinct categories of research specifically targeting the use of legumes as green manures that reflect broad differences in ecosystem properties as well as differences in the human subsystem (i.e., differences in government policies, agricultural and environmental goals across geopolitical units). The first category emphasized maximum crop yield in intensively managed, high yielding conventional annual systems and were designed to assess the N equivalency of green manures or green manures with supplemental N fertilizer (cf. Ranells and Wagger, 1997a; Torbert et al., 1996; Vaughan et al., 2000). Only a subset of these studies reported yield values from legume-fertilized plots which did not receive supplemental fertilizer N. These are the studies which comprise our meta-analysis and are described below. A second category of study emphasized low-input cropping systems where, for a variety of reasons, purchased N fertilizer was not the typical practice. The goal of these studies was to optimize the management of leguminous green manures and so they did not include an N

Table 3
Number of comparisons used in the yield meta-analysis by selected category variables separated into leguminous cover crops and non-N-fixing cover crops (recommended fertilizer rate only)

	Leguminous cover crops	Non-N fixing cover crops
Tillage		
No-till	116	42
Conservation	29	16
Conventional	62	11
Legume		
Vetches	109	
Red clover	27	
Sweet clover	4	
Other clovers	47	
Alfalfa	14	
Field pea	17	
Bell bean	2	
Mix	2	
Cover crop		
Cereal rye		52
Annual rye		1
Oilseed radish		8
Oat		8
Soil order		
Alfisol	67	43
Mollisol	39	4
Inceptisol	28	10
Ultisol	69	10
Entisol	2	2

fertilizer treatment for comparison (cf. Snapp and Silim, 2002; Anderson et al., 1998; Dalal et al., 1995; Hossain et al., 1996a,b). Finally, there is rich literature focusing on integrated farming systems and organic agriculture. This literature generally includes animal manure based alternative systems and complex rotations (Younie, 1996; Olesen et al., 2002; Thomsen and Christensen, 1998; Wivstad et al., 1996). Most of these studies could not be included in our analysis because (1) the treatments included animal manures or composts or (2) the complex rotations did not permit yield comparisons of the same crops.

The studies used in this analysis (Tables 1 and 2) report data covering a wide range of environmental and management conditions (Tables 3 and 4). The research sites included a wide range of climatic conditions, with the yield data sites spanning 33–46°N latitudes, whereas the soil data sites extend to 55°N. Based on the USDA hardiness index, the yield studies used in this meta-analysis represent climates typical of important grain regions of the U.S. and western Europe. Greater than 55% of the data are from USDA hardiness zones 4–6. More specifically, the representation of USDA hardiness zones in the database followed a distribution of 20, 7, 30, 36, and 7% for zones 4–8, respectively. This distribution in USDA hardiness zones corresponds to winter climates significantly harsher than those of western Europe, which are classified as UK (zones 8–9), France (zones 8–9), or Germany (zones 6–7). Our study has good representation of hardiness zones 5–6, climates representative of eastern Norway, southern Sweden, Denmark, Poland and most of eastern Europe.

Table 4
Number of comparisons used in the soil meta-analysis by selected category variables separated into leguminous cover crops and non-N-fixing cover crops

	Leguminous cover crops	Non-N fixing cover crops
Tillage		
No-till	18	27
Conventional	15	66
Legume		
Vetches	11	
Red clover	11	
Other clovers	2	
Cover crop		
Cereal rye		82
Forage radish		4
Winter rape		6
Soil order		
Alfisol	9	9
Mollisol	9	6
Inceptisol	0	8
Ultisol	6	0
Entisol	0	8
Other		61

Although the majority of the data came from study sites on Alfisols and Ultisols, Mollisols and Inceptisols were also represented among the studies. Since many legume-based agroecosystem studies were focused on designing alternative cropping systems, no-till systems were the largest tillage category. Vetches were the most common legume cover crop, followed by clovers. In the non-legume cover crop studies, cereal rye was most common.

The data were analyzed based on soil order, soil texture, legume phenology, and tillage applied, though no significant trends emerged from these groupings. For this reason, the proceeding analysis highlights trends based on system N inputs and planted cash crop.

3.2. Crop yield trends

The data used in this analysis were representative of typical production systems (Table 5). As in commercial

Table 5
Comparisons by N source for corn and sorghum yields at recommended fertilizer rates

Crop and N source	Yield (Mg ha^{-1})			
	n	Mean	Minimum	Maximum
Corn				
Fertilized	146	7.0	0.8	13.4
Legume	228	6.4	0.6	13.4
Sorghum				
Fertilized	44	5.2	1.5	8.6
Legume	60	4.6	2.0	9.1

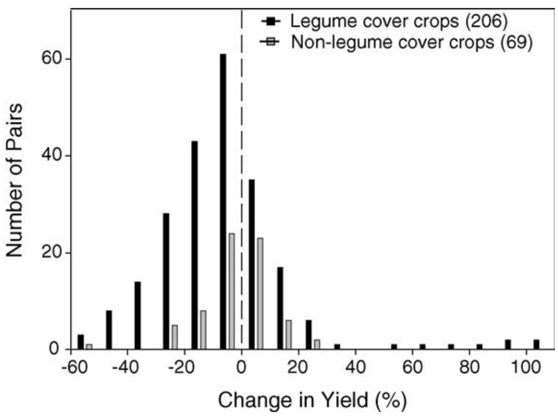

Fig. 1. Distribution of the number of pairs showing the effect of diversified rotations on cash crop yield in deciles of percent change from the control (recommended fertilizer rate following winter bare fallow). Crop yield under unfertilized, legume winter cover crop and fertilized, non-legume winter cover crop treatments are compared to yield in fertilized, winter bare fallow control plots. Each unique treatment-control pair is recorded as an individual comparison. Mean values and 95% confidence intervals of the back-transformed response ratios are shown in the legend (number of comparisons in parentheses).

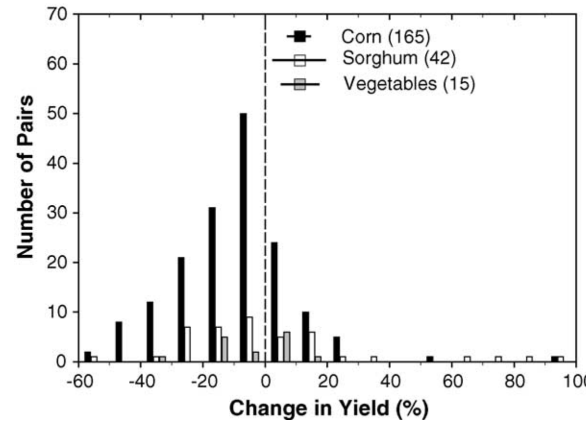

Fig. 2. Distribution of the number of pairs showing the effect of legume cover crops on cash crop yield grouped according to crop type in deciles of percent change from the control (recommended fertilizer rate following winter bare fallow). Each unique treatment-control pair is recorded as an individual comparison. Mean values and 95% confidence intervals of the back-transformed response ratios are shown in the legend (number of comparisons in parentheses).

production systems, these experimental systems included years with extremely low yields from climate or management induced crop failure. However, the mean yields were comparable to commercial production systems. Given the wide range of climatic conditions tested, these are robust comparisons of these management systems for temperate agricultural systems.

Yield under recommended fertilizer levels following a non-legume cover crop did not significantly differ from yield following a bare fallow (Fig. 1). Though yields under non-legume cover crop management averaged a 3% decline relative to bare fallow management, the 95% confidence interval overlaps with zero, indicating this decline is not statistically significant. A histogram of the change in yield under non-legume cover crop relative to bare fallow management indicates that the studies are equally distributed between slight positive and slight negative yields. Furthermore, the mean change in yield is biased by one outlier datapoint which experienced a 52% yield decline relative to bare fallow management.

Relative to conventional systems managed at recommended fertilizer levels, diversified systems using a legume cover crop as a green manure showed a small decline in yield (Fig. 1). Legume-fertilized systems averaged a 10% decline in yield relative to inorganically-fertilized systems with a winter bare fallow. Yield trends were not statistically different between USDA hardiness zones 5–8, however the decline in yield under legume management was greater in USDA hardiness zone 4 relative to the other climatic zones. The percent change in yield in legume-based relative to conventional systems varied by cash crop (Fig. 2). Relative to conventional systems receiving recommended fertilizer inputs, corn yields in legume-based systems were 12% lower. In contrast, sorghum yields were not statistically different under either conventional or legume N management. Though a small number of studies, vegetable systems also demonstrated a statistically insignificant change in yield under legume fertilization. The histogram comprising all crops studied showed a wide range in percent change in yield; however, 43% of the studies were within the range where legume systems showed a −10 to 10% change in yield relative to conventional systems. Studies which resulted in significant yield benefits under legume-fertilization represent data for non-irrigated corn yields in Nebraska and non-irrigated sorghum yields in Kansas. These data suggest short-term legume-management can provide non-nitrogen system benefits, including increased soil water holding capacity and increased water use efficiency.

When considering all conventional fertilizer levels tested, the change in yield under legume systems relative

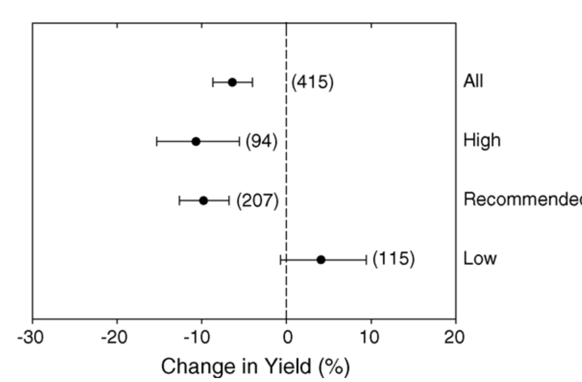

Fig. 3. Effect of legume cover crops on cash crop yield in units of percent change from the control (fertilizer followed by a bare winter fallow). Data are grouped by fertilizer application rate in the control plots for all legume data. Mean values and 95% confidence intervals of the back-transformed response ratios are shown (number of comparisons in parentheses).

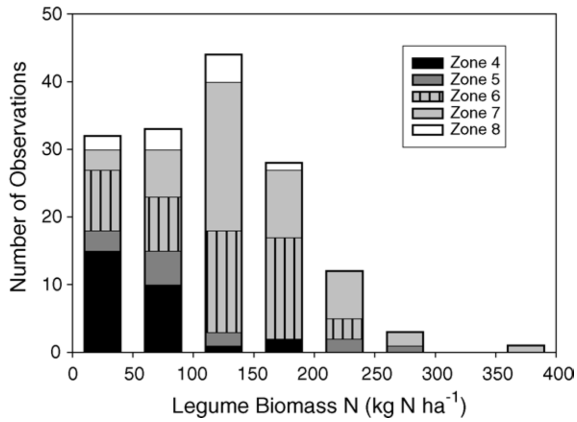

Fig. 4. Distribution of number of observations showing the N content of aboveground legume biomass in 50 kg N ha^{-1} bins. Legume biomass N is sorted by USDA hardiness zone.

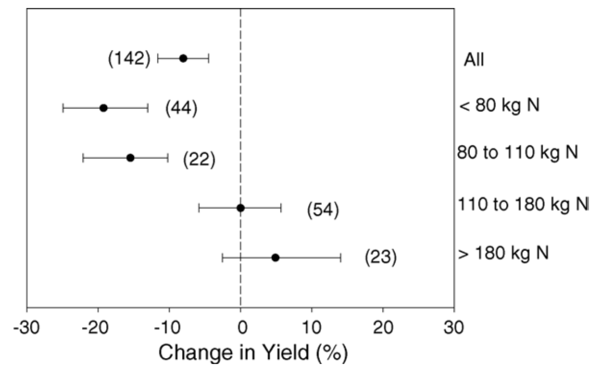

Fig. 6. Effect of legume cover crops on cash crop yields in units of percent change from the control (recommended fertilizer rate following winter bare fallow) grouped by legume N input rate. Mean values and 95% confidence intervals of the back-transformed response ratios are shown (number of comparisons in parentheses).

to high applications of fertilizer was not statistically different from the trends for recommended fertilization (Fig. 3). However, compared to low inorganic fertilizer application, legume systems averaged a 5% yield improvement. As a result, the overall effect size under all fertilizations tested was a 7% decline in yield in legume relative to conventional systems.

Some of the variation in yield response can be understood by characterizing legume N inputs. Legume N inputs varied from 8 to 350 kg N ha^{-1} in a fairly continuous distribution, with 50% of the studies having 50–150 kg N ha^{-1} inputs (Fig. 4). The potential for high legume biomass N accumulation was demonstrated in all USDA hardiness zones studied, though the coldest climate (zone 4) demonstrated the highest proportion of low biomass inputs. Climates representative of conditions in important agricultural regions, zones 5–7, demonstrated good legume biomass N accumulation. A comparison of the relative N inputs contributed by legumes versus fertilizer in each study pair further demonstrated the importance of legume N input variation. The distribution of legume-derived N inputs observed in this review indicated legume N inputs were generally 28% lower than recommended inorganic fertilizer applications (Fig. 5). In this context, the conventional system under recommended fertilization received 28% greater N inputs on average, but attained only 10% greater crop yield relative to the legume-fertilized system.

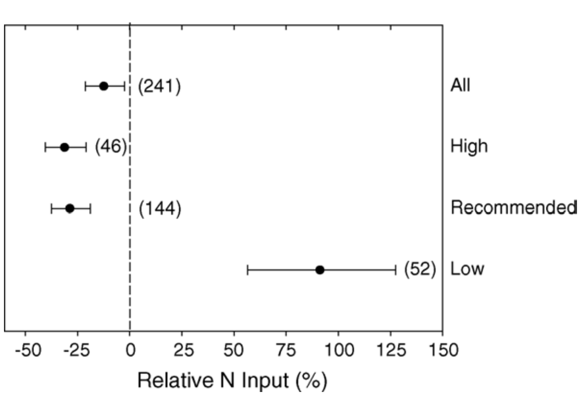

Fig. 5. Relative N added to cash crop cultivation in treatment (unfertilized, legume cover crop) compared to control (fertilized, winter bare fallow) systems grouped by fertilizer additions to conventional systems. Mean values and 95% confidence intervals of the back-transformed response ratios are shown (number of comparisons in parentheses).

Sorting the studies by legume-derived N inputs allowed us to examine the effect of this variability in legume biomass on cash crop yield (Fig. 6). There was no statistical difference in crop yield between conventional systems applying recommended fertilizer N and diversified systems where legume N inputs ranged from 110 to 180 kg N ha^{-1}, a rate comparable to recommended inorganic fertilizer applications. The response ratio for this comparison demonstrated no difference in crop yield across systems. Positive relative yield in legume-fertilized systems was also seen for legume-derived N inputs exceeding 180 kg N ha^{-1}, with these systems averaging a 5% increase in yield relative to conventional systems; however, excessive legume N inputs would likely result in poor N balance. Only legume systems with inputs <110 kg N ha^{-1} resulted in reduced crop yields relative to conventional systems. There was a measurable difference in yield when legume biomass was reduced, with a moderate legume input of 80–110 kg N ha^{-1} averaging a 15% yield decline, while legume inputs <80 kg N ha^{-1} averaged a 19% yield decline relative to conventional systems. Each legume biomass N category was well-represented in the data, with limited-growth legume systems comprising 46%, adequate-performance legume systems comprising 38%, and high legume N systems representing 16% of the data, respectively.

3.3. N dynamics

A comprehensive review of the literature revealed few studies where leaching or soil inorganic N was simultaneously measured in conventional fertilizer-driven and legume-based systems. For this reason, the leaching meta-analysis was dominated by comparisons of Haber-Bosch N

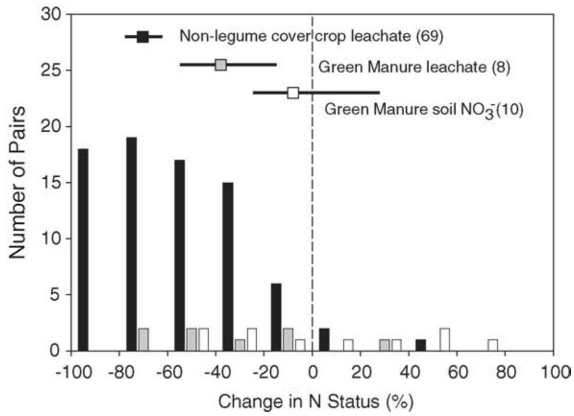

Fig. 7. Distribution of number of pairs showing the effect of cover crops on soil N status in deciles of percent change from the control (recommended fertilizer rate with a winter bare fallow). The meta-analysis compares nitrate leaching from non-legume cover crop systems (fertilized), nitrate leaching from legume cover crop systems (unfertilized), and post-harvest soil nitrate in legume systems (unfertilized) to fertilized systems with a winter bare fallow. Mean values and 95% confidence intervals of the back-transformed response ratios are shown in the legend (number of comparisons in parentheses).

fertilized systems in which the cash crop was followed by either a non-legume cover crop or a bare fallow. Nitrate leaching was clearly reduced when a cover crop was present (Fig. 7). The meta-analysis showed a 70% overall reduction in leaching under the non-legume cover crop relative to bare fallow systems, with a narrow 95% CI. Though a limited sample size, the comparison between legume-fertilized systems and conventional systems showed a significant, 40% reduction in nitrate leaching. Trends in post-harvest soil inorganic N were highly variable. Legume-fertilized systems had post-harvest soil inorganic N pools ranging from 50% below to 80% above conventional systems (Fig. 7).

Static post-harvest soil N measurements can only indicate potential, not actual, N leaching. These static measurements must be supplemented with additional information to assess the environmental impact of post-harvest surplus inorganic N pools. A comparison of post-harvest N uptake by non-legume cover crops using 53 datapoints showed 47% of the cover crops scavenged N at rates equivalent to >20% of applied fertilizer N and 26% of the cover crops took up the equivalent of 10–20% of applied fertilizer N. Though the cover crop N uptake data is highly variable due to different cash crop fertilization levels, non-legume cover crop uptake of inorganic N averaged 37 kg N ha^{-1}, with 50% of the studies reporting cover crop N uptake ranging from 20 to 60 kg N ha^{-1}, suggesting cover crops can scavenge a significant proportion of post-harvest surplus inorganic N.

4. Discussion

The goal of this meta-analysis was to evaluate the potential for cover cropping to serve as a tool for reducing reactive N introduced to the environment from intensive agricultural systems, while maintaining cash crop yields. We addressed the broad practice of replacing bare fallows with cover crops, which facilitate internal N cycling capacity by altering a range of ecosystem processes (Drinkwater and Snapp, 2005). We were particularly interested in leguminous cover crops because replacing a portion of Haber-Bosch N with BNF offers the opportunity to reduce fossil fuel subsidy of food production. Due to the high energy demand of N fertilizer production, we expect management of BNF can offer significant reductions in net farm fossil fuel use. Using state average values from Illinois for N-fertilizer and chemical application and energy budgets from West and Marland (2002), we estimate conventional IL practice consumes 13 GJ fossil fuel energy ha^{-1}, while legume-based systems (including chemical application and additional land management) would consume 6 GJ fossil fuel energy ha^{-1}. Therefore, legume-based corn production could operate using approximately 45% of current fossil fuel demand in intensive production systems. Furthermore, since field-scale N use efficiency of legume-based agroecosystems is improved compared to conventional fertilizer-driven rotations, appropriate use of BNF may reduce total N requirements and N losses (Drinkwater et al., 1998; Drinkwater and Snapp, 2005).

We first examined the wide-spread perception that legume-fertilized agroecosystems require twice the land-base to maintain comparable yields because an entire growing season is needed for N-fixation by a leguminous cover crop. While many studies conducted in temperature- or water-limited climates do focus on cropping systems that alternate between a cover crop and a cash crop year (Izaurralde et al., 1993, 1995), this is not the typical practice in most regions (Snapp et al., 2005). Our analysis only included experimental rotations designed to produce a cash crop every year by including cover crops during periods when fields are normally in a bare fallow. We did find that, in some cases, crop rotation is modified to permit sufficient time for N-fixation; for example, winter annual cash crops (wheat, barley and oats) are often added to grain systems that produce only summer annuals (soybean, corn, cf. Liebhardt et al., 1989). Other perceived limitations that stem from specific aspects of managing cover crops effectively will be addressed later in the discussion. Overall, our meta-analysis supports the potential for well-managed, diversified cropping systems to achieve high yields while improving N balances and reducing N loses. We discuss these findings in detail below.

4.1. *Yield potential of diversified systems*

On average, non-legume cover crop management under recommended N fertilization did not incur a yield decline relative to conventional management. When all studies of legume cover crops were considered, yields were reduced by an average of 10% under legume cover crop management. This average reduction was explained by inadequate legume biomass. A legume cover crop which provided $\geq$110 kg N ha^{-1} was sufficient to achieve crop yields equivalent to yields in conventional fertilizer-driven systems, and represented 55% of the observations. This rate of legume-N addition is equivalent to the average corn N harvested from inorganically fertilized systems. Given the wide range of soil types, climatic conditions, tillage methods, and cover crops included in this comparison, the yield meta-analysis represents a robust comparison of legume- versus conventional fertilizer-driven cropping systems. The yields in diversified relative to conventional systems did not show trends based on soil order, soil texture, or management, supporting the potential for productive diversified systems under a wide range of environmental, climatic, and management conditions.

One limitation of our analysis is that the majority of these studies did not compare long-term yield trends. The data available for our analysis were dominated by 2–3 year studies conducted on agricultural experiment stations. Yield potential is influenced by internal biogeochemical processes occurring at various temporal scales, regardless of N source. However, temporal scale is particularly relevant to agroecosystem studies where the plant-available N is primarily the result of net N mineralization and management practices being investigated alter SOM dynamics. Typically, for crops receiving inorganic N fertilizer, 40–60% of the total N in crop biomass is derived from SOM (Kramer et al., 2002; Harris et al., 1994; Ladd and Amato, 1986; Ladd et al., 1983; Azam et al., 1985). In contrast, crops grown following legume green manure incorporation obtain $\leq$20% of their N from the direct mineralization of the newly added legume, while the remaining 80% is obtained from SOM reservoirs already present (Harris et al., 1994; Kramer et al., 2002). Nissen and Wander (2003) demonstrated that plant uptake of soil-derived N is correlated with particulate organic matter carbon (POM-C). The accumulation of decomposable and recalcitrant SOM pools provides a large N reservoir that influences short time-scale N availability (Drinkwater and Snapp, 2005; Nissen and Wander, 2003).

Since conventional management has been practiced for decades at agricultural research stations, these comparisons have mainly been conducted in soils reflecting steady-state conditions for fertilizer-driven systems with bare fallows. For this reason, the meta-analysis results represent crop yields during the transition from conventional to legume-based or cover cropped systems. This is an important point since SOM content, soil biotic activity, and N-mineralization potential are generally reduced in conventional fertilizer-driven systems compared to diversified rotations which include the use of legume and non-legume cover crops (Drinkwater et al., 1995, 1998; Wander et al., 1994; Clark et al., 1998). We expect systems with a moderate legume input of 80–110 kg N ha^{-1} to produce more favorable relative yields as SOM pools that contribute to crop N assimilation increase and reach a new steady state under long-term legume management (Drinkwater and Snapp, 2005). The time frame required to accrue labile SOM pools sufficient to support cash crop yields comparable to inorganically fertilized systems varies (Martini et al., 2004; Liebhardt et al., 1989). As a general principle, the time frame will depend on soil type, management history, and the status of SOM pools.

4.2. N dynamics of diversified systems

Regardless of the form of N inputs provided to an agroecosystem, the replacement of bare fallow periods with cover crops can increase retention of post-harvest surplus inorganic soil N, which would otherwise be lost to leaching and denitrification (McCracken et al., 1994; Thorup-Kristensen et al., 2003). Our literature survey demonstrated non-legume cover crop uptake of post-harvest N averaged between 20 and 60 kg N ha^{-1} and showed winter cover crops reduced nitrate leaching by 40–70% compared to a winter bare fallow. The soil nitrate and nitrate leaching data analyzed in the meta-analysis were from a wide range of soil types, climatic conditions, and tillage methods, and included both leguminous and non-leguminous cover crops. Therefore, the leaching meta-analysis provides a robust assessment of cover crop ability to reduce nitrate leaching, regardless of the N source applied.

Tracer N studies indicate legume N has a different fate than inorganic fertilizer N. Yields in conventional systems are maintained by inorganic N surpluses, in which only 45–55% of applied N is recovered in the crop biomass (Smil, 1999; Galloway and Cowling, 2002). Because soil organisms are dependent on organic C as an energy source, microbial immobilization of surplus inorganic fertilizer N is fundamentally limited by organic matter additions. As a result, this surplus inorganic N is readily lost from conventional agricultural systems. In green manure systems, however, a greater proportion of added N cycles into soil organic N pools. The recovery of labeled N added by legume green manures ranged from 10 to 22% in the wheat crop, from 52 to 78% in soil organic N, and only 0.6 to 3.5% in inorganic soil N pools (Ladd et al., 1981, 1983). Higher rates of crop uptake of legume-derived N were reported by Peoples et al. (2004), in which barley fertilized with white clover attained 32% of its N from clover-fixed N. The high retention of N in SOM pools in legume systems reduces N leaching potential, providing a mechanism for achieving significant reductions in N loss compared to current losses of 45–55% of applied N in conventional fertilized systems (Drinkwater and Snapp, 2005).

The partitioning of agroecosystem N amendments depends on the initial SOM and organic N content of the soil relative to the steady state values for the system. Short-term studies do not have a consistent method for dealing with unequal starting conditions; trends from long-term studies illustrate how C and N budgets differ across management regimes. In green manure systems supplemented with inorganic N fertilizer, an 8-year field study by

Clark et al. (1998) demonstrated a tighter N balance relative to conventional fertilizer management. In a 15-year study, Drinkwater et al. (1998) reported that green manure systems exhibited half of the N surpluses measured under conventional management and demonstrated increased soil N in the plough layer. The conventional systems showed a significant decline in total soil N of the plough layer despite receiving large additions of surplus N. In both studies, improved N retention in green manure systems corresponded to increased soil C.

The potential for reduced N leaching from legume-fertilized systems due to greater retention of organic N is supported by short-term isotopic experiments, long-term systems comparisons, and our meta-analysis. Soil organic matter reservoirs exert significant control on N dynamics in legume-based systems and ultimately determine how tightly the N cycle can be managed. To achieve optimal yields and N balance in legume-fertilized cropping systems, we must characterize interactions between SOM pools, N-fixation, and microbially-mediated processes; all of these areas require further research.

4.3. Toward an ecosystem-based approach to N management: balancing production and stewardship

Agroecosystem management should not compromise long-term soil productivity by focusing management on short time-scale yield. The current approach to N management emphasizes single-year outcomes, and is based on assessments of fertilizer uptake by the cash crop immediately following nutrient additions (Cassman et al., 2002; Balasubramanian et al., 2004). The success or failure of a management practice is determined by short-term performance, limiting improvements that could be realized by managing nutrient pools with slower turnover times (Drinkwater and Snapp, 2005). Practices such as green manures, which have a greater reliance on the full range of N reservoirs, do not appear to be particularly efficient since relatively small proportions of newly added N are captured by the following cash crop. Likewise, cover crops that retain excess N for use in the subsequent year are not viewed as important components of increased fertilizer use efficiency. A recent survey assessing the adoption rate of 18 different management practices that either increase or compromise soil and water protection in the Midwestern grain region did not even include cover crops as a potential best management practice (Napier and Tucker, 2001). An ecosystem-based approach integrates management of short-term and long-term N dynamics and requires nutrient use efficiency indices which reflect cropping system N retention capacity and yield (Drinkwater, 2004). This broader perspective will expand the management options applied to improve cropping systems and will reconcile production and environmental goals.

The incorporation of cover crops in annual rotations impacts a number of ecosystem functions including some that are not directly related to N management (Drinkwater and Snapp, in press). Inclusion of cover crops can increase the bio-availability of mineral-derived nutrients, most notably, P (Vance et al., 2003). A greater proportion of the productive capacity of an agroecosystem can be tapped by replacing bare fallow periods with cover crops. In the case of leguminous species, N-fixation coincides with C-fixation, and solar energy rather than fossil fuel, is the dominant energy source in these systems. The extended period of primary productivity creates organic C which is returned to the soil, where the mineralization of labile SOM provides subsequent crop N needs, and recalcitrant litter adds to the SOM pools assisting N recycling. The impact of cover crops on soil processes through this C cascade includes increased soil aggregate formation and stability (Roberson et al., 1991), increased soil pore space and infiltration (Colla et al., 2000; Lotter et al., 2003), and reduced soil erosion (Delgado et al., 1999), which are all critical for the long-term sustainability of the soil resource (Doran et al., 1996). Incorporation of cover crops in rotations can also enhance disease suppression (Abawi and Widmer, 2000), reduce weed competition and herbicide requirements (Gallandt et al., 1999) and support the beneficial arthropod communities that permit reductions in pesticide applications (Lewis et al., 1997). Including these functions, as well as functions relating directly to N supply, in cost/benefit analyses is necessary to accurately assess the economic value of managing rotational diversity in place of multiple chemical inputs.

4.4. Optimizing cover crop management

Ultimately, the success of agroecosystems that are based on internal ecological processes will depend on the development of regionally-specific cropping systems that are fine-tuned for local ecosystem and socio-cultural conditions. Regardless of whether N- or non-N-fixing species are used, adding cover crops to intensive rotations requires attention to a different set of management details compared to those emphasized in conventional systems (Snapp et al., 2005). While management problems resulting in yield limitations did not dominate the literature, cover-crop related problems did cause some yield reductions. Problems such as interference with cash crop planting, inadequate N-fixation (in the case of legumes), or ill-timed cover crop incorporation did occur in some of the studies included in our analysis and do need to be addressed for wider adoption of cover crops to succeed.

Regarding the potential for crop yield reduction due to poor legume performance and insufficient N additions, the reviewed literature reported a wide range in legume N inputs, a range likely resulting from uncontrollable climatic conditions, as well as poor management decisions. While poor legume performance can lead to inadequate N inputs in some years, insufficient organic N inputs can be supplemented with inorganic N fertilizer when necessary. Quantitative metrics for discerning when supplemental N fertilizer is needed in conjunction with legume inputs would be an extremely valuable management tool. In addition to N limitation, management must address the potential for surplus N additions in legume-driven systems, as the upper range of N-fixation far exceeds harvested N exports (LaRue and Patterson, 1981; Peoples et al., 1995).

Adequately timing cover crop incorporation to avoid interference with cash crop planting is a prominent management constraint in both legume and non-legume cover crop systems. Yield reductions are often observed when a cover crop interferes with the cash crop planting date (Clark et al., 1997; Thorup-Kristensen et al., 2003). Appropriate matching of cover crop species with available niches and cash crops is often a successful strategy that can identify optimally selected legume-cash crop pairs (Sarrantonio, 1991; Holderbaum et al., 1990; Decker et al., 1994). Though long advocated as a research agenda, insufficient resources have been allocated toward developing improved cover crop varieties that are compatible with dominant crop rotations and climatic constraints (Frye et al., 1988).

Attaining high yields while minimizing environmental impacts requires optimal timing of net N-mineralization relative to crop uptake. The need for pulsed delivery of N in annual cropping systems and our incomplete understanding of the complex biological processes governing N availability render precise N-mineralization management to be a significant challenge. The use of primary tillage to incorporate low C:N residues, particularly those produced by legume monocultures, can result in a very rapid net release of mineral N when plant uptake is still minimal (Sarrantonio and Scott, 1988; Drinkwater et al., 2000). Under these conditions, increased NO_3^- leaching can occur, particularly in years when high precipitation coincides with rapid mineralization in the absence of crop uptake (Sarrantonio and Scott, 1988; Drinkwater et al., 2000). On the other hand, strict no-till management often results in yield limitations due to the delay of N mineralization relative to crop uptake (Doran, 1980; Groffman et al., 1987; Power et al., 1991; Sarrantonio and Scott, 1988; Varco et al., 1989). Developing management schemes which adjust the timing and intensity of tillage and soil disturbance can greatly improve synchronization of N mineralization, and will be instrumental in optimizing N mineralization (Wagger, 1989; Drinkwater et al., 2000). Varying cover crop composition by planting mixed stands of N- and non-N-fixing plants as well as careful selection of legume species has a significant impact on the timing and extent of net N-mineralization (Yadvinder-Singh et al., 1992; Ranells and Wagger, 1997b). For example, the decomposition of rye-legume bicultures released N more slowly relative to legume monocultures, with N release slowed by as much as three weeks (Ranells and Wagger, 1997b). These studies illustrate that a variety of approaches could be used concurrently to optimize the timing of N-mineralization (Ranells and Wagger, 1997b; Drinkwater et al., 2000).

5. Conclusions: the future of agroecosystems

The development of Haber-Bosch N fertilized cropping systems allowed increased crop yields to support an unprecedented increase in the human population. In the coming decades, agriculture must provide adequate nutrition for an increased population, as well as insure agricultural practice does not limit potable water supplies or other food sources such as regional fisheries. Legume-based cropping systems use traditionally fallow periods to extend the annual primary productivity of a land unit. Increased C-fixation, rather than fossil fuel, is the dominant energy source in theses systems. This extended period of primary productivity creates organic C which serves as the energy source for microbes capable of N-fixation. Nitrogen added to the system by N-fixation during the growth of the legume ultimately provides nutrition for subsequent cash crop growth, limiting the need for inorganic N application. In addition, the use of legumes as green manures builds the soil organic C pool, facilitating the long-term management of agroecosystem N requirements. By managing for balanced N inputs and outputs, legume-based cropping systems have the potential to reduce freshwater and estuary nitrate pollution. Furthermore, as agriculture increasingly dominates the landscape, it is important for agricultural land to provide ecological needs currently met by unmanaged habitat. This meta-analysis suggests diversified cropping systems have the potential to achieve these goals. Further mechanistic research is necessary to follow the fate of N in alternative systems, and to develop viable, regional, optimal management strategies.

Acknowledgements

The NSF-Biocomplexity in the Environment-Coupled Biogeochemical Cycles Program (BES-0216316 to LED) provided support for this research. The authors would like to thank Sieglinde Snapp, Jude Maul and Meagan Cocke for suggestions on an earlier draft of the manuscript.

References

Abawi, G.S., Widmer, T.L., 2000. Impact of soil health management practices on soilborne pathogens, nematodes and root diseases of vegetable crops. Appl. Soil Ecol. 15, 37–47.

Adams, W.E., Morris, H.D., Dawson, R.N., 1970. Effect of cropping systems and nitrogen levels on corn (*Zea mays*) yields in the southern piedmont region. Agron. J. 62, 655–659.

Anderson, G.C., Fillery, I.R.P., Dunin, F.X., Dolling, P.J., Asseng, S., 1998. Nitrogen and water flow under pasture-wheat and lupin-wheat rotations in deep sands in Western Australia 2. Drainage and nitrate leaching. Aust. J. Agric. Res. 49, 345–361.

Aronsson, H., Torstensson, G., 1998. Measured and simulated availability and leaching of nitrogen associated with frequent use of catch crops. Soil Use Manage. 14, 6–13.

Auclair, A.N., 1976. Ecological factors in the development of intensive management ecosystems in the midwestern USA. Ecology 57, 431–444.

Azam, F., Malik, K.A., Sajjad, M.I., 1985. Transformations in soil and availability to plants of ^{15}N applied as inorganic fertilizer and legume residues. Plant Soil 86, 3–13.

Balasubramanian, V., Alves, B., Aulakh, M., Bekunda, M., Cai, Z., Drinkwater, L., Mugendi, D., van Kessel, C., Oenema, O., 2004. Crop, environmental and management factors affecting fertilizer nitrogen use efficiency. In: Mosier, A.R., Syers, J.K., Freney, J.R., (Eds.), Agriculture and the Nitrogen Cycle: Assessing the Impacts of Fertilizer Use on Food Production and the Environment. SCOPE Nitrogen Fertilizer RAP.

Ball-Coelho, B.R., Roy, R.C., 1997. Overseeding rye into corn reduces NO_3 leaching and increases yields. Can. J. Soil Sci. 77, 443–451.

Blevins, R.L., Herbek, J.H., Frye, W.W., 1990. Legume cover crops as a nitrogen source for no-till corn and grain sorghum. Agron. J. 82, 769–772.

Bollero, G.A., Bullock, D.G., 1994. Cover cropping systems for the central corn belt. J. Prod. Agric. 7, 55–58.

Bowen, J., Jordan, L., Biehle, D., 1991. Economics of No-Till Corn Planted Into Winter Cover Crops. Cover Crops for Clean Water Soil and Water Conservation Society, Jackson, TN, pp. 181–182.

Brandi-Dohrn, F.M., Dick, R.P., Hess, M., Kauffman, S.M., Hemphill Jr., D.D., Selker, J.S., 1997. Nitrate leaching under a cereal rye cover crop. J. Environ. Qual. 26, 181–188.

Burket, J.Z., Hemphill, D.D., Dick, R.P., 1997. Winter cover crops and nitrogen management in sweet corn and broccoli rotations. Hortscience 32, 664–668.

Burle, M.L., Mielniczuk, J., Focchi, S., 1997. Effect of cropping systems on soil chemical characteristics, with emphasis on soil acidification. Plant Soil 190, 309–316.

Cassman, K.G., Dobermann, A., Walters, D.T., Yang, H., 2003. Meeting cereal demand while protecting natural resources and improving environmental quality. Annu. Rev. Environ. Res. 28, 315–358.

Cassman, K.G., Dobermann, A., Walters, D.T., 2002. Agroecosystems, nitrogen-use efficiency, and nitrogen management. Ambio 31, 132–140.

Cassman, K.G., 1999. Ecological intensification of cereal production systems: Yield potential, soil quality, and precision agriculture. Proc. Natl. Acad. Sci. USA 96, 5952–5959.

Clark, A.J., Decker, A.M., Meisinger, J.J., McIntosh, M.S., 1997. Kill date of vetch, rye, and a vetch-rye mixture. II. Soil moisture and corn yield. Agron. J. 89, 434–441.

Clark, M.S., Horwath, W.R., Shennan, C., Scow, K.M., 1998. Changes in soil chemical properties resulting from organic and low-input farming practices. Agron. J. 90, 662–671.

Colla, G., Mitchell, J.P., Joyce, B.A., Huyet, L.M., Wallender, W.W., Temple, S.R., Hsiao, T.C., Poudel, D.D., 2000. Soil physical properties and tomato yield and quality in alternative cropping systems. Agron. J. 92, 924–932.

Corak, S.J., Frye, W.W., Smith, M.S., 1991. Legume mulch and nitrogen fertilizer effects on soil water and corn production. Soil Sci. Soc. Am. J. 55, 1395–1400.

Dalal, R.C., Strong, W.M., Weston, E.J., Cooper, J.E., Lehane, K.J., King, A.J., Chicken, C.J., 1995. Sustaining productivity of a Vertisol at Warra, Queensland, with fertilizers, no-tillage, or legumes 1. Organic matter status. Aust. J. Exp. Agric. 35, 903–913.

Decker, A.M., Clark, A.J., Meisinger, J.J., Mulford, F.R., McIntosh, M.S., 1994. Legume cover crop contributions to no-tillage corn production. Agron. J. 86, 126–135.

Delgado, J.A., Sparks, R.T., Follett, R.F., Sharkoff, J.L., Riggenbach, R.R., 1999. Use of Winter Cover Crops to Conserve Soil and Water Quality in the San Luis Valley of South Central Colorado, Soil Quality and Soil Erosion. Soil and Water Conservation Society, pp. 125–142.

Doran, J.W., 1980. Soil microbial and biochemical changes associated with reduced tillage. Soil Sci. Soc. Am. J. 44, 765–771.

Doran, J.W., Sarrantonio, M., Liebig, M.A., 1996. Soil health and sustainability. Adv. Agron. 56, 2–54.

Dou, Z., Fox, R.H., Toth, J.D., 1995. Seasonal soil nitrate dynamics in corn as affected by tillage and nitrogen source. Soil Sci. Soc. Am. J. 59, 858–864.

Drinkwater, L.E., 2004. Improving nitrogen fertilizer use efficiency through an ecosystem-based approach. In: Mosier, A.R., Syers, J.K., Freney, J.R. (Eds.), Agriculture and the Nitrogen Cycle: Assessing the Impacts of Fertilizer Use on Food Production and the Environment. SCOPE Nitrogen Fertilizer RAP, vol. 65. Island Press, Washington, DC, pp. 93–102.

Drinkwater, L.E., Janke, R.R., Rossoni, L.L., 2000. Effects of tillage intensity on nitrogen dynamics and productivity in legume-based grain systems. Plant Soil 227, 99–113.

Drinkwater, L.E., Letourneau, D.K., Workneh, F., Vanbruggen, A.H.C., Shennan, C., 1995. Fundamental differences between conventional and organic tomato agroecosystems in California. Ecol. Appl. 5, 1098–1112.

Drinkwater, L.E., Wagoner, P., Sarrantonio, M., 1998. Legume-based cropping systems have reduced carbon and nitrogen losses. Nature 396, 262–265.

Drinkwater, L.E., Snapp, S.S., 2005. Nutrients in agriculture: rethinking the management paradigm, http://dspace.library.cornell.edu/handle/1813/1477.

Drinkwater, L.E., Snapp, S.S., in press. Understanding and managing the rhizosphere in agroecosystems. In: Cardon, Z.G., J.L. Whitbeck (Eds.), The Rhizosphere – An Ecological Perspective. Elsevier Press.

Ebelhar, S.A., Frye, W.W., Blevins, R.L., 1984. Nitrogen from legume cover crops for no-tillage corn. Agron. J. 76, 51–55.

Fleming, A.A., Giddens, J.E., Beaty, E.R., 1981. Corn yields as related to legumes and inorganic nitrogen. Crop Sci. 21, 977–980.

Frye, W.W., Blevins, R.L., Smith, M.S., Corak, S.J., Varco, J.J., 1988. Role of annual legume cover crops in efficient use of water and nitrogen. Cropping Strategies for Efficient Use of Water and Nitrogen, vol. 51. W.L. Hargrove, Madison, WI, ASA-CSSA-SSSA, pp. 129–154.

Gallandt, E.R., Liebman, M., Huggins, D.R., 1999. Improving soil quality: implications for weed management. J. Crop Prod. 2, 95–121.

Galloway, J.N., Cowling, E.B., 2002. Reactive nitrogen and the world: 200 years of change. Ambio 31, 64–71.

Groffman, P.M., Hendrix, P.F., Crossley, D.A., 1987. Nitrogen dynamics in conventional and no-tillage agroecosystems with inorganic fertilizer or legume nitrogen inputs. Plant Soil 97, 315–332.

Gurevitch, J., Hedges, L.V., 1999. Statistical issues in ecological meta-analyses. Ecology (Washington, DC) 80, 1142–1149.

Hansen, E.M., Djurhuus, J., 1997. Nitrate leaching as influenced by soil tillage and catch crop. Soil Tillage Res. 41, 203–219.

Hargrove, W.L., 1986. Winter legumes as a nitrogen source for no-till grain sorghum. Agron. J. 78, 70–74.

Harris, G.H., Hesterman, O.B., Paul, E.A., Peters, S.E., Janke, R.R., 1994. Fate of legume and fertilizer nitrogen-15 in a long-term cropping systems experiment. Agron. J. 86, 910–915.

Hedges, L.V., Gurevitch, J., Curtis, P.S., 1999. The meta-analysis of response ratios in experimental ecology. Ecology (Washington DC) 80, 1150–1156.

Hedges, L.V., Olkin, I., 1985. Statistical methods for meta-analysis. Academic Press, Inc., Orlando, Florida.

Hendrix, P.F., Coleman, D.C., Crossley, D.A., 1992. Using knowledge of soil nutrient cycling processes to design sustainable agriculture. J. Sustain. Agric. 2, 63–82.

Herzog, H., Konrad, R., 1992. Nitrogen movement in an arable sandy soil and ways of reducing nitrogen losses preliminary results. J. Agron. Crop Sci. 169, 135–143.

Hesterman, O.B., Griffin, T.S., Williams, P.T., Harris, G.H., Christenson, D.R., 1992. Forage legume-small grain intercrops nitrogen production and response of subsequent corn. J. Prod. Agric. 5, 340–348.

Holderbaum, J.F., Decker, A.M., Meisinger, J.J., Mulford, F.R., Vough, L.R., 1990. Fall-seeded legume cover crops for no-tillage corn in the humid east. Agron. J. 82, 117–124.

Holderbaum, J.F., Decker, A.M., Mulford, F.R., Meisinger, J.J., Vough, L.R., 1987. Forage contributions of winter legume cover crops in no-till corn production. In: The Role of Legumes in Conservation Tillage Systems, Soil Conservation Society of America, Athens, Georgia, pp. 98–99.

Hossain, S.A., Dalal, R.C., Waring, S.A., Strong, W.M., Weston, E.J., 1996a. Comparison of legume-based cropping systems at Warra Queensland I. Soil nitrogen and organic carbon accretion and potentially mineralisable nitrogen. Aust. J. Soil Res. 34, 273–287.

Hossain, S.A., Strong, W.M., Waring, S.A., Dalal, R.C., Weston, E.J., 1996b. Comparison of legume-based cropping systems at Warra Queensland II. Mineral nitrogen accumulation and availability to the subsequent wheat crop. Aust. J. Soil Res. 34, 289–297.

Iragavarapu, T.K., Randall, G.W., Russelle, M.P., 1997. Yield and nitrogen uptake of rotated corn in a ridge tillage system. Agron. J. 89, 397–403.

Isse, A.A., MacKenzie, A.F., Stewart, K., Cloutier, D.C., Smith, D.L., 1999. Cover crops and nutrient retention for subsequent sweet corn production. Agron. J. 91, 934–939.

Izaurralde, R.C., Feng, Y., Robertson, J.A., McGill, W.B., Juma, N.G., Olson, B.M., 1995. Long-term influence of cropping systems, tillage methods, and N sources on nitrate leaching. Can. J. Soil Sci. 75, 497–505.

Izaurralde, R.C., Juma, N.G., McGill, W.B., Chanasyk, D.S., Pawluk, S., 1993. Performance of conventional and alternative cropping systems in cryoboreal subhumid central Alberta. J. Agric. Sci. 120, 33–41.

Janke, R.R., Claassen, M.M., Heer, W.F., Jost, J., Freyenberger, S., Norman, D., 2002. The use of winter annual legume cover crops in a wheat-grain sorghum rotation in south central Kansas. J. Sustain. Agric. 20, 69–88.

Johnson, D.W., Curtis, P.S., 2001. Effects of forest management on soil C and N storage: meta analysis. For. Ecol. Mgt. 140, 227–238.

Koerner, P.T., Power, J.F., 1987. Hairy vetch winter cover for continuous corn in Nebraska. In: The Role of Legumes in Conservation Tillage Systems, Soil Conservation Society of America, Athens, Georgia.

Kramer, A.W., Doane, T.A., Horwath, W.R., van Kessel, C., 2002. Short-term nitrogen-15 recovery vs. long-term total soil N gains in conventional and alternative cropping systems. Soil Biol. Biochem. 34, 43–50.

Kuo, S., Jellum, E.J., 2000. Long-term winter cover cropping effects on corn (*Zea mays* L.) production and soil nitrogen availability. Biol. Fertil. Soils 31, 470–477.

Ladd, J.N., Amato, M., Jackson, R.B., Butler, J.H.A., 1983. Utilization by wheat crops of nitrogen from legume residues decomposing in soils in the field. Soil Biol. Biochem. 15, 231–238.

Ladd, J.N., Amato, M., 1986. The fate of nitrogen from legume and fertilizer sources in soils successively cropped with wheat under field conditions. Soil Biol. Biochem. 18, 417–425.

Ladd, J.N., Oades, J.M., Amato, M., 1981. Distribution and recovery of nitrogen from legume residues decomposing in soils sown to wheat in the field. Soil Biol. Biochem. 13, 251–256.

LaRue, T.A., Patterson, T.G., 1981. How much nitrogen do legumes fix? Adv. Agron. 34, 15–38.

Lemon, R.G., Hons, F.M., Saladino, V.A., 1990. Tillage and clover cover crop effects on grain sorghum yield and nitrogen uptake. J. Soil Water Conserv. 125–127.

Lewis, W.J., Van, L.J.C., Phatak, S.C., Tumlinson III, J.H., 1997. A total system approach to sustainable pest management. Proc. Natl. Acad. Sci. USA 94, 12243–12248.

Liebhardt, W.C., Andrews, R.W., Culik, M.N., Harwood, R.R., Janke, R.R., Radke, J.K., Riegerschwartz, S.L., 1989. Crop production during conversion from conventional to low-input methods. Agron. J. 81, 150–159.

Lotter, D.W., Seidel, R., Liebhardt, W., 2003. The performance of organic and conventional cropping systems in an extreme climate year. Am. J. Alternative Agric. 18, 146–154.

Martinez, J., Guiraud, G., 1990. A lysimeter study of the effects of a ryegrass catch crop during a winter wheat-maize rotation on nitrate leaching and on the following crop. J. Soil Sci. 41, 5–16.

Martini, E.A., Buyer, J.S., Bryant, D.C., Hartz, T.K., Denison, R.F., 2004. Yield increases during the organic transition: improving soil quality or increasing experience? Field Crops Res. 86, 255–266.

Matson, P.A., Parton, W.J., Power, A.G., Swift, M., 1997. Agricultural intensification and ecosystem properties. Science 277, 504–509.

McCracken, D.V., Smith, M.S., Grove, J.H., MacKown, C.T., Blevins, R.L., 1994. Nitrate leaching as influenced by cover cropping and nitrogen source. Soil Sci. Soc. Am. J. 58, 1476–1483.

Mitchell, J.P., Shennan, C., Singer, M.J., Peters, D.W., Miller, R.O., Prichard, T., Grattan, S.R., Rhoades, J.D., May, D.M., Munk, D.S., 2000. Impacts of gypsum and winter cover crops on soil physical properties and crop productivity when irrigated with saline water. Agric. Water Manage. 45, 55–71.

Mitchell, W.H., Teel, M.R., 1977. Winter annual cover crops for no-tillage corn production. Agron. J. 69, 569–573.

Mitsch, W.J., Day Jr., J.W., Gilliam, J.W., Groffman, P.M., Hey, D.L., Randall, G.W., Wang, N., 2001. Reducing nitrogen loading to the Gulf of Mexico from the Mississippi River Basin: Strategies to counter a persistent ecological problem. Bioscience 51, 373–388.

Napier, T.L., Tucker, M., 2001. Use of soil and water protection practices among farmers in three Midwest watersheds. Environ. Manage. 27, 269–279.

Neely, C.L., McVay, K.A., Hargrove, W.L., 1987. Nitrogen contribution of winter legumes to no-till corn and grain sorghum. In: The Role of Legumes in Conservation Tillage Systems, Soil Conservation Society of America, Athens, Georgia.

Nissen, T.M., Wander, M.M., 2003. Management and soil-quality effects on fertilizer-use efficiency and leaching. Soil Sci. Soc. Am. J. 67, 1524–1532.

Olesen, J.E., Rasmussen, I.A., Askegaard, M., Kristensen, K., 2002. Whole-rotation dry matter and nitrogen grain yields from the first course of an organic farming crop rotation experiment. J. Agric. Sci. 139, 361–370.

Osenberg, C.W., Sarnelle, O., Cooper, S.D., Holt, R.D., 1999. Resolving ecological questions through meta-analysis: Goals, metrics, and models. Ecology (Washington, DC) 80, 1105–1117.

Oyer, L.J., Touchton, J.T., 1990. Utilizing legume cropping systems to reduce nitrogen fertilizer requirements for conservation-tilled corn. Agron. J. 82, 1123–1127.

Peoples, M.B., Angus, J.F., Swan, A.D., Dear, B.S., Hauggaard-Nielsen, H., Jensen, E.S., Ryan, M.H., Virgona, J.M., 2004. Nitrogen dynamics in legume-based pasture systems. In: Mosier, A.R., Syers, J.K., Freney, J.R. (Eds.), Agriculture and the Nitrogen Cycle: Assessing the Impacts of Fertilizer Use on Food Production and the Environment. SCOPE Nitrogen Fertilizer RAP.

Peoples, M.B., Herridge, D.F., Ladha, J.K., 1995. Biological nitrogen fixation: an efficient source of nitrogen for sustainable agricultural production? Plant Soil 174, 3–28.

Power, J.F., Doran, J.W., Koerner, P.T., 1991. Hairy vetch as a winter cover crop for dryland corn production. J. Prod. Agric. 4, 62–67.

Ranells, N.N., Wagger, M.G., 1997a. Grass-legume bicultures as winter annual cover crops. Agron. J. 89, 659–665.

Ranells, N.N., Wagger, M.G., 1997b. Winter annual grass-legume bicultures for efficient nitrogen management in no-till corn. Agric. Ecosyst. Environ. 65, 23–32.

Rasse, D.P., Ritchie, J.T., Peterson, W.R., Wei, J., Smucker, A.J.M., 2000. Rye cover crop and nitrogen fertilization effects on nitrate leaching in inbred maize fields. J. Environ. Qual. 29, 298–304.

Reganold, J.P., Elliott, L.F., Unger, Y.L., 1987. Long-term effects of organic and conventional farming on soil erosion. Nature 330, 370–372.

Ritter, W.F., Scarborough, R.W., Chirnside, A.E.M., 1998. Winter cover crops as a best management practice for reducing nitrogen leaching. J. Contam. Hydrol. 34, 1–15.

Roberson, E.B., Sarig, S., Firestone, M.K., 1991. Cover crop management of polysaccharide-mediated aggregation in an orchard soil. Soil Sci. Soc. Am. J. 55, 734–739.

Rosenberg, M.S., Adams, D.C., Gurevitch, J., 2000. Metawin statistical software for meta-analysis. Sinauer Associates, Inc..

Samson, R.A., Foulds, C.M., Patriquin, D.G., 1991. Effect of Cover Crops on Cycling of Nitrogen and Phosphorus in a Winter Wheat-Corn Sequence. Cover Crops for Clean Water Soil and Water Conservation Society, Jackson, TN, pp. 106–107.

Sanchez, J.E., Willson, T.C., Kizilkaya, K., Parker, E., Harwood, R.R., 2001. Enhancing the mineralizable nitrogen pool through substrate diversity in long term cropping systems. Soil Sci. Soc. Am. J. 65, 1442–1447.

Sanderson, J.B., MacLeod, J.A., Kimpinski, J., 1999. Glyphosate application and timing of tillage of red clover affects potato response to N, soil N profile, and root and soil nematodes. Can. J. Soil Sci. 79, 65–72.

Sarrantonio, M., 1991. Methodologies for Screening Soil-Improving Legumes. Rodale Institute Research Center, p. 310.

Sarrantonio, M., Scott, T.W., 1988. Tillage effects on availability of nitrogen to corn following a winter green manure crop. Soil Sci. Soc. Am. J. 52, 1661–1668.

Shepherd, M.A., 1999. The effectiveness of cover crops during eight years of a UK sandland rotation. Soil Use Manage. 15, 41–48.

Sinclair, T.R., Cassman, K.G., 1999. Green revolution still too green. Nature 398, 556.

Smil, V., 2000. Feeding the World: A Challenge for the Twenty-First Century. MIT Press, Cambridge, MA.

Smil, V., 1999. Nitrogen in crop production: an account of global flows. Global Biogeochem. Cycles 13, 647–662.

Snapp, S.S., Silim, S.N., 2002. Farmer preferences and legume intensification for low nutrient environments. Plant Soil 245, 181–192.

Snapp, S.S., Swinton, S.M., Labarta, R., Mutch, D., Black, J.R., Leep, R., Nyiraneza, J., ONeil, K., 2005. Evaluating benefits and costs of cover crops for cropping system niches. Agron. J. 97, 322–332.

Stivers, L.J., Shennan, C., 1991. Meeting the nitrogen needs of processing tomatoes through winter cover cropping. J. Prod. Agric. 4, 330–335.

Stute, J.K., Posner, J.L., 1995a. Legume cover crops as a nitrogen source for corn in an oat-corn rotation. J. Prod. Agric. 8, 385–390.

Stute, J.K., Posner, J.L., 1995b. Synchrony between legume nitrogen release and corn demand in the upper Midwest. Agron. J. 87, 1063–1069.

Sweeney, D.W., Moyer, J.L., 1994. Legume green manures and conservation tillage for grain sorghum production on prairie soil. Soil Sci. Soc. Am. J. 58, 1518–1524.

Thomsen, I.K., Christensen, B.T., 1998. Cropping system and residue management effects on nitrate leaching and crop yields. Agric. Ecosyst. Environ. 68 (1–2), 73–84.

Thomsen, I.K., Christensen, B.T., 1999. Nitrogen conserving potential of successive ryegrass catch crops in continuous spring barley. Soil Use Manage. 15, 195–200.

Thorup-Kristensen, K., Magid, J., Jensen, L.S., 2003. Catch crops and green manures as biological tools in nitrogen management in temperate zones. Adv. Agron. 79, 227–302.

Tiffin, P., Hesterman, O.B., 1998. Response of corn grain yield to early and later killed red clover green manure and subirrigation. J. Prod. Agric. 11, 112–121.

Tilman, D., 1999. Global environmental impacts of agricultural expansion: the need for sustainable and efficient practices. In: Proceedings of the National Academy of Sciences of the United States of America '96. pp. 5995–6000.

Torbert, H.A., Reeves, D.W., Mulvaney, R.L., 1996. Winter legume cover crop benefits to corn: rotation vs. fixed-nitrogen effects. Agron. J. 88, 527–535.

Torstensson, G., Aronsson, H., 2000. Nitrogen leaching and crop availability in manured catch crop systems in Sweden. Nutr. Cycl. Agro. 56, 139–152.

Utomo, M., Frye, W.W., Blevins, R.L., 1990. Sustaining soil nitrogen for corn using hairy vetch cover crop. Agron. J. 82, 979–983.

Vance, C.P., Uhde, S.C., Allan, D.L., 2003. Phosphorus acquisition and use: critical adaptations by plants for securing a nonrenewable resource. New Phytol. 157, 423–447.

Varco, J.J., Frye, W.W., Smith, M.S., MacKown, C.T., 1989. Tillage effect on nitrogen recovery by corn from a nitrogen-15 labeled legume cover crop. Soil Sci. Soc. Am. J. 53, 822–827.

Vaughan, J.D., Hoyt, G.D., Wollum, A.G., 2000. Cover crop nitrogen availability to conventional and no-till corn: Soil mineral nitrogen, corn nitrogen status, and corn yield. Comm. Soil Sci. Plant Anal. 31, 1017–1041.

Vitousek, P.M., Aber, J.D., Howarth, R.W., Likens, G.E., Matson, P.A., Schindler, D.W., Schlesinger, W.H., Tilman, D.G., 1997. Human alteration of the global nitrogen cycle: sources and consequences. Ecol. Appl. 7, 737–750.

Vyn, T.J., Faber, J.G., Janovicek, K.J., Beauchamp, E.G., 2000. Cover crop effects on nitrogen availability to corn following wheat. Agron. J. 92, 915–924.

Wagger, M.G., 1989. Time of desiccation effects on plant composition and subsequent nitrogen release from several winter annual cover crops. Agron. J. 81, 236–241.

Wander, M.M., Traina, S.J., Stinner, B.R., Peters, S.E., 1994. Organic and conventional management effects on biologically active soil organic matter pools. Soil Sci. Soc. Am. J. 58, 1130–1139.

West, T.O., Marland, G., 2002. A synthesis of carbon sequestration, carbon emissions, and next carbon flux in agriculture: comparing tillage practices in the United States. Agric. Ecosyst. Environ. 91, 217–232.

Wivstad, M., Salomonsson, L., Salomonsson, A.C., 1996. Effects of green manure, organic fertilizers and urea on yield and grain quality of spring wheat. Acta Agric. Scand. Sect. B Soil Plant Sci. 46, 169–177.

Woodmansee, R.G., 1984. Comparative nutrient cycles of natural and agricultural ecosystems: a step toward principles. In: Lowrance, R.Stinner, B.R., House, G.J. (Eds.), Agricultural Ecosystems: Unifying Concepts. John Wiley and Sons, pp. 145–156.

Wyland, L.J., Jackson, L.E., Chaney, W.E., Klonsky, K., Koike, S.T., Kimple, B., 1996. Winter cover crops in a vegetable cropping system: impacts on nitrate leaching, soil water, crop yield, pests and management costs. Agric. Ecosyst. Environ. 59, 1–17.

Yadvinder-Singh, Bijay-Singh, Khind, C.S., 1992. Nutrient transformations in soils amended with green manures. Adv. Soil Sci. 20, 237–309.

Younie, D., 1996. Legumes in Sustainable Farming Systems. Joint Conference of the British Grassland Society and the Sustainable Farming Systems Initiative SAC Craibstone British Grassland Society, Aberdeen, UK.