Published October 11, 2018

Journal of Environmental Quality REVIEWS AND ANALYSES

Cover Crops Reduce Nitrate Leaching in Agroecosystems: A Global Meta-Analysis

Resham Thapa, Steven B. Mirsky, and Katherine L. Tully*

Abstract

Cover crops are well recognized as a tool to reduce NO_3^- leaching from agroecosystems. However, their effectiveness varies from site to site and year to year depending on soil, cash and cover crop management, and climate. We conducted a meta-analysis using 238 observations from 28 studies (i) to assess the overall effect of cover crops on NO_3^- leaching and subsequent crop yields, and (ii) to examine how soil, cash and cover crop management, and climate impact the effect of non-leguminous cover crops on NO_3^- leaching. There is a clear indication that nonleguminous cover crops can substantially reduce NO_3^- leaching into freshwater systems, on average by 56%. Nonlegume–legume cover crop mixtures reduced NO_3^- leaching as effectively as nonlegumes, but significantly more than legumes. The lack of variance information in most published literature prevents greater insight into the degree to which cover crops can improve water quality. Among the factors investigated, we identified cover crop planting dates, shoot biomass, and precipitation relative to long-term mean precipitation as potential drivers for the observed variability in nonleguminous cover crop effectiveness in reducing NO_3^- leaching. We found evidence indicating greater reduction in NO_3^- leaching with nonleguminous cover crops on coarse-textured soils and during years of low precipitation (<90% of the long-term normal). Earlier fall planting and greater nonleguminous shoot biomass further reduced NO_3^- leaching. Overall, this meta-analysis confirms many prior studies showing that nonleguminous cover crops are an effective way to reduce NO_3^- leaching and should be integrated into cropping systems to improve water quality.

Core Ideas

- Nonleguminous cover crops reduced NO_3^- leaching by 56% over no cover crop controls.
- Nonlegume–legume mixtures reduced NO_3^- leaching equivalent to nonlegumes, but significantly more than legumes.
- Cover crop planting date, shoot biomass, and precipitation affected nonlegume effects on NO_3^- leaching.
- Nonlegumes reduced NO_3^- leaching more effectively on coarse-textured soils and in drier years.
- Earlier planting dates and greater shoot biomass enhanced NO_3^- leaching reductions with nonlegumes.

J. Environ. Qual. 47:1400–1411 (2018)
doi:10.2134/jeq2018.03.0107
Supplemental material is available online for this article.
Received 19 Mar. 2018.
Accepted 13 Sept. 2018.
*Corresponding author (kltully@umd.edu).

The invention of the Haber–Bosch process in the 20th century exponentially increased the production and consumption of synthetic N fertilizers, enabling global food production to support >7 billion people worldwide (Erisman et al., 2008). However, the inefficient use of fertilizer N leads to negative environmental consequences (Thapa et al., 2016; Russo et al., 2017; Thapa and Chatterjee, 2017). For example, excessive use of fertilizer N and the inability to precisely estimate N mineralization from previous crop residues and organic matter results in surplus N that can be lost to the environment after cash crop harvest. Even when fertilizer N is not supplied in excess, asynchrony between N supply and crop N demand can result in surplus N that is susceptible to leaching and denitrification. It has been reported that, on average, more than half of the fertilizer N applied to croplands enters into the environment, posing serious threats to air, water, and soil quality, as well as human health (Lassaletta et al., 2014).

Excess N after cash crop uptake is prone to leaching and can increase NO_3^- concentrations in ground and surface water bodies (Quemada et al., 2013; Zhao et al., 2016; Russo et al., 2017; Thapa and Chatterjee, 2017). Increased NO_3^- levels in aquatic ecosystems may result in eutrophication (i.e., algal blooms), which degrades aquatic habitats and harms aquatic species (Carpenter et al., 1998; McIsaac et al., 2001; Craig et al., 2005). The relationship between ecological damage associated with NO_3^- leaching into aquatic ecosystems has been well documented around the globe, including in the Baltic Sea, the Gulf of Mexico, and the Chesapeake Bay watershed (Rabalais et al., 2002; Kemp et al., 2005; Diaz and Rosenberg, 2008). Increased interest in restoring these aquatic ecosystems has resulted in significant efforts to tighten N cycling within the soil–crop–soil interface and minimize NO_3^- flows into ground- and surface water bodies.

Baker (2001) reported that fine-tuning farm management practices such as crop rotation, no-tillage, and N management for greater N use efficiency (i.e., application of the "4Rs") can collectively reduce NO_3^- leaching by 25 to 30%. However, adoption of these practices alone does not reduce NO_3^- leaching to acceptable levels because most NO_3^- leaching occurs during the fallow (late fall, winter, and early spring) period when there is no crop present to take up surplus N after cash crop harvest (Dinnes et al., 2002). Winter annual cover crops have been recognized

R. Thapa and S.B. Mirsky, Sustainable Agricultural Systems Lab., USDA-ARS, 10300 Baltimore Ave., Beltsville, MD 20705; R. Thapa and K.L. Tully, Dep. of Plant Science and Landscape Architecture, Univ. of Maryland, College Park, MD 20742. Assigned to Associate Editor Girisha Ganjegunte.

Abbreviations: CI, confidence interval; SOC, soil organic carbon.

as an effective means to capture surplus N and reduce NO_3^- leaching during this period (Meisinger et al., 1991; Dinnes et al., 2002; Tonitto et al., 2006; Quemada et al., 2013; Chatterjee and Clay, 2017; Tully and Ryals, 2017). Previous studies suggested that winter cover crops, especially nonlegumes such as grasses and broadleaf species, can reduce NO_3^- leaching by 35 to 70% depending on intrinsic (soil and climate) and extrinsic factors (management) (Tonitto et al., 2006; Quemada et al., 2013; Teixeira et al., 2016). The clear benefits of cover crops to reduce NO_3^- leaching has led to numerous state (IDALS, 2018; MACS, 2018) and federal (CSP, 2018; EQIP, 2018; NWQI, 2018) financial incentive programs in the United States to help offset cover crop expenses for farmers.

Besides reduction of NO_3^- leaching, cover crops also influence soil N, soil water, and weed dynamics, thereby affecting subsequent cash crop yields (Marcillo and Miguez, 2017). The N scavenged by cover crops during its growth will be rereleased and become available to the subsequent main crop after its termination Besides direct N contribution from decomposing cover crop residues, they also provide non-N rotation effects such as soil water storage and availability, weed suppression, reduction in disease and pest pressure, and improvement in soil physical, chemical, and biological properties (Torbert et al., 1996; Clark et al., 1997; Mirsky et al., 2013; Poeplau and Don, 2015). All these effects of cover crop residues after their termination will affect subsequent crop yields.

The amount of NO_3^- leached from croplands and the extent to which cover crops can reduce it depends on soil, cash and cover crop management, and climate factors (Baker, 2001; Dinnes et al., 2002; Macdonald et al., 2005; Silva et al., 2005; Teixeira et al., 2016). Using a modeling approach, Teixeira et al. (2016) identified cover crop planting dates, soil water-holding capacity, and precipitation as potential drivers for the observed variability in NO_3^- leaching reduction by cover crops. However, it is difficult to assess the effect of multiple covariates in a single field study. Resource limitations confine individual field studies to the assessment of the effect of cover crops on NO_3^- leaching reduction under specific soil types, cash and cover crop and soil management, and climate conditions; place-based research constrains the number of experimental treatments that can be contrasted. Using a meta-analytic approach, we can pool results from such field studies to investigate multiple confounding variables impacting the effect of cover crops on NO_3^- leaching.

Tonitto et al. (2006) conducted a meta-analysis involving studies that evaluated either catch crops undersown in the spring or winter cover crops and found 70% reduction in NO_3^- leaching with nonlegumes as compared with bare fallow controls. Since 2005, a substantial body of research (17 new peer-reviewed articles) has been conducted on the effects of winter cover crops on NO_3^- leaching. Three of these articles ended up in the Quemada et al. (2013) meta-analysis, who found 50% reduction in NO_3^- leaching with nonlegumes as compared with no cover crop controls. Moreover, neither of these meta-analyses assessed the impact of soil, cover and cash crop management, and climate on the relative effectiveness of winter cover crops on NO_3^- leaching. Although such explanatory variables were considered in Valkama et al. (2015), their work focused on catch crops undersown in spring cereals in the Nordic countries. Therefore, our work both integrates the plethora of new studies on the effects of winter cover crops on NO_3^- leaching and links the magnitude of these effects to a suite of explanatory variables. The main objectives of this meta-analysis were (i) to assess the effect of cover crops on NO_3^- leaching and subsequent crop yields, and (ii) to investigate the extent to which soil, cash and cover crop management, and climate impact the effectiveness of nonleguminous cover crops in reducing NO_3^- leaching.

Materials and Methods

Literature Review and Data Collection

We conducted a search of primary articles that compared NO_3^- leaching losses between cover crop and no cover crop treatments using the ISI Web of Science (Thompson Reuters) database. The following search terms were used for the literature survey: ('cover crop*' OR 'green manure*' OR 'catch crop*' OR 'rye' OR 'oat' OR 'vetch' OR 'clover' OR 'winter') AND ('nitrate leach*' OR 'nitrogen leach*' OR 'leach*' OR 'drain*'). This search produced 237 articles published in scientific journals from 1931 to 2017. All of these articles were screened for the following inclusion criteria: (i) the study compared winter cover crop treatments with no cover crop (control); (ii) NO_3^- leaching was measured during at least the cover crop growth period or for the entire year (during both cover crop and cash crop phases); (iii) cumulative NO_3^- leaching was calculated using both NO_3^- concentrations in the soil solution and the drainage volume; (iv) the study was conducted under natural field conditions (i.e., model-based simulation and indoor lysimeter studies were excluded); (v) all other factors (soil, management, and climate) for each pairwise comparison between no cover crop and cover crop treatments were the same; and (vi) the experimental design, approach, and sampling protocols were clearly described. We excluded studies in which the potential risk of NO_3^- leaching was assessed by comparing profile soil N over the cover crop season. Studies with a long history of pasture prior to the experimental year were also excluded because of the potential legacy effect of previous pasture or forage crops on NO_3^- leaching that could mask the true cover crop effect. Similarly, studies that were conducted on recently constructed drainage lysimeters or monoliths using disturbed soils were also discarded because the disturbed soil structure in these monoliths could influence drainage characteristics and, hence, NO_3^- leaching. We also excluded studies in which the treatment combinations impeded sole comparison between no cover crop and cover crop treatments.

Out of 14 studies included in the meta-analysis by Tonitto et al. (2006), only five of them fulfilled our abovementioned inclusion criteria and were included in this meta-analysis. The remaining nine studies included in the Tonitto et al. (2006) meta-analysis did not fulfill our inclusion criteria: four studies evaluated catch crops undersown in the spring (Hansen and Djurhuus, 1997; Aronsson and Torstensson, 1998; Thomsen and Christensen, 1999; Torstensson and Aronsson, 2000), three studies reported only NO_3^- concentrations (Herzog and Konrad, 1992; Ball-Coelho and Roy, 1997; Isse et al., 1999), one study used recently constructed drainage lysimeters (McCracken et al., 1994), and one study compared different farming systems (Drinkwater et al., 1998). Similarly, only five out of eight studies included in the Quemada et al. (2013) meta-analysis fulfilled our inclusion criteria. Among the remaining three studies that were not included in this meta-analysis, one study evaluated catch crops undersown in the spring (Hansen and Djurhuus, 1997), one used recently constructed drainage lysimeters (McCracken et al., 1994), and the study by Salmerón et al. (2010) applied differing amount of N inputs between cover crop and no cover crop control treatments. In total, we found 22 articles that fulfilled our inclusion criteria. Additional articles were identified by screening the citation and reference lists of the articles already included in our database. There were 28 relevant articles that were finally included in our meta-analysis (Table 1).

We extracted data on NO_3^- leaching for the no cover crop and cover crop treatments from the selected articles. If the study provided NO_3^- leaching data separately for the cover crop (during cover crop growth) and the subsequent main crop (after cover crop termination) season, we calculated annual NO_3^- leaching by adding them together. When available, data on cash crop yields were also recorded. We also collected information on study site location (latitude and longitude), soil (texture and organic C), cash crop management (tillage and crop rotation), cover crop management (species, planting dates, and shoot biomass), and climate (total water input), variables that could potentially influence cover crop effectiveness in NO_3^- leaching reduction. Data were collected from both tables and figures. Data presented in figures were extracted using WebPlotDigitizer version 3.8 (Rohatgi, 2017). Moreover, there were differences in methodology used to measure NO_3^- leaching among studies (Table 1). Although studies conducted in drainage lysimeters and drained fields directly measured drainage volumes, studies using ceramic cup lysimeters used simple water balance or simulation models to estimate drainage volume beyond the crop root zone.

Cover crop species were divided into three groups: nonleguminous, leguminous, and nonlegume–legume cover crop mixtures. Nonleguminous cover crops included both grasses and broadleaves. To further evaluate variability on the relative effectiveness of nonleguminous cover crops in reducing NO_3^- leaching, we collected information related to soil texture, cash and cover crop management, and climate. The soil texture subgroups included fine (>30% clay), medium (<30% clay and <45% sand), and coarse (>45% sand) (Thapa et al., 2016). If the particle size distribution data were not available, we used textural class information to categorize soil. The soil organic C (SOC) content subgroups included: <1, 1 to 2, and >2%. The tillage subgroups included reduced versus conventional tillage. There were also grass versus broadleaf comparisons, planting date subgroups (August, September, October, and November), and shoot biomass subgroups (<1, 1–2, 2–4, 4–8, and >8 Mg ha^{-1}). The planting date subgroups were appropriate for temperate regions of North America and Europe. To elucidate the relationship between NO_3^- leaching reduction with nonleguminous cover crops and total water input (precipitation + irrigation) over the monitoring period, we calculated precipitation relative to the long-term mean precipitation (Zhao et al., 2016). Precipitation relative to the long-term mean precipitation was calculated by dividing the total water input (precipitation + irrigation) at each site during the monitoring period by the long-term mean precipitation during the same period at that site. We categorized precipitation relative to the long-term mean precipitation values into five subgroups: <70, 70 to 90, 90 to 110, 110 to 130, and >130%, respectively (Zhao et al., 2016).

Cumulative Meta-analysis

The effect sizes of cover crops on NO_3^- leaching and cash crop yields were calculated as the natural logarithm of the response ratios (Hedges et al., 1999):

$$\ln(R) = \ln\left(\bar{X}_{\mathrm{CC}}/\bar{X}_{\mathrm{NCC}}\right) = \ln\left(\bar{X}_{\mathrm{CC}}\right) - \ln\left(\bar{X}_{\mathrm{NCC}}\right) \quad [1]$$

where ln(R) is the natural log of response ratios, and $\bar{X}_{\mathrm{CC}}$ and $\bar{X}_{\mathrm{NCC}}$ are the mean values of the response variables (NO_3^- leaching or crop yields) for cover crop and no cover crop treatments, respectively. As such, ln(R) could not be calculated when the mean value for any one of the treatments was zero. In such cases, we substituted zero with the minimum possible value (e.g., a NO_3^- leaching value of 0.0 kg ha^{-1} was replaced with 0.1 kg ha^{-1} and a value of 0.00 kg ha^{-1} with 0.01 kg ha^{-1}, respectively). Since our meta-analysis was based on ln(R) calculated for each pairwise comparison, with and without cover crops, the overall effect size was independent of the differences related to variability in methodology adopted to measure NO_3^- leaching (data not shown).

More than one ln(R) was calculated for the same study when results from multiple cover crop treatments, years, and sites were reported; these effect sizes were considered independent observations during analysis. We also included effect sizes when more than one study was conducted on the same site as independent observations in the analysis. However, our approach could be confounded by nonindependence (Van den Noortgate et al., 2013). Nonindependence occurs when multiple effect sizes from the same study and from the same experimental site are more correlated with each other than effect sizes from different studies and different sites. Similarly, multiple cover crop treatments sharing the same control (no cover crop) treatment may lead to dependent effect sizes (Lajeunesse, 2011). To account for various sources of dependency between effect sizes within and across studies, we created a multilevel mixed effects meta-analytic model using the *nlme* package in R (Van den Noortgate et al., 2013; Pinheiro et al., 2017). Effect sizes were treated as fixed effects, whereas random effects were specified in the nesting structure site/study/site-year/controls to account for dependencies between multiple effect sizes sharing the same control and multiple effect sizes from the same site-year, study, and experimental site (Thapa et al., 2018).

In a conventional meta-analysis, individual effect sizes are typically weighted by the inverse of sampling variances to provide more weight to studies with greater precision or lower within-study variability (Philibert et al., 2012). Many studies included in this analysis, however, did not report information on within-study variability (SDs, SEs, or CV), information that is required to compute sampling variances. Therefore, we used an alternative weighting technique based on experimental replications (Adams et al., 1997):

$$w_i = \left(N_{\mathrm{CC}} N_{\mathrm{NCC}}\right) / \left(N_{\mathrm{CC}} + N_{\mathrm{NCC}}\right) \quad [2]$$

where w_i is the weight for i^{th} observation and N_{CC} and N_{NCC} are the number of replications for the cover crop and no cover crop treatments, respectively. In one study with no true replication (Ritter et al., 1998), we averaged the response variable over years and used the number of experimental years as replication size. Finally, we employed a cluster-based robust variance estimation

Table 1. Summary of the studies included in this meta-analysis.

Reference	Location	Experimental years	Soil texture	Cover crop species	Cash crop	NO_3^- leaching measurements			Response variable	
						Method	Duration	Sampling depth	NO_3^- leaching	Crop yields
								cm		
Beckwith et al., 1998	UK	1990–1994	Sandy loam, loamy sand	Cereal rye	NA†	Ceramic cup lysimeters	Cover crop	90	Yes	NA†
Brandi-Dohrn et al., 1997	Oregon, USA	1992–1995	Loam/Silt loam	Cereal rye	Sweet corn, broccoli	Capillary wick lysimeters	Cover crop	120	Yes	Yes‡
Campiglia et al., 2011	Italy	1999–2001	Sandy clay loam	Vetch, clover, vetch–oat	Wheat, pepper	Drainage lysimeters	Annual§	NA	Yes	Yes
Catt et al., 1998	UK	1988–1993	Clay	Mustard, Rape	Barley, beans	Drained fields	Annual	100	Yes	Yes
Constantin et al., 2010	France	1990–2007	Loam	Cereal rye, mustard, radish	Wheat, barley, pea, corn, sugarbeet	Ceramic cup lysimeters	Annual	90–110	Yes	Yes
Daigh et al., 2015	Iowa, USA	2010–2013	Clay loam, sandy clay loam	Cereal rye	Corn	Subsurface drains	Annual	110	Yes	Yes
Drury et al., 2014	Ontario, Canada	1999–2005	Clay loam	Winter wheat	Corn, soybean	Tile drained fields	Annual	60–70	Yes	Yes
Feaga et al., 2010	Oregon, USA	1992–2002	Loam, silt loam	Cereal rye, triticale, vetch–triticale	Sweet corn, broccoli, snap beans	Capillary wick lysimeters	Annual	120	Yes	NA
Fraser et al., 2013	New Zealand	2000–2007	Silt loam	Rape	Barley, wheat, peas	Ceramic cup lysimeters	Cover crop	60	Yes	NA
Gabriel et al., 2012	Spain	2006–2010	Silty clay loam	Barley, vetch	Corn	Ceramic cup lysimeters	Annual	120	Yes	Yes‡
Heinrich et al., 2014	California, USA	2010–2012	Loam, clay loam	Cereal rye	Lettuce	Ceramic cup lysimeters	Cover crop	60	Yes	NA
Herrera and Liedgens, 2009	Switzerland	2000–2002	Sandy loam	Sunflower, phacelia, mustard	Spring wheat	Drainage lysimeters	Annual	110	Yes	Yes
Herrera et al., 2010	Switzerland	2000–2002	Sandy loam	Sunflower, phacelia, mustard, turnip–cabbage hybrid	Spring wheat	Drainage lysimeters	Cover crop	110	Yes	NA
Hooker et al., 2008	Ireland	2003–2005	Sandy loam	Mustard	Barley	Ceramic cup lysimeters	Annual	90	Yes	NA
Kaspar et al., 2007	Iowa, USA	2002–2005	Clay loam	Cereal rye	Corn, soybean	Tile drained fields	Annual	120	Yes	Yes
Kaspar et al., 2012	Iowa, USA	2006–2009	Clay loam	Cereal rye, oat	Corn, soybean	Tile drained fields	Annual	120	Yes	Yes
Macdonald et al., 2005	UK	1991–1994	Silty clay loam	Cereal rye, rape, mustard, phacelia	Barley	Ceramic cup lysimeters	Annual	90	Yes	NA
Martinez and Guiraud, 1990	France	1987–1988	Loam	Cereal rye	Wheat, corn	Drainage lysimeters	Annual	100	Yes	Yes
Meisinger and Ricigliano, 2017	Maryland, USA	1994–1997	Silt loam	Cereal rye, barley, winter wheat	NA	Drainage lysimeters	Annual	100	Yes	NA
Premrov et al., 2014	Ireland	2006–2009	Sandy loam	Mustard	Barley	Ceramic cup lysimeters	Cover crop	90	Yes	NA
Qi et al., 2011	Iowa, USA	2005–2009	Clay loam	Cereal rye	Corn, soybean	Subsurface drains	Annual	100	Yes	Yes
Rasse et al., 2000	Michigan, USA	1995–1998	Sandy loam	Cereal rye	Corn	Drainage lysimeters	Annual	183	Yes	Yes
Ritter et al., 1998	Delaware, USA	1989–1991	Loamy sand	Cereal rye	Corn	Monitoring wells	Annual	300–450	Yes	Yes
Shepherd and Webb, 1999	UK	1993–1997	Loamy sand	Stubble turnips	Barley	Drainage lysimeters	Cover crop	120	Yes	Yes
Shepherd, 1999	UK	1988–1996	Loamy sand	Cereal rye, stubble turnips	Sugarbeet, potato	Ceramic cup lysimeters	Cover crop	100	Yes	Yes
Shepherd and Lord, 1996	UK	1989–1993	Loamy sand	Cereal rye	Wheat	Ceramic cup lysimeters	Cover crop	100	Yes	NA
Strock et al., 2004	Minnesota, USA	1998–2002	Clay loam	Cereal rye	Corn, soybean	Subsurface tile drains	Annual	120	Yes	Yes
Tosti et al., 2014	Italy	2006–2009	Clay loam	Barley, vetch, barley–vetch	NA	Ceramic cup lysimeters	Cover crop	90	Yes	NA

† NA, data not available.

‡ Data for crop yields were taken from other sources: Burket et al. (1997) and Gabriel and Quemada (2011) for Brandi-Dohrn et al. (1997) and Gabriel et al. (2012), respectively.

§ Both cover crop and cash crop seasons.

technique (clustering on site) using the *clubSandwich* package to estimate robust SEs for mean effect sizes (Pustejovsky, 2017). Using robust SEs, we calculated the 95% confidence interval (CI) for the weighted natural log mean effect sizes [ln(R)]. For ease of interpretation, ln(R) values were back-transformed to mean effect sizes and expressed as percentage change in response due to cover crop treatments:

$$\%\text{ change in response} = \left[e^{\ln(R)} - 1\right] \times 100\% \quad [3]$$

The mean effect sizes for each response variable were considered significantly different from the controls ($p < 0.05$) only if the 95% CI did not include zero.

Moderator Analysis

We further assessed if the mean effect size of nonleguminous cover crops on NO_3^- leaching was affected by potential covariates, such as soil (soil texture and SOC), management (tillage), cover crop (nonlegume category, planting dates, and shoot biomass), and climate (precipitation relative to the long-term precipitation). For moderator analysis, a separate ln(R) was calculated using each moderator variables as a sole covariate in the multilevel mixed effect meta-analytic model described above; robust SEs were estimated following cluster-based robust variance estimation. To protect against experiment-wise Type I errors, we calculated 99% CI around ln(R) for each moderator variable (Thapa et al., 2018). The mean effect sizes for each moderator variable were considered significant ($p < 0.01$) only if the 99% CI did not include zero. When the 99% CI for different categories of each moderator variables did not overlap, they were also considered to be significantly different from each other ($p < 0.01$). To examine the relationship between effectiveness of nonleguminous cover crops in NO_3^- leaching reductions and other moderator variables such as shoot biomass and precipitation relative to the long-term mean precipitation, linear and quadratic regression analysis were performed and the best fits were reported.

Publication Bias and Sensitivity Analysis

We investigated our meta-analysis for publication bias. In the literature, publication bias is assessed using funnel plots that compare effect sizes to precision (inverse of sampling variances) or sample sizes (Møller and Jennions, 2001; Philibert et al., 2012). However, funnel plots are not an appropriate tool to detect bias in our analysis because sampling variances were not available in most of the studies included and the sample sizes did not have sufficient range to create meaningful funnel plots (Basche and DeLonge, 2017). Therefore, we indirectly evaluated this meta-analysis for biases toward publishing significant positive or negative results using histogram of the individual effect sizes (Basche and DeLonge, 2017). Histograms of overall effect size estimates suggested that observations were equally distributed between slightly positive and slightly negative values, indicating no publication bias (Supplemental Fig. S1). We also performed sensitivity analysis using the *Jacknife* procedure to test the robustness of the overall effect sizes to individual study sites (Philibert et al., 2012). Using this stepwise procedure, we excluded one study site from our database at a time and recalculated the overall effect size estimates by fitting the above statistical model to the remaining data. The overall effect size estimates (both in magnitude and direction) did not vary due to omission of any study site, indicating that the estimates from this meta-analysis were highly robust (Supplemental Fig. S2).

Results

Most of the studies included in this meta-analysis evaluated the effectiveness of nonleguminous cover crops in reducing NO_3^- leaching (216 observations from 27 studies), whereas leguminous and nonlegume–legume cover crop mixtures were evaluated in only three studies with 9 and 13 observations, respectively. Compared with no cover crop controls, nonleguminous cover crops significantly reduced NO_3^- leaching by 56% (95% CI = −66 to −43%, Fig. 1a); legumes alone or in combination with nonlegumes had no significant effect on NO_3^- leaching. Analysis of data, after exclusion of observations from a study by Campiglia et al. (2011) conducted in Italy, showed significant reduction in NO_3^- leaching with both leguminous cover crops (mean = −10%, 95% CI = −16 to −5%) and nonlegume–legume cover crop mixtures (mean = −45%, 95% CI = −48 to −42%). There was no significant effect of cover crops on subsequent crop yields (Fig. 1b).

We further explored the extent to which nonleguminous cover crops reduce NO_3^- leaching by examining how this effect is influenced by soil, cash and cover crop management, and climate. Across all soil textural and SOC groups, there was significant reduction in NO_3^- leaching with nonleguminous cover crops compared with no cover crop controls (Fig. 2a and 2b). The effectiveness of nonleguminous cover crops to reduce NO_3^- leaching did not differ among soil textural and SOC groups (Fig. 2a and 2b). Although not significantly different, there was a trend toward greater effectiveness of nonleguminous cover crops in NO_3^- leaching reduction on coarse-textured soils (mean = −65%, 99% CI = −77 to −49%) than on fine-textured soils (mean = −43%, 99% CI = −59 to −20%). Compared with no cover crop controls, nonleguminous cover crops also significantly reduced NO_3^- leaching across both tillage (reduced vs. conventional) groups (Fig. 3). However, the mean effect of nonleguminous cover crops on NO_3^- leaching reduction did not differ between reduced and conventional tillage systems.

In this meta-analysis, we observed that both grasses and broadleaf species were equally effective in reducing NO_3^- leaching losses (Fig. 4a). Compared with no cover crop controls, grasses and broadleaf species reduced NO_3^- leaching by 50% (99% CI = −61 to −37%) and 67% (99% CI = −77 to −54%), respectively. Cover crop planting dates and shoot biomass at termination also impacted the mean effect of nonleguminous cover crops on NO_3^- leaching (Fig. 4b and 5). Early-planted nonleguminous cover crops significantly reduced NO_3^- leaching compared with no cover crop controls (mean reduction of 64, 60, and 49% for August-, September-, and October-planted nonlegume cover crops, respectively). When planting nonleguminous cover crops after November, there was no advantage of having a cover crop on NO_3^- leaching (mean = −28%, 99% CI = −50 to 3%; Fig. 4b). Similarly, there was a significant proportional relationship between shoot biomass (nonleguminous) and NO_3^- leaching, relative to no cover crop controls (Fig. 5). For the five shoot biomass categories of <1, 1 to 2, 2 to 4, 4 to 8, and >8 Mg ha^{-1}, the weighted mean effects of nonleguminous cover crops on NO_3^- leaching were −36, −48, −70, −74, and −71%,

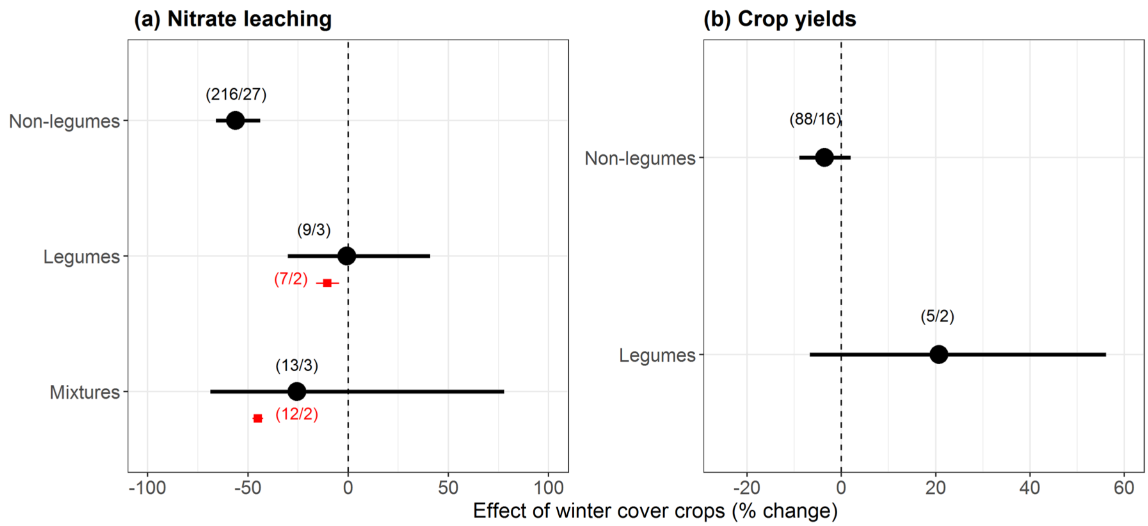

Fig. 1. Percentage change in (a) NO_3^- leaching and (b) subsequent crop yields due to cover crops compared with no cover crop controls. Numbers in parentheses represent the number of observations followed by the number of studies for each pairwise comparison. Error bars are 95% confidence intervals (CIs). The solid red rectangles and corresponding CIs in Panel a represent results of the analysis after excluding observations from a study by Campiglia et al. (2011). The mean effect sizes were considered significantly different only when the 95% CIs did not overlap with zero.

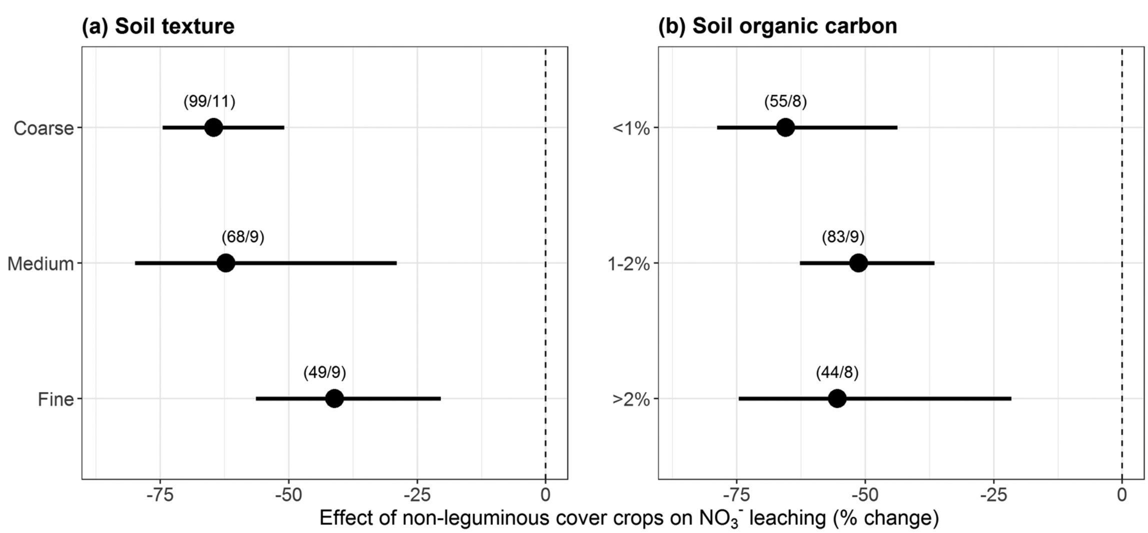

Fig. 2. Percentage change in NO_3^- leaching due to nonleguminous cover crops compared with no cover crop controls for each soil group: (a) soil texture and (b) soil organic C. Numbers in parentheses represent the number of observations followed by the number of studies for each pairwise comparison. Error bars are 99% confidence intervals (CIs). The mean effect sizes were considered significantly different only when the 99% CIs did not overlap with zero. The mean effect sizes for different subgroups were considered significantly different from one another only if the 99% CIs did not overlap.

respectively. Reduction in NO_3^- leaching with nonleguminous cover crops was significantly greater in the higher biomass categories of 4 to 8 Mg ha^{-1} (mean = −74%, 99% CI = −83 to −59%) and >8 Mg ha^{-1} (mean = −71%, 99% CI = −80 to −58%) than in the lower biomass category of <1 Mg ha^{-1} (mean = −36%, 99% CI = −53 to −13%). The quadratic curve provided the best fit between cover crop shoot biomass and the relative effectiveness of nonleguminous cover crops in NO_3^- leaching reductions, suggesting that the NO_3^- leaching reductions with nonleguminous cover crops increased with increasing shoot biomass and plateaued between 4 and 8 Mg ha^{-1} (Fig. 5).

The mean values for the relative precipitation categories (<70, 70–90, 90–110, 110–130, and >130% of the long-term mean) were 60, 80, 103, 120, and 157%, respectively (Fig. 6). The weighted mean effects of nonleguminous cover crops on NO_3^- leaching reduction in response to these five relative precipitation categories were −71, −67, −52, −44, and −41%, respectively (Fig. 6). Although there was no significant difference between specific categorical contrasts, when examined with regression, the effectiveness of nonleguminous cover crops in reducing NO_3^- leaching decreased linearly with increase in precipitation relative to the long-term mean precipitation (Fig. 6). In other words, nonleguminous cover crops were slightly better at reducing NO_3^- leaching in drier years (years with precipitation below the long-term average) than in wet years (years with precipitation above the long-term average).

Discussion

Overall Effect of Cover Crops

Despite the high degree of variability that is typical to NO_3^- leaching experiments, our results indicate that nonleguminous

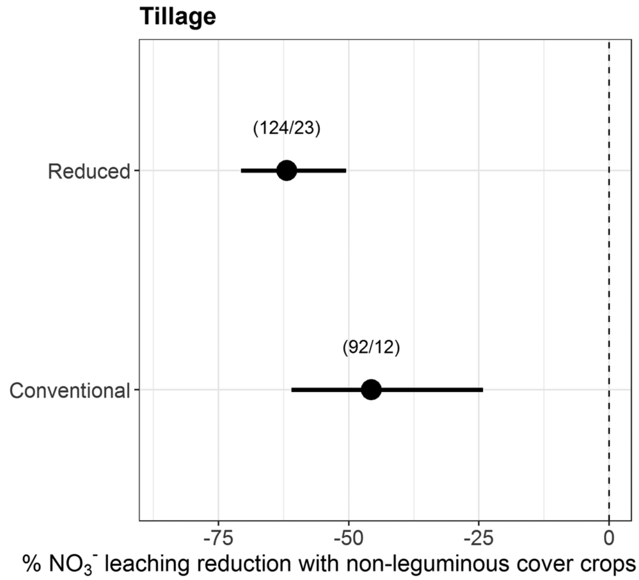

Fig. 3. Percentage change in NO_3^- leaching due to nonleguminous cover crops compared with no cover crop controls for different soil tillage systems. Numbers in parentheses represents the number of observations followed by the number of studies for each pairwise comparison. Error bars are 99% confidence intervals (CIs). The mean effect sizes were considered significantly different only when the 99% CIs did not overlap with zero. The mean effect sizes for different subgroups are considered significantly different from one another only if the 99% CIs did not overlap.

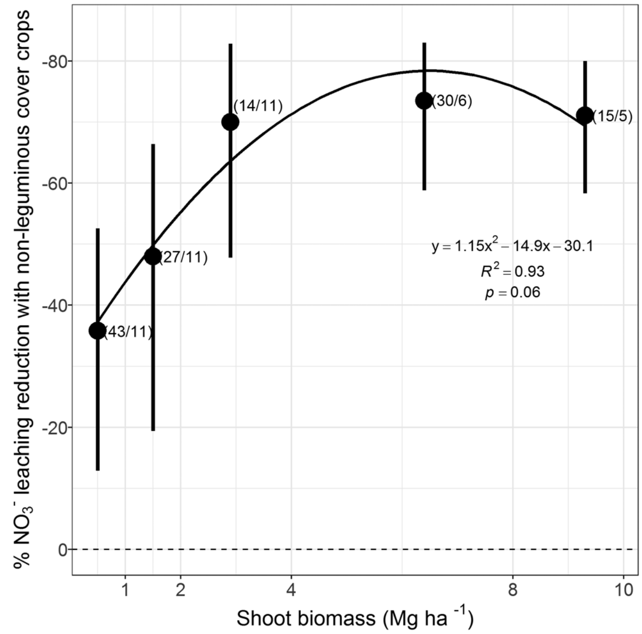

Fig. 5. Percentage change in NO_3^- leaching due to nonleguminous cover crops compared with no cover crop controls for each cover crop shoot biomass groups. Numbers in parentheses represent the number of observations followed by the number of studies for each pairwise comparison. Error bars are 99% confidence intervals (CIs). The mean effect sizes were considered significantly different only when the 99% CIs did not overlap with zero. The mean effect sizes for different subgroups are considered significantly different from one another only if the 99% CIs did not overlap.

cover crops reduced NO_3^- leaching by 56% compared with no cover crop controls (Fig. 1a). This is in line with the previous meta-analysis conducted by Quemada et al. (2013). In another meta-analysis, Valkama et al. (2015) evaluated the effects of nonleguminous catch crops undersown in spring cereals in Nordic countries and found a 50% reduction in N leaching. However, the reduction in NO_3^- leaching with nonleguminous cover crops found in our meta-analysis was slightly lower than that found by Tonitto et al. (2006), who calculated a 70% reduction in NO_3^- leaching with nonleguminous cover crops compared with no cover crop controls. The reductions in NO_3^- leaching with nonleguminous cover crops could be explained by three major mechanisms: (i) reduction in drainage or leachate volume due to an increase in evapotranspiration in cover crops compared to no cover crop control, (ii) reduction in NO_3^- concentrations in the leachate by growing cover crops via uptake of residual soil N in the fall that is otherwise leached from the system, and (iii) microbial immobilization from C inputs to soil from cover crop roots (Strock et al., 2004; Macdonald et al., 2005; Kaspar et al., 2007, 2012; Qi and Helmers, 2010; Gabriel et al., 2012; Blesh and Drinkwater, 2014).

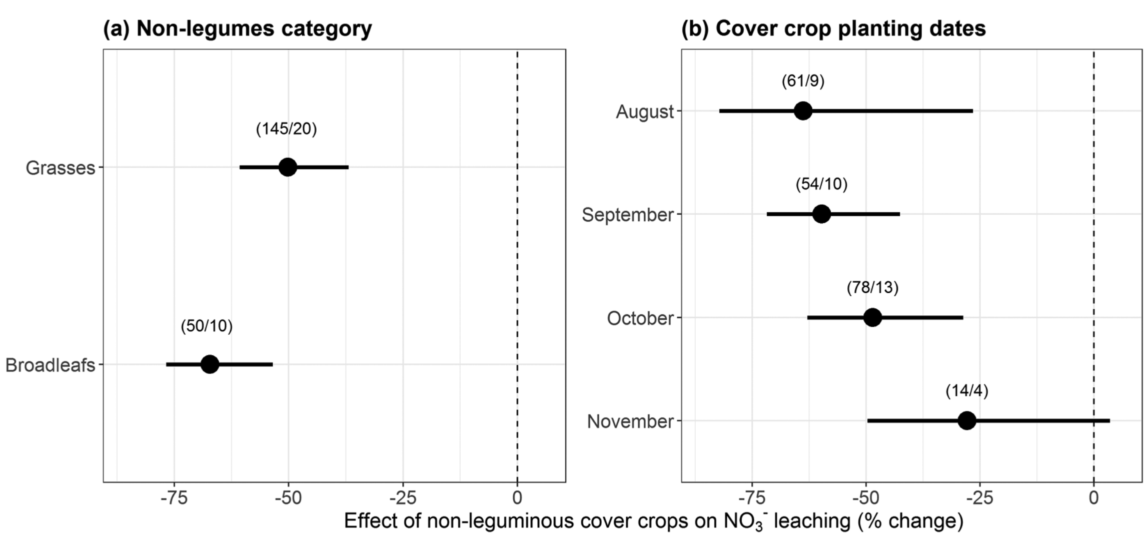

Fig. 4. Percentage change in NO_3^- leaching due to nonleguminous cover crops compared with no cover crop controls for each cover crop factors: (a) nonlegume category and (b) cover crop planting dates. Numbers in parentheses represent the number of observations followed by the number of studies for each pairwise comparison. Error bars are 99% confidence intervals (CIs). The mean effect sizes were considered significantly different only when the 99% CIs did not overlap with zero. The mean effect sizes for different subgroups are considered significantly different from one another only if the 99% CIs did not overlap.

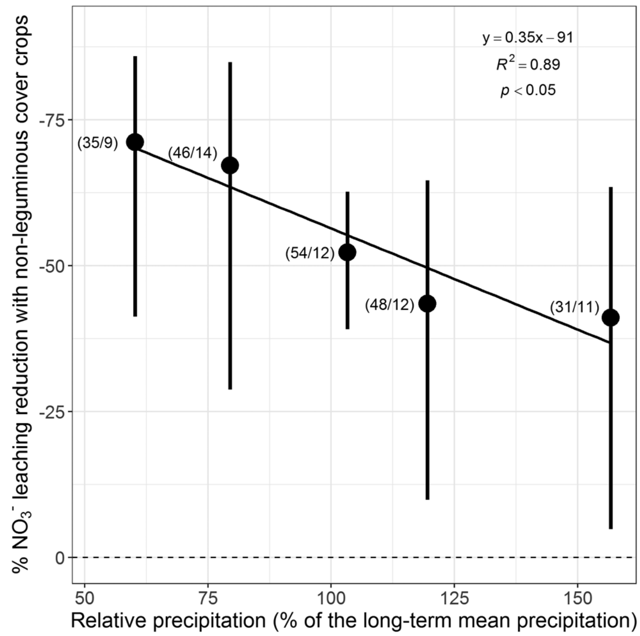

Fig. 6. Percentage change in NO_3^- leaching due to nonleguminous cover crops compared with no cover crop controls for each relative precipitation group. Numbers in parentheses represent the number of observations followed by the number of studies for each pairwise comparison. Error bars are 99% confidence intervals (CIs). The mean effect sizes were considered significantly different only when the 99% CIs did not overlap with zero. The mean effect sizes for different subgroups are considered significantly different from one another only if the 99% CIs did not overlap.

Leguminous and nonlegume–legume cover crop mixtures, on the other hand, had no significant effect on NO_3^- leaching losses (Fig. 1a and 1c). However, it should be noted that the observed effect of leguminous and nonlegume–legume cover crop mixtures on NO_3^- leaching was based on a relatively small number of observations. We found only three studies with 9 and 13 observations, respectively, that reported NO_3^- leaching values for leguminous cover crops and nonlegume–legume cover crop mixtures, respectively, in comparison with no cover crop controls. In only one study conducted by Campiglia et al. (2011) in Italy, both legumes and nonlegume–legume cover crop mixtures had significantly higher NO_3^- leaching values than no cover crop controls. Campiglia et al. (2011) further observed that greater NO_3^- leaching from legumes and nonlegume–legume cover crop mixtures occurred during the subsequent cash crop period after termination of cover crops and was associated with the asynchrony between N released from cover crop residues and N demand of the cash crop. In an experiment by Campiglia et al. (2011), the quick release of N from cover crop residues (low C/N ratio), the poor ability of coarse-textured soils (53.1% sand) to retain N, and the low N uptake by cash crop pepper (*Capsicum annuum* L.) as a result of slower growth altogether resulted in poor asynchrony and greater NO_3^- leaching losses following hairy vetch (*Vicia villosa* Roth), subterranean clover (*Trifolium subterraneum* L.), and hairy vetch–oat (*Avena sativa* L.) mixtures. In the remaining three studies (Feaga et al., 2010; Gabriel et al., 2012; Tosti et al., 2014) that evaluated NO_3^- leaching losses with leguminous, nonlegume–legume cover crop mixtures, or both, cover crops either had no effect or significantly reduced NO_3^- leaching compared with no cover crop controls. When Campiglia et al. (2011) was excluded from the analysis, we found that nonlegume–legume cover crop mixtures (mean = −45%, 95% CI = −48 to −42%) reduced NO_3^- leaching more effectively than leguminous cover crops (mean = −10%, 95% CI = −16 to −5%), but as effectively as nonleguminous cover crops (mean = −56%, 95% CI = −66 to −43%) (Fig. 1a). Besides NO_3^- leaching reductions, the intermediate C/N ratio (25–30:1) in the residues from nonlegume–legume cover crop mixtures results in a more balanced N mineralization and immobilization turnover and improves N synchrony as compared with both nonleguminous and leguminous cover crops (Ranells and Wagger, 1997; Rosecrance et al., 2000; Poffenbarger et al., 2015; Thapa et al., 2018). Therefore, if the goal is to effectively reduce NO_3^- leaching and reduce N fertilizer requirements of the subsequent cash crop through cover crop N credits, we suggest cover crop mixtures composed of both nonleguminous (for N scavenging) and leguminous (for N supply) components.

Our results indicated that cover crops had no significant effect on subsequent cash crop yields (Fig. 1b). However, our results were limited to smaller datasets and, therefore, may not reflect the actual effect of cover crops on crop yields. A more comprehensive meta-analysis of the effects of cover crops on subsequent corn (*Zea mays* L.) yields in the United States and Canada was conducted by Marcillo and Miguez (2017) involving 268 observations from 65 studies conducted between 1965 and 2015. They found that nonleguminous cover crops had no effect on subsequent corn yields, but leguminous cover crops and legume–nonlegume cover crop mixtures significantly increased subsequent corn yields by 21 and 13%, respectively, compared with no cover crop controls. These authors further suggest that the positive response of corn yields to cover crops was more pronounced in no-till systems, at lower N application rates, and when cover crops were terminated late.

Effect of Moderator Variables

Soil

In agreement with the findings from a previous meta-analysis by Valkama et al. (2015) and a simulation experiment by Teixeira et al. (2016), we found that nonleguminous cover crops consistently reduced NO_3^- leaching across all soil textural groups and SOC levels (Fig. 2a and 2b). This suggests that adopting nonleguminous cover crops is a crucial strategy to mitigate NO_3^- leaching from agroecosystems. Reduction in NO_3^- leaching with nonleguminous cover crops could be ascribed to decrease in both leachate volume and NO_3^- concentrations in the soil water through uptake by cover crops during its growth. This is particularly important for coarse-textured soils and soils deprived in SOC; these soils are naturally well drained, have low water-holding and NO_3^- retentive capabilities, and are more prone to NO_3^- leaching (Silva et al., 2005; Dean and Weil, 2009; Teixeira et al., 2016). Although not statistically different, in this meta-analysis, we observed greater reductions in NO_3^- leaching with nonleguminous cover crops in coarse-textured soils (−65%) than in fine-textured soils (−43%). In the long run, use of cover crops may also improve water-holding and NO_3^- retention abilities of the soil matrix by building up SOC stocks (Poeplau and Don, 2015).

Management

In a recent meta-analysis, Daryanto et al. (2017) found that NO_3^- leaching was significantly greater in reduced tillage systems than in conventional tillage systems primarily due to increased leachate volume under reduced tillage systems. Higher leachate loads under reduced tillage systems may be linked to frequent availability of macropores (preferential flow channels) and better soil infiltrability (Baker, 2001). Our meta-analysis suggests that reduced tillage systems should be supplemented with nonleguminous cover crops to improve soil N retention, reduce leachate loads, and ultimately minimize the risk of NO_3^- leaching (Fig. 3). We found that nonleguminous cover crops reduced NO_3^- leaching by 62% compared with no cover crop controls in reduced tillage systems. Even in conventional tillage systems, nonleguminous cover crops reduced NO_3^- leaching by 46%. According to this meta-analysis, nonleguminous cover crops should be the integral part of cropping systems to reduce NO_3^- leaching and improve water quality irrespective of tillage practices.

Cover Crop Species

We found that both grasses and broadleaf species were equally effective in reducing NO_3^- leaching as no cover crop controls (Fig. 4a). However, it is important to note that the observed differences in NO_3^- leaching between grasses and broadleaf species are limited by study characteristics. In all the studies included in this meta-analysis, broadleaf species were planted early (late August to early September) in the fall. Moreover, most of these studies had mild winters with temperatures not low enough to winterkill broadleaf species. Both early planting and mild winters resulted in a long growing season for broadleaf species, favoring shoot and root growth and enabling them to reduce NO_3^- leaching as effectively as grasses. Our results align with previous studies reporting that early-planted broadleaf species are equally effective or, in some cases, outcompete grasses in terms of biomass production, N accumulation, and N scavenging (Vos and van der Putten, 1997; Weinert et al., 2002; Kristensen and Thorup-Kristensen, 2004; Dean and Weil, 2009). However, in practice, farmers cannot achieve such early planting dates in many row cropping systems. When these species were planted at typical planting dates (late September to October) that many cropping systems can afford, Vos and van der Putten (1997) found that grasses (e.g., winter rye [*Secale cereale* L.]) outperform broadleaf species (e.g., forage rape [*Brassica napus* L.]) in terms of biomass production and N accumulation. This could translate into lower effectiveness of broadleaf species for reducing NO_3^- leaching than grasses in many row crops, where planting of cover crops is usually delayed to late September or October. In such systems, alternative planting techniques such as interseeding or aerial seeding might help early establishment of broadleaf species for effective N scavenging. Our hypothesis, however, needs further investigation. The effectiveness of broadleaf species to reduce NO_3^- leaching can be further exacerbated by severe winters and frost periods during their growth. Most broadleaf species such as mustard (*Sinapis alba* L.), rape, radish (*Raphanus sativus* L.), or phacelia (*Phacelia tanacetifolia* Benth.) winterkill at temperatures below −5°C, release N early in the spring, and can increase the risk of NO_3^- leaching risk, particularly in well-drained coarse-textured soils (Dean and Weil, 2009; Herrera and Liedgens, 2009).

Cover Crop Planting Dates

Compared with no cover crop controls, significant reductions in NO_3^- leaching were observed when nonleguminous cover crops were planted in August, September, and October (Fig. 4b). Delay in the planting of nonleguminous cover crops until November resulted in no significant reduction in NO_3^- leaching compared with no cover crop controls (Fig. 4b). Teixeira et al. (2016) also estimated that delaying nonleguminous cover crop planting date can suppress their ability to reduce NO_3^- leaching. This reduction in efficacy results from the shortened growth period and concomitantly decreased biomass yield and N uptake as compared to early-planted cover crops (Vos and van der Putten, 1997; Kristensen and Thorup-Kristensen, 2004; Feyereisen et al., 2006). Decline in biomass accumulation and N uptake with delayed planting dates are more prominent for broadleaf than grass species and underscores the importance of cover crop planting date and the species-specific dynamics (Vos and van der Putten, 1997). Moreover, the yields and N uptake of late-planted cover crops may be negatively affected by harsh winter weather (low temperature and solar radiation) (Teixeira et al., 2016). Therefore, timely establishment of cover crops in the fall is a must to maximize biomass production and N accumulation (i.e., greater immobilization of soil N in plant tissues) and minimize NO_3^- leaching.

Cover Crop Shoot Biomass

Our results further suggest that the efficacy of nonleguminous cover crops in reducing NO_3^- leaching was positively correlated with the shoot biomass at termination (Fig. 5). The quadratic curve provided the best fit, suggesting that the NO_3^- leaching reductions with nonleguminous cover crops peaked at biomass levels between 4 and 8 Mg ha^{-1}. Finney et al. (2016) also observed that the soil N retention capacity of cover crops was positively correlated with shoot biomass and concluded that the efficacy of cover crops in reducing potentially leachable NO_3^- increased with increasing biomass. All these results suggest that greater cover crop biomass at termination increased N uptake and decreased soil NO_3^- susceptibility to leaching. A decline in soil NO_3^- concentrations with increasing cover crop biomass will consequently decrease NO_3^- concentrations in soil drainage water, thereby reducing NO_3^- leaching more effectively as biomass levels increase (Blesh and Drinkwater, 2014). Besides reductions in NO_3^- leaching, increased cover crop biomass can enhance numerous other agroecosystem services in cropping systems, including weed suppression (Mohler and Teasdale, 1993; Mirsky et al., 2013; Finney et al., 2016), SOC sequestration (Blanco-Canqui et al., 2015; Poeplau and Don, 2015), and soil protection by reducing water and wind erosion (Blanco-Canqui et al., 2013), and can also influence soil N and water availability for the subsequent main crop.

Climate

Increases in total precipitation, in general, increased NO_3^- leaching with and without cover crops (data not shown). In a recent meta-analysis, Zhao et al. (2016) also observed that NO_3^- leaching increased with increasing precipitation relative to the long-term mean precipitation. Drainage volume increases as total precipitation increases; consequently, the risk of NO_3^- leaching also increases (Qi and Helmers, 2010). Interannual rainfall variability also impacted the effectiveness of nonleguminous cover crops in reducing NO_3^- leaching. We found that the effect of nonleguminous cover crops in reducing NO_3^- leaching decreases with increasing precipitation relative to the long-term mean precipitation, suggesting greater reductions in NO_3^- leaching with nonleguminous cover crops in drier than in wetter years (Fig. 6). In drier years (when the relative precipitation falls below 90% of the long-term mean precipitation), nonleguminous cover crops reduced NO_3^- leaching by 67 to 71% compared with no cover crop controls. However, in wet years (when the relative precipitation falls beyond 110% of the long-term mean precipitation), the effectiveness of nonleguminous cover crops in reducing NO_3^- leaching decreased (41–44% reductions compared with no cover crop controls).

Limitations of this Study and Future Considerations

Nitrate fluxes in agricultural soils have a high degree of spatial variability. However, most studies included in this meta-analysis did not report any information on within-study variability such as SD, SE, CV, or LSD. We therefore strongly suggest that some measures of within-study variability be reported to provide readers a general sense of spatial variability within each treatment and to allow quantitative data analysis. Even within each plot, the NO_3^- fluxes varied spatially to a great extent. The commonly practiced method of measuring soil solution NO_3^- concentrations using ceramic cup lysimeters may not truly capture the existing spatial variability of NO_3^- fluxes. If available, multiple ceramic cup lysimeters should be installed within each plot to capture spatial variability over small areas.

This meta-analysis documents the strong positive correlation between high nonleguminous cover crop biomass at termination and effectiveness in reducing NO_3^- leaching. Given these results, any factors that influence cover crop growth and productivity will also influence its effectiveness in reducing NO_3^- leaching. One such factor is soil N availability (residual soil N left after previous crop uptake in the fall and N mineralized from previous crop residues or soil organic matter) during the fall and spring growth period. In general, NO_3^- leaching increases as soil N availability increases (White et al., 2017). Under such conditions, cover crops could be an effective tool to retain soil N and reduce NO_3^- leaching. However, studies included in this meta-analysis did not report residual soil N and leftover previous crop residues in the fall, limiting our ability to evaluate the impact of these factors. Future studies should, therefore, report these variables so that the effectiveness of cover crops in reducing NO_3^- leaching can be assessed under high versus low soil N availability scenarios. The interaction between soil N availability in the fall, cover crop growth and productivity, and NO_3^- leaching can also be tested by creating soil N gradients through application of varying rates of N fertilizers in the fall before planting cover crops (Mirsky et al., 2017).

Conclusions

Our results clearly indicate that integrating nonleguminous cover crops into a cropping system can substantially reduce NO_3^- leaching (on average by 56%). The lack of variance information included in most published work prevents greater insight into the degree to which cover crops can mitigate NO_3^- loadings into freshwater systems. Leguminous cover crops, once terminated, can increase the risk of NO_3^- leaching if the N released while growing and during early decomposition is not recaptured by a companion cover crop or the subsequent cash crop. Since cover crops are typically terminated 2 to 6 wk prior to cash crop planting, there are long periods of time where there are no living plants removing reactive N. Therefore, strategies to reduce NO_3^- leaching should not only focus on growing cover crops to efficiently scavenge N during its growth, but also on efficient use of the N captured by cover crops after termination. To tailor N release from leguminous and broadleaf cover crops with N demand of the succeeding cash crop, we suggest planting leguminous and broadleaf cover crops in mixture with grasses (White et al., 2017).

The ability of nonleguminous cover crops to reduce NO_3^- leaching was affected by cover crop planting date, shoot biomass, and climate (relative precipitation). There was some indication of greater effectiveness of nonleguminous cover crops in reducing NO_3^- leaching on coarse-textured soils than on fine-textured soils. Early planting in the fall and increasing shoot biomass in the spring both increased the duration of cover crop growth and therefore N scavenging. Finally, the impact of nonleguminous cover crops on reducing NO_3^- leaching increased as precipitation relative to the long-term mean precipitation decreased, suggesting a greater effect of nonleguminous cover crops in drier years. If the goal is to reduce NO_3^- leaching and concomitant environmental impacts, we strongly recommend integrating nonleguminous cover crops in regions that have sufficient precipitation to support both cover and cash crops.

Supplemental Material

The supplemental material includes publication bias and sensitivity analysis to text the robustness of the analysis. Supplemental Fig. S1 depicts histograms of the individual effect sizes for different response variables: (a) NO_3^- leaching and (b) subsequent crop yields. Supplemental Fig. S2 depicts variations in the overall effect size estimates (mean ± 95% CIs) of cover crops on(a) NO_3^- leaching and (b) subsequent crop yields, when a particular study site is omitted from the analysis.

Acknowledgments

We sincerely thank the authors of all primary studies from which data were extracted for this meta-analysis. We also express our gratitude to Dr. Victoria Ackroyd (Research Scientist, Sustainable Agricultural Systems Laboratory, USDA-ARS) for reviewing the early draft of this meta-analysis, and to the associate editor and three anonymous reviewers for their valuable comments that improved our manuscript. The first author (R. Thapa) is also grateful for the funding support from the USDA National Resources Conservation Services, Conservation Innovation Grant no. 8042-21660-004-36-R, and a Northeast Sustainable Agriculture Research and Education graduate student grant (Award no. GNE17-160-31064).

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