A critical review of the impacts of cover crops on nitrogen leaching, net greenhouse gas balance and crop productivity

Abdalla, M; Hastings, A; Cheng, Kun; Yue, Q; Chadwick, David; Espenberg, Mikk; Truu, Jaak; Rees, RM; Smith, Pete

Published in:
Global Change Biology

DOI:
10.1111/gcb.14644

Print publication: 01/08/2019

Document Version
Peer reviewed version

Citation for pulished version (APA):
Abdalla, M., Hastings, A., Cheng, K., Yue, Q., Chadwick, D., Espenberg, M., Truu, J., Rees, RM., & Smith, P. (2019). A critical review of the impacts of cover crops on nitrogen leaching, net greenhouse gas balance and crop productivity. *Global Change Biology*, *25*(8), 2530-2543. https://doi.org/10.1111/gcb.14644

A critical review of the impacts of cover crops on nitrogen leaching, net greenhouse gas balance and crop productivity

Mohamed Abdalla[a], Astley Hastings[a], Kun Cheng[b], Qian Yue[b], Dave Chadwick[c], Mikk Espenberg[d], Jaak Truu[d], Robert M Rees[e], Pete Smith[a]

[a]Institute of Biological and Environmental Sciences, School of Biological Sciences, University of Aberdeen, Aberdeen, AB24 3UU, UK.

[b]Institute of Resource, Ecosystem and Environment of Agriculture, and Centre of Climate Change and Agriculture, Nanjing Agricultural University, Nanjing, Jiangsu, China.

[c]School of Natural Resources, Bangor University, Bangor, Gwynedd, LL57 2UW, UK.

[d]Faculty of Science and Technology, University of Tartu, Tartu, Estonia.

[e]Scotland's Rural College (SRUC) Edinburgh, West Mains Road, Edinburgh, EH93JG, UK.

Key words: Cover crop, Catch crop, N leaching, Soil organic carbon, N in grain, Nitrous oxide emissions, net greenhouse gas balance, green manure, yield, N content, nitrate, C sequestration

Abstract

Cover crops play an increasingly important role in improving soil quality, reducing agricultural inputs and improving environmental sustainability. The main objectives of this critical global review and systematic analysis were to assess cover crop practices in the context of their impacts on nitrogen leaching, net greenhouse gas balances (NGHGB) and crop productivity. Only studies that investigated the impacts of cover crops and measured one or a combination of: nitrogen leaching, soil organic carbon (SOC), nitrous oxide (N_2O), grain yield and nitrogen in grain of primary crop, and had a control treatment were included in the analysis. Long-term studies were uncommon, with most data coming from studies lasting 2-3 years. The literature search resulted in 106 studies carried out at 372 sites and covering different countries, climatic zones and management. Our analysis demonstrates that cover crops significantly ($p<0.001$) decreased N leaching and significantly ($p<0.001$) increased SOC sequestration without having significant ($p>0.05$) effects on direct N_2O emissions. Cover crops could mitigate the NGHGB by 2.06 ±2.10 Mg CO_2-eq ha^{-1} y^{-1} and significantly ($p<0.05$) increase N in grain of the primary crops. One of the potential disadvantages of cover crops identified was the reduction in grain yield of the primary crop by ≈3.9%, compared to the control treatment. This drawback could be avoided by selecting mixed cover crops with a range of legumes and non-legumes, which increased the yield by ≈13%. These advantages of cover crops justify their widespread adoption. However, management practices in relation to cover crops will need to be adapted to specific soil, management and regional climatic conditions.

Introduction

Increasing crop productivity with reduced inputs and lower impacts on the environment is a major current challenge for global food production. Cover crops (also known as catch crops) are plants mostly grown after a primary crop is harvested, in regions of the world where only a single main crop is grown (such as North Europe, North China and Canada). This avoids periods of bare soil which are associated with greater risk of erosion and nitrogen leaching losses (Battany and Grismer, 2000). Cover cropping can comprise of a single species or a mixture of species and can use annual, biennial, or perennial vegetation. Cover crops can be killed (or ploughed-in) in winter or spring, or grazed, and incorporated in soils by tillage to prevent competition with the primary crop, and to promote mineralization of organic N (Dabney et al., 2011). They can also left on the soil surface over the fall and winter periods, until a primary crop in no-till is planted, to provide weed control and N inputs (Halde et al., 2014).

Cover crops can increase water holding capacity, soil porosity, aggregate stability, the size of the microbial population and its activity and nutrient cycling (Lotter et al., 2003; Drinkwater and Snapp, 2007; Harunaa & Nkongolo, 2015). There are four classes of cover crops: legumes (e.g. alfalfa, vetches and clover), non-legumes (spinach, canola and flax), grasses (e.g. ryegrass and barley) and brassicas (e.g. radishes and turnips). The two main types of cover crops are legumes and non-legumes. Legume cover crops have the ability to fix nitrogen (N) biologically and increase soil organic matter (SOM) content (Lüsher et al., 2014). They can be used as a green manure to improve soil nutrition for the subsequent primary crop. On the other hand, non-legume cover crops can absorb excess nitrate from the soil, increase crop biomass, and improve soil quality (Finney et al., 2016; White et al., 2016). Farmers, generally, select specific types of cover crops based on their own needs and goals influenced by biological, environmental, social, cultural and economic factors of the farming systems in which they operate (Snapp et al., 2005). Additionally, cover crops have become of greater interest for their potential to provide additional ecosystem services in agricultural systems (e.g. reduce erosion, improve water quality and enhance biodiversity). In Spain, Hontoria et al. (2019) found that the use of barley as a winter CC is an appropriate choice to promote arbuscular mycorrhizal fungal populations and biological activity in soils with intercropping systems.

Nitrogen leaching from agricultural soils is of great concern due to its contribution to excess nitrate (NO_3) concentrations in ground water and run-off (Ascott et al., 2017), indirect emissions of greenhouse gases (GHGs) e.g. nitrous oxide (N_2O) (Delgado et al., 2008), and loss of expensive N fertilizer (Cardenas et al., 2011). This problem is more pronounced in areas with fertilized coarse-textured soils (Basche et al., 2014) or areas with high precipitation (Thorup-Kristensen et al., 2003). In England, Allingham et al. (2002) reported an average NO_3

leaching value of 65 kg N ha^{-1}, which is approximately 25% of total N input. Similar NO_3 losses, as a proportion of the total N applied, have been reported following livestock slurry and poultry manure applications to arable soils (Chambers et al., 2000). Previous studies have found that replacing fallow periods with non-legume cover crops is an effective management practice to withdraw soil N into the biomass of the cover crops and to reduce NO_3 leaching (Kaspar and Singer, 2011; Quemada et al., 2013; Basche et al., 2014). Cover crops can also increase soil organic carbon (SOC) stocks in agricultural soils (Poeplau and Don, 2015), since more C and N are added to the soil pools as cover crop residues decompose (Steenwerth and Belina, 2008; Kaspar and Singer, 2011). The amounts of C and N incorporated into the soil depend on many factors e.g. the amount, quality and management of the residues, soil type, frequency of tillage and climatic conditions (Stevenson, 1982; Smith et al., 1996). However, it is still not clear how cover crops affect the net greenhouse gas balance (NGHGB). Further, there is conflicting evidence on the influence of the cover crops on grain yields and N in the grain of primary crops. Some previous studies found that under-sowing of cover crops in spring could lead to a high level of competition with the primary crop for nutrients, soil moisture and light, and result in some loss of the grain yield (Karlsson-Strese et al., 1998; Känkänen et al., 2001, 2003). Other studies found that grain yield of the primary crops was not affected (Wallgren and Lindén, 1994; Ohlander et al., 1996) or was even increased (Campiglia et al., 2011). Mixed results have also been reported for the effects of cover crops on N in grain of the primary crop (Thomsen, 2005; Rinnofner et al., 2008; Doltra and Olesen, 2013).

The main objectives of this global review and systematic analysis were to investigate the impacts of cover crops (legume, non-legume and legume-non-legume mixed) on N leaching, the NGHGB and crop productivity in terms of grain yield and N content in the grain of the primary crop. We also investigated whether soil characteristics, field management and climatic zones can modify these effects, and through this, we assessed the viability of cover crops as a management tool to enhance C sequestration, reduce N loss from agroecosystems and maintain crop production. The specific hypotheses we critically evaluated were as follows: 1) cover crops decrease N loss and increase SOC accumulation, 2) the impacts of cover crops on N loss and SOC are modified by soil, management and climatic zones, and 3) including cover crops in crop rotations improves grain yield and N in grain of the primary crop.

Materials and Methods

Data collection

To analyse the publications that have investigated the impacts of cover crops on N leaching, SOC, N_2O, grain yield and N in grain for different primary crops (e.g. wheat, barley, oats, corn and others), we made a comprehensive search on the Web of Science database (accessed between January, 2017 and September, 2018) using the keywords: Cover crop, Catch crop, N leaching, Soil organic carbon, N in grain, Nitrous oxide emissions, GHG balance, green manure, yield, N content, nitrate and C sequestration. To gain the best possible coverage of the topic, we also checked all references in the papers collected from the Web of Science search. We only selected studies that investigated the effects of cover crops (legume, non-legume and legume-non-legume mixed), covered at least one growing season and measured one or a combination of: N leaching, SOC, N_2O, grain yield and N in grain of primary crop, and had a control treatment. Nitrous oxide data were collected from studies that measured the flux from cropland and applied either a static or automated chamber method. In some studies SOC values are given as concentrations. To convert these values to stocks (t ha^{-1}), we applied equation 1 below (Guo & Gifford, 2002):

$$Cs = (SOC * BD * D)/10 \tag{1}$$

Where, Cs is soil organic carbon stocks (Mg ha^{-1}); SOC is soil organic carbon concentration (g kg^{-1}); BD (g cm^{-3}); and D is soil depth (cm).

For SOC and N leaching data, we selected studies that measured them from zero and up to 30 and 100 cm soil depth, respectively. To improve comparability of the different studies, we normalized the SOC data to the top 30 cm and the N leaching data to the top 100 cm depth, using the depth distribution method produced by Jobbágy and Jackson (2001) (equations 2-4).

$$Y = 1 - \beta^{d} \quad (2)$$

$$SOC_{30} = ((1-\beta^{30}) / (1-\beta^{d0})) * SOC_{d0} \quad (3)$$

$$N_{100} = ((1-\beta^{100}) / (1-\beta^{d0})) * N_{d0} \quad (4)$$

Where Y is the cumulative proportion of the SOC or soil N leaching pool from the soil surface to depth d (cm); ß is the relative rate of decrease in the soil SOC or N pool with soil depth (0.9786 for SOC and 0.9831 for N) (Jobbágy and Jackson 2000; Jobbágy and Jackson 2001). SOC_{30} or N_{100} is the SOC (t ha^{-1}) or N (kg N ha^{-1}) pool in the upper 30 or 100 cm depth, respectively; d_0 is the original soil depth available in individual studies (cm); SOC_{d0} or N_{d0} is the original soil SOC or N pool.

We defined the control treatment as an annual fertilized primary crop with a bare fallow period between harvest and the establishment of the next primary crop. Where two main crops are grown synchronously, they are usually then referred to as intercrops, and such systems were not considered further in this review. We excluded many studies either because there was no control or because the experimental treatments did not meet the above criteria. Our literature search resulted in 106 studies carried out at 372 sites (Tables S1-S5) that investigated the impacts of cover crops on N leaching, grain yield and N in grain of primary crop, SOC, N_2O emissions, respectively, and covering different countries, climatic zones and management systems. The majority of the studies collected were short-term experiments of 2-3 years. Locations, climatic conditions as well as primary crop, cover crops, type of cover crops (legume, non-legume or legume-non-legume mixed), study duration, tillage, N fertilizer application rate, soil texture, soil depth (cm), bulk density (BD), soil pH and measurements from control and treatments i.e. N leaching, grain yield, N in grain of primary crop, SOC and N_2O, are shown in Tables S1-S5. When there was more than one year of study in the original paper, we used the mean value for different years. We included different methods for measuring N leaching (e.g. field cores, ceramic suction cup lysimeter, and subsurface drainage lysimeter). Nitrogen leaching was measured/ calculated in kg N ha^{-1} y^{-1} whilst SOC and grain yield in t ha^{-1} y^{-1}, and N in grain in g N m^{-2} y^{-1}. We found 78% of the N leaching dataset collected had conventional tillage systems whilst the rest (22%) was divided between the different types of conservation tillage systems (i.e. no-till, reduced till and minimum till) or had no data. Therefore, we investigated the influence of tillage on cover crop efficiency to reduce N leaching, N_2O and SOC by comparing between conventional and conservation tillage systems.

To investigate the impacts of climate, we divided our dataset into four groups depending on the climatic zones. Climatic zones were distinguished on the basis of temperature and moisture regimes (cool, warm, dry and moist zone) to represent the global variations of soil moisture and temperature. The cool zone covers the temperate (oceanic, sub-continental, and continental) and boreal (oceanic, sub-continental and continental) areas, whilst the warm zone covers the tropics (lowland and highland) and subtropical (summer rainfall, winter rainfall, and low rainfall) areas (Smith et al., 2008; Abdalla et al., 2018). The dry zone includes the areas where the annual precipitation is ≤ 500 mm, whilst the moist zone includes areas where the annual precipitation is > 500 mm (Smith et al., 2008). The four climate categories were; moist cool (MC), moist warm (MW), dry cool (DC) and dry warm (DW). However, to investigate the influences of climatic zones on the efficiency of cover crops to reduce N leaching and SOC, comparisons were made between the MC and MW only as most of the dataset belong to these two climatic zones: MC (68%) and MW (24%). The two other climatic zones both have only four observations.

For the different studies, different methods were used to measure soil pH e.g. using a pH probe or meter in deionized water or 0.01 M $CaCl_2$ in 1:1 and 1:2 or 1:5 (v:v) soils: solution ratios. We assumed the pH results to be equivalent, and where a range of values were reported we took the arithmetic mean. The mean annual air temperature (MAAT, in ^oC) value, and mean annual precipitation (MAP, in mm) values for each study, were collected from the original published papers. The locations of experiments used in this study were plotted on a map of net primary production (NPP) calculated using the Miami method (Lieth, 1972; Grieser et al., 2006), to indicate the diversity of arable capability included (Fig. 1).

2.2 Direct/ indirect N_2O emissions and net greenhouse gas balance (NGHGB)

The direct N_2O emissions data were collected from the literature (Table S5). Following Tier I IPCC protocol (IPCC, 2006) and Parkin et al. (2016), we estimated the indirect N_2O emissions for the control and cover crop treatments from the N leaching using the EF of 0.0075 multiplied by the mass of N leached. The change in the indirect N_2O emissions due to cover crops were then calculated as shown in Table S1. The indirect emissions associated with NH_3 and NO_x were not estimated. The contributions of SOC (Table S4) and N_2O to the NGHGB were calculated using the IPCC (2013) approach, where on a mass basis, N_2O has a global warming potential (GWP) of 298 times that of CO_2, over a 100-year timescale. The methane (CH_4) flux was considered to be negligible as, generally, cropland soils tend to be well drained and oxygenated and are often small net CH_4 sinks (Lee et al., 2006; Abdalla et al., 2014). The NGHGB was calculated as the difference between the increases in GWP due to higher direct N_2O emissions and the decreases due to higher SOC accumulation and lower indirect N_2O emissions under the cover crops.

Data analyses

We used R version 3.5.2 (R Development Core Team, 2018) to perform exploration, harmonisation and analyses of the data. The distributions of N leaching, grain yield, N in grain, N_2O and SOC measurements were characterised using the “fitdistrplus” package version 1.0-14 (Delignette-Muller and Dutang 2015). To investigate difference on all sites where both the control and cover crop treatments (cover crop types, climatic zones, tillage systems) had N leaching, grain yield, N in grain, N_2O and SOC measurements, we used the “glmer” method with random effect (different studies) and Gamma (link “log”) distribution (version 1.1-19) (Bates et al., 2015), while p-values were calculated in order to confirm the significance of the relationships using the “lmerTest” package version 3.0-1 (Kuznetsova et al., 2017). The same method was performed to test whether there was a significant difference in N leaching, grain yield, N in grain, N_2O emissions and SOC between cover crops, tillage, climatic zones and soil texture types. A linear mixed effects model function was applied to investigate whether there was an effect of cover crops, tillage, climatic zones and soil texture types on physicochemical values. Analysis of covariance (ANCOVA) was used to compare N leaching (%) of cover crops (legume, non-legume and legume-non-legume mixed), with added N fertilizer as covariate in the model. The package “akima” version 0.6-2 was used to create interpolated contour plots (Akima and Gebhardt, 2015) of pairs of the BD, pH and added N as x-axis and y-axis with N leaching and SOC as the z variable. A contour plot is a graphical technique for representing a 3-dimensional surface by plotting constant z slices on a 2-dimensional format. That is, given a value for z, lines are drawn for connecting the (x,y) coordinates where that z value occurs. We performed linear regressions of different variables against N leaching and SOC.

Results

Impacts of cover crops (legume, non-legume and legume-non-legume mixed) on N leaching

The inclusion of cover crops in the crop rotation significantly decreased N leaching compared to the control treatments ($p<0.001$; n=75). All types of cover crops had significant effects on N leaching; legume ($p<0.05$; n=11), non-legume ($p<0.001$; n=55) and legume-non-legume mixed cover crops ($p<0.001$; n=9) (Fig. 2a). A one-way ANOVA showed no significant ($p>0.05$) difference in N leaching between legume, non-legume and legume-non-legume mixed cover crops. Additionally, an analysis of covariance (ANCOVA) showed no significant ($p>0.05$) effect of cover crops on the change of N leaching (%), after controlling for the effect of added N fertilizer application rate (the covariate) (F= 1.23, p=0.3) (Fig. 3).

Impacts of cover crops (legume, non-legume and legume-non-legume mixed) on SOC and direct N_2O emissions

A paired t-test showed that SOC under the cover crops was significantly higher compared to that in the control treatments ($p<0.001$; n=43). Both legume ($p<0.001$, n=29) and non-legume ($p<0.001$; n=13) cover crops significantly increased SOC (Fig. 2d). A paired t-test showed that cover crops (n=28) had no significant effect ($p>0.05$) on direct N_2O emissions, compared to the control treatment. Only legume (n=8) cover crops significantly increased direct N_2O

emissions but non-legume (n=17) and legume-non-legume had no effects, compared to the control treatment.

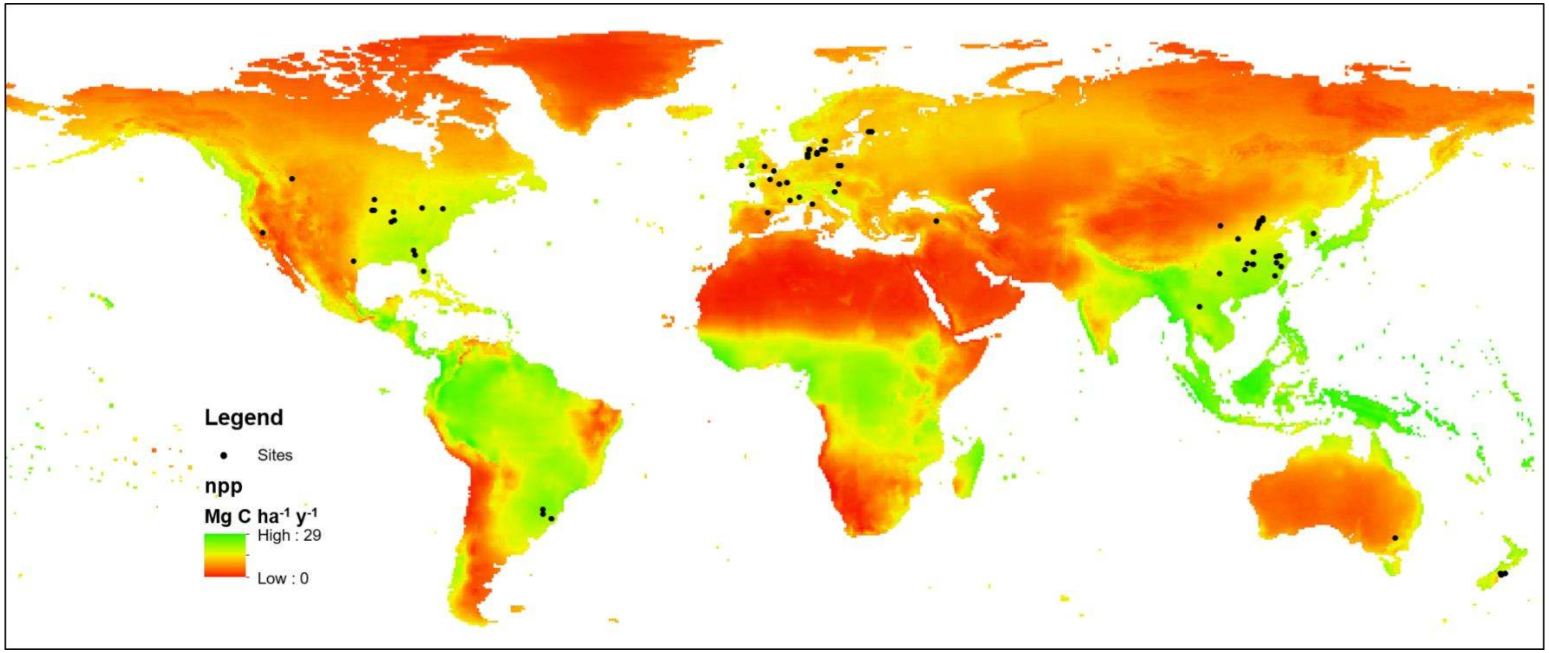

Fig. 1: Map showing the net primary productivity (NPP) and locations of experimental sites considered in this paper. NPP calculated using the Miami method (Lieth, 1972; Grieser et al., 2006).

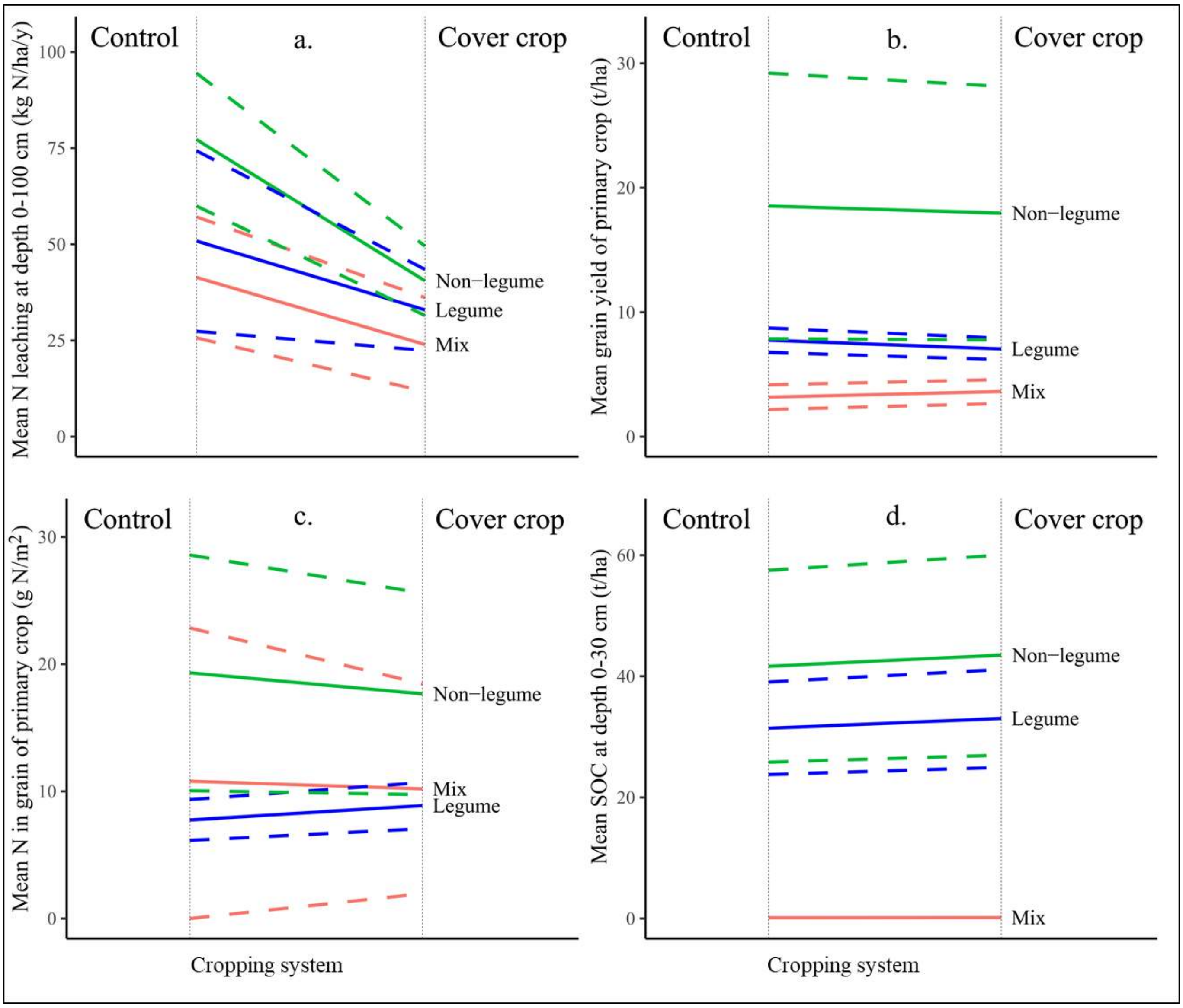

Fig. 2: Comparisons between N leaching (a), grain yield (b), N in grain (c) and SOC (d) from control and cover crops (CC) treatments. Types of cover crops (legume (blue), non-legume (green) or mixed (red)) and their 95% confidence intervals (CI).

Tillage had no effect on direct N_2O emissions. However, the changes in direct N_2O emissions (%) under conservation tillage were significantly lower compared to that under conventional tillage treatment (Table 1).

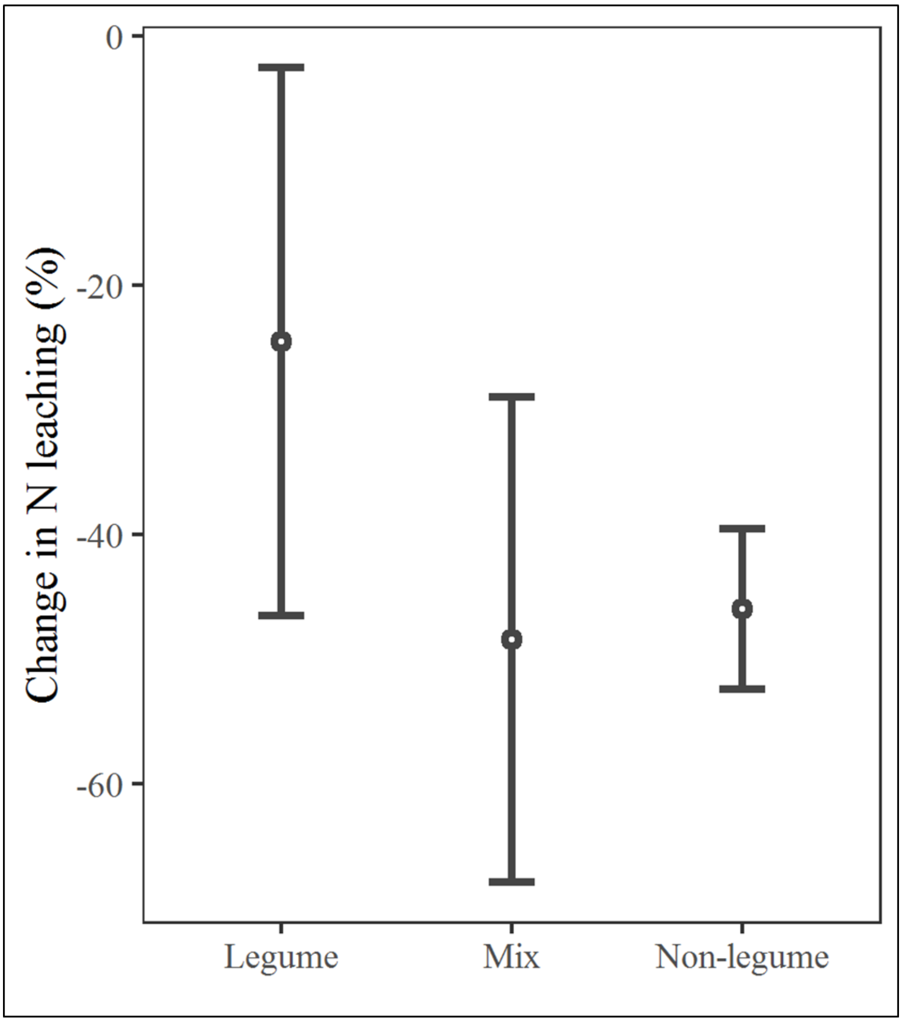

Fig. 3: Relationships between change in N leaching (%) and legume, non-legume and mixed cover crops. Least squares means of N leaching after analysis of covariance (ANCOVA, F=1.23, n=86, p=0.3) with added N fertilizer used as covariates (vertical bars denote 95% confidence intervals).

Table 1: Effects of tillage on direct N_2O emission (kg $ha^{-1}y^{-1}$) from control and cover crop treatments.

Treatment	Mean±StDev. (conventional)	N* (conventional)	Mean±StDev. (conservation)	N (conservation)	t-value	p
Control	0.94±1.0	12	3.70±2.74	10	3.25	ns
Cover crops	1.46±1.61	12	3.95±2.91	10	2.55	ns
Change in N_2O emissions (%)	50.58±148.34	12	16.65±38.94	10	4.74	p<0.001

N* = number of observation; StDev. = standard deviation; ns= not significant.

Impacts of cover crops (legume, non-legume and legume-non-legume mixed) on grain yields and N in grain of primary crop

Overall, the cover crops significantly decreased grain yield of the primary crops compared to the control treatments (on average -3.9%; $p<0.05$; n=154) (Fig. 2b). Both legume and non-legume cover crops significantly decreased ($p<0.001$; n=52 and $p<0.01$; n=96, respectively) grain yield of the primary crop whilst legume-non-legume mixed cover crops significantly increased ($p<0.01$, n=6) grain yield of the primary crop (by ≈13%). Cover crops significantly (n=118; $p<0.001$) decreased grain yield of the primary crop under conventional tillage but had no effect under conservation tillage (n=20; $p>0.05$). The cover crops, generally, had no effect on N content in the grain of the primary crop (n.s; n=58) (Fig. 2c). Though, both legume and non-legume cover crops significantly increased N in the grain of the primary crop ($p<0.001$; n=15 and $p<0.05$; n=39, respectively). Legume-non-legume mixed cover crops had no effects ($p>0.05$; n=4) on N in grain of the primary crop.

Influences of management, soil and climatic zones on cover crop efficiency to decrease N leaching and to increase SOC

For N leaching at 0-100 cm depth, contour plots based on available data, showed that BD and N fertilizer application rate explained 11.6% of overall variance ($p<0.01$; n=38). N leaching was significantly related to BD ($p<0.05$) (Fig. 4). For the SOC at 0-30 cm depth, BD and N fertilizer application rate explained 57% of the overall variance in SOC ($p<0.001$; n=41). The increase in SOC under cover crops was significantly related to both N fertilizer application rate ($p<0.01$) and BD ($p<0.001$) (Fig. 5). The interaction between soil pH and N fertilizer application rate had no significant effect on N leaching ($p>0.05$; n=43). Soil pH and added N fertilizer application rate significantly influenced SOC and explained 31% of the overall variance ($p<0.01$; n=35). However, changes in SOC varied significantly with soil pH ($p<0.001$)

(Fig. 6). Soil texture had no significant ($p>0.05$) impacts on the change in N leaching or SOC. The N leaching and SOC under the control and cover crop treatments were both not significantly ($p>0.05$) influenced by MAAT.

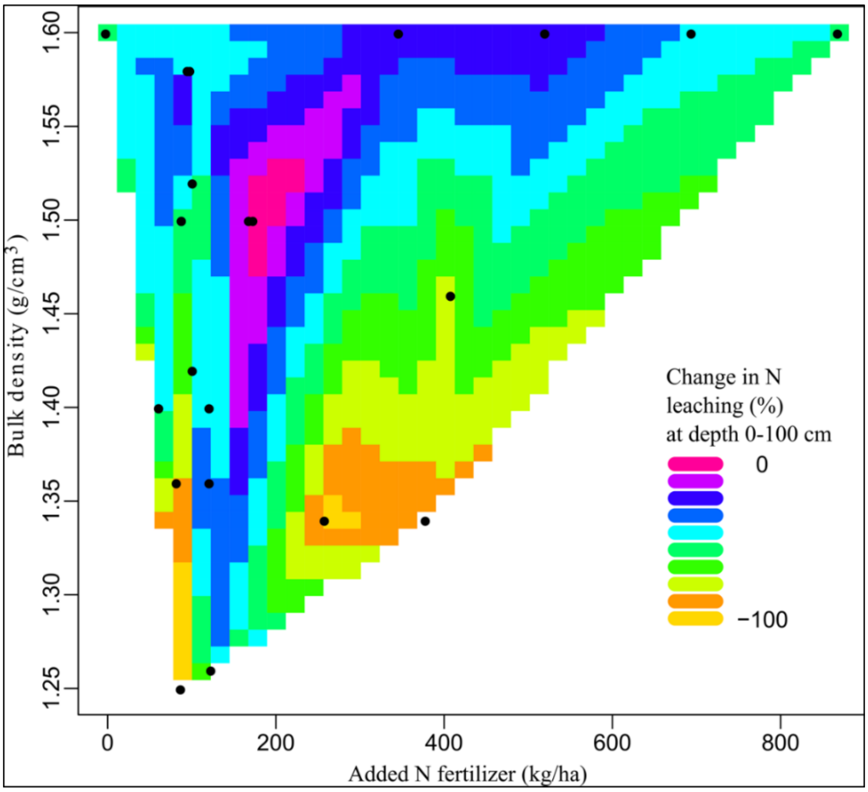

Fig. 4: Contour plot (n=38) showing relationships between added N fertilizer application rate, BD and change in N leaching (%) at 0-100 cm depth. These two variables explain 11.6% of N leaching overall variation ($p<0.05$). N leaching significantly depended on BD (t=2.62; $p<0.01$). One outlier was removed (BD=2.5).

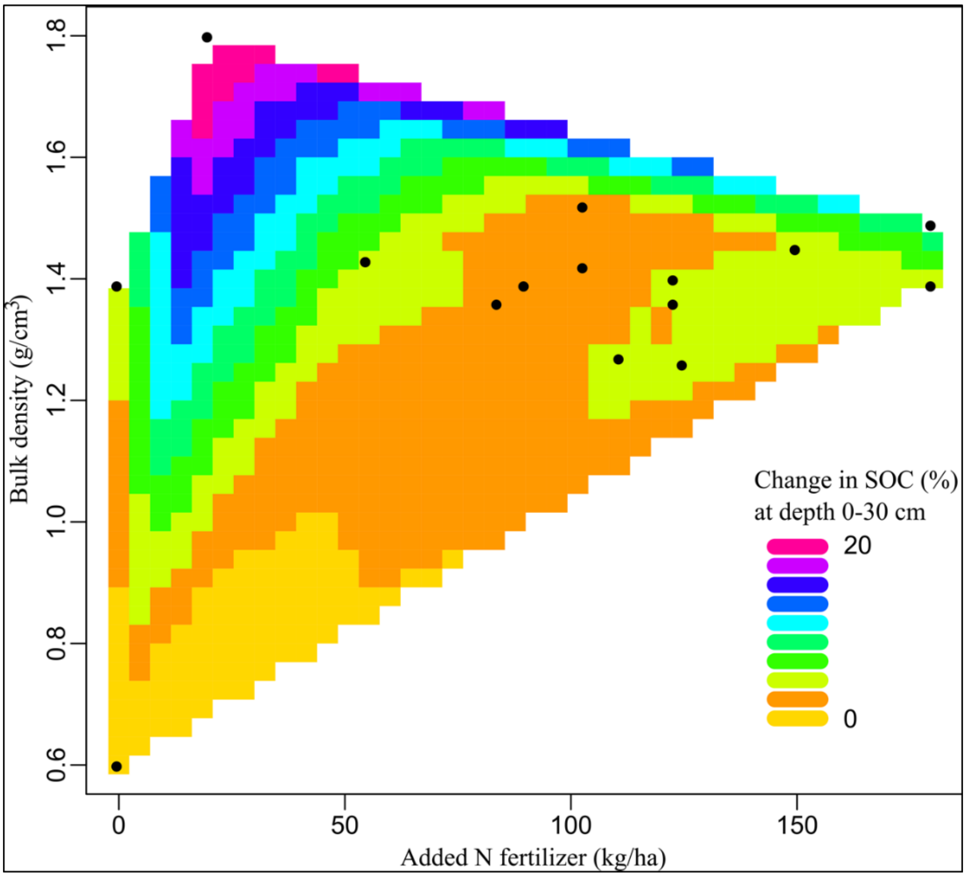

Fig. 5: Contour plot (n=41) showing relationships between added N fertilizer application rate, BD and change in SOC (%). Added N fertilizer and BD explain 57% of SOC overall variation ($p<0.001$). The SOC depended significantly on added N ($t = -3.2$; $p<0.01$) and BD ($t = 7.1$; $p<0.001$).

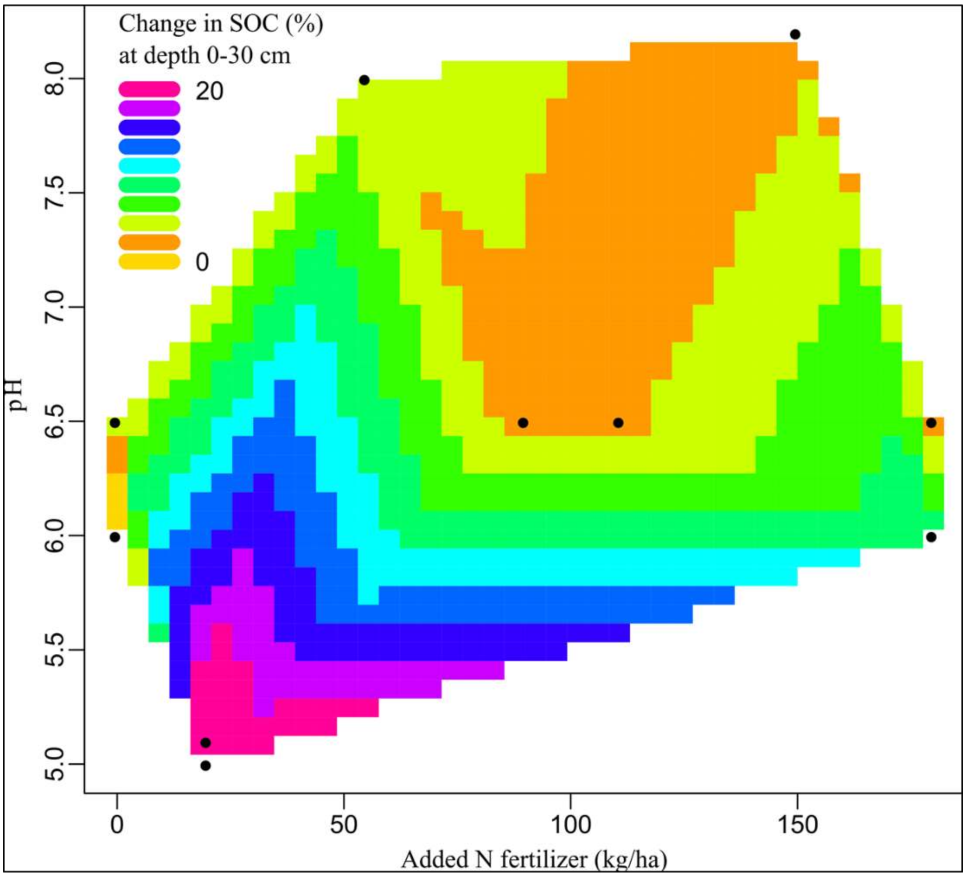

Fig. 6: Contour plot (n=35) showing relationships between added N fertilizer application rate, pH and change in SOC. Added N fertilizer and pH explain 31% of SOC overall variation. SOC depended significantly on pH (t = -3.94; $p<0.001$).

Cover crops significantly decreased N leaching under both MW ($p<0.001$; n=13) and MC ($p<0.001$; n=58) climatic zones. MAP positively correlated with SOC for the control (r^2=0.39, $p<0.001$; n=43), and cover crops (r^2=0.39, $p<0.001$; n=43) treatments (Fig. 7). Cover crops significantly increased SOC under MW ($p<0.001$; n=37) and under MC ($p<0.001$; n=6) climatic zones. Under both the conventional (n=62) and conservation (n=12) tillage systems, cover crops significantly ($p<0.001$) decreased N leaching compared to the control. A t-test showed that conservation tillage (n=62) significantly increased N leaching for the control ($p<0.05$) treatment compared to conventional tillage (n=12). There were no significant ($p>0.05$) effects on SOC due to tillage systems. The SOC was significantly higher under both the conventional ($p<0.05$, n=18) and conservation ($p<0.01$, n=17) tillage systems compared to the control.

Impacts of cover crops on net greenhouse gas balance

Cover crops increased SOC and decreased N leaching and thereby, lowered the indirect N_2O emissions (i.e. from N leaching) without significantly increasing direct N_2O emissions. This combination of higher SOC and the lower indirect N_2O emissions under the cover crops resulted in a lower NGHGB compared to the control treatment. The estimated reduction in NGHGB due to cover crops, compared to the control treatments, was 2.06 ±2.10 Mg CO_2-eq ha^{-1} y^{-1}. The reduction in NGHGB due to different cover crop types, compared to the control treatments, were 1.87±1.82, 1.82±1.44 and 5.15±3.51 Mg CO_2-eq ha^{-1} y^{-1} for the legume, non-legume and legume-non-legume mixed cover crops, respectively (Table 2). No significant difference ($p>0.05$) was found between the different cover crop types.

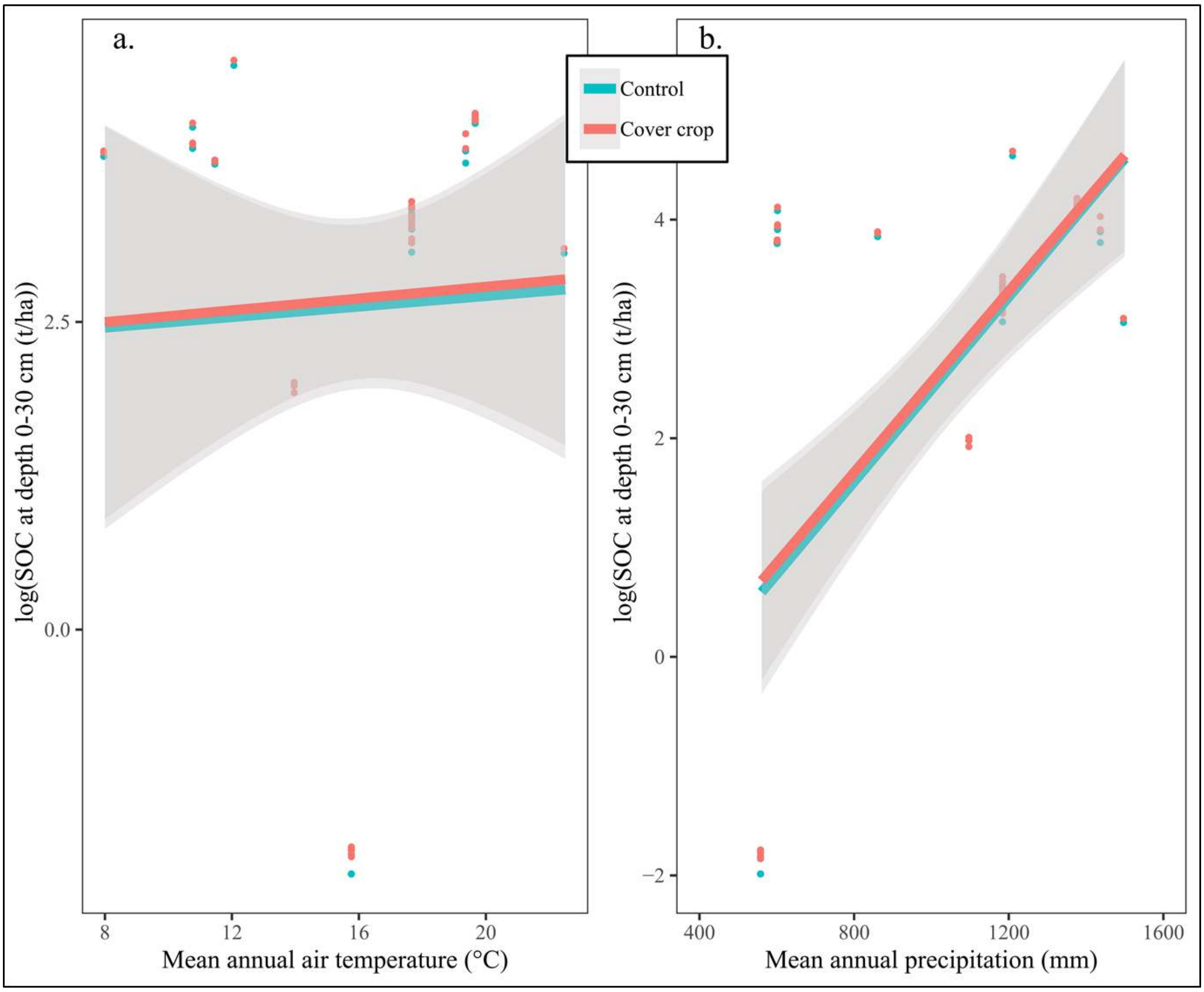

Fig. 7: Relationships between SOC and mean annual air temperature (MAAT) (a) and mean annual precipitation (MAP) (b) under control and cover crops. MAAT was not significantly correlated with SOC ($p>0.05$). MAP was positively correlated with SOC for both the control ($t=5.0$, $p<0.001$; $r^2=0.39$, $p<0.001$, $n=43$), and cover crop ($t=5.0$, $p<0.001$; $r^2=0.39$, $p<0.001$, $n=43$).

Table 2: Descriptive statistics of the reduction in net greenhouse gas balance (NGHGB) related to the reduction of indirect nitrous oxide (N_2O) emission and the soil organic carbon sequestration (Mg CO_2-eq ha $^{-1}$ y^{-1}).

Type of cover crop	Change in direct N_2O (mean±StDev*)	Change in indirect N_2O (mean±StDev*)	Change in SOC (mean±StDev*)	N**	NGHGB (mean±StDev*)
Legume	0.04±0.05	-0.30±0.37	1.61±1.82	30	1.87±1.82
Non-legume	0.09±0.11	-0.07±0.28	5.12±5.51	13	1.82±1.44
Mixed	0.04±0.03	-0.50±0.37	0.30±0.37	4	5.15±3.51
All types	0.08±0.10	-0.16±0.33	1.97±2.10	47	2.06±2.10

*StDev. = standard deviation. Negative numbers represent gas emissions, while positive numbers represent gain of C by the soil. **N is the number of observations.

Discussion

Impacts of cover crops (legume, non-legume and legume-non-legume mixed) on N leaching

In this critical global review and systematic analysis, we found that all types of cover crops significantly decreased N leaching. However, no statistically significant differences between legume, non-legume and legume-non-legume mixed cover crops were found. Previous studies reported that non-legume (Torstensson and Aronsson, 2000; Aronsson et al., 2011; Thomsen and Hansen, 2014) legume (Salmerón et al., 2010; Askegaard and Eriksen, 2008; Askegaard et al., 2005) and legume-non-legume mixed (Askegaard et al., 2011; Benoit et al., 2014) cover crops can all reduce N leaching, but with different efficiencies. In the USA, Kaspar et al. (2012) reported that the use of non-legume cover crops (e.g. oat and rye) is a suitable management option for reducing N leaching from corn-soybean rotations and thereby, improving both water and soil quality. Non legume cover crops reduced soil NO_3 content which is vulnerable to N leaching during autumn and winter (Thorup-Kristensen et al., 2003), and made additional soil N available for the primary crop following mineralisation of their residues (Kaspar and Singer, 2011). In studying future scenarios over a period of 45-years, Tribouillois et al. (2018) found that non-legume cover crops continuously decreased N leaching compared to that of bare soil, but legume cover crop scenarios did not. Moreover, some simulation studies have suggested that the efficiency of legume cover crops species to reduce N leaching was about half of that of non-legume species (e.g. Brassicaceae and Poaceae; Justes et al., 2012). Nevertheless, Valkama et al. (2015) reported that legume cover crops may not be effective in reducing N leaching but growing non-legume cover crops within a spring cereal crop is an effective method for reducing N leaching from different crop varieties, soils and weather conditions. Here, it is accepted that there is a trade-off between potential grain yield loss and environmental benefits, but this could be compensated for in environmental stewardship schemes in those countries. Leslie et al. (2017) recommended growing cover crops in some years only, to avoid a pre-emptive competition where the cover crops could recover soil NO_3 that would otherwise have been available to the subsequent primary crop. The non-legume cover crops can also increase N leaching when grown too late in spring or in dry areas, where the risk for N leaching is low (Thorup-Kristensen, 2003).Thus, the timing and location of the non-legume cover crops need to be considered carefully to avoid competition with the primary crop.

Impacts of cover crops (legume, non-legume and legume-non-legume mixed) on SOC and direct N_2O emissions

Cover crops (i.e. both legume and non-legume) increased SOC, and so they can enhance C sequestration in soils. Similar conclusions regarding the impact of cover crops on SOC were reported by Wortman et al. (2012), Olson et al. (2014), Poeplau and Don (2015) and others. According to Ding et al. (2006), both organic carbon and light fraction C contents increased in soils under cover crops, with or without N fertilizer. Here, the decomposition of dead roots and biomass of cover crops result in improved SOM quantity and quality (Villamil et al., 2006). This could help improve food security, reduce NGHGB and mitigate climate change.

We found that cover crops had no significant effect on direct N_2O emissions compared to the control. According to Webb et al. (2000), cover crops increase the direct N_2O emissions when residues are incorporated into the soil or by increasing the photo-synthetically-derived C supply from actively growing root systems. However, adjusting the N fertilizer application rate (e.g. by integrated soil fertility management) could help in reducing the gas emissions (Guardia et al., 2016; Tribouillois et al., 2018). Previous studies reported contrasting results with regard to cover crop effects on direct N_2O emissions (Abdalla et al., 2013; Mitchell et al., 2013; Basche et al., 2014). This could be explained by the large variations in many factors, e.g. cover crop types and performances, climate, soil characteristics, tillage and seasons of N_2O samplings, between the different studies. Cover crops have the ability to decrease the indirect N_2O emissions (i.e. from N leaching). Cover crop species influence abiotic and biotic soil factors differently (Abalos et al., 2014). They have the capacity to simultaneously mitigate N leaching and indirect N_2O emissions (Kim et al., 2015) by limiting N availability. They deplete the soil NO_3 pool which is the major substrate for denitrification (Liebig et al., 2015), reducing N leaching and consequently decreasing the contribution of indirect N_2O emissions to the NGHGB. However, this depends on many factors, e.g. cover crop types, performances, climate, tillage and soil characteristics. In contrast, Zhou and Butterbach-Bahl (2013) found that for coarser textured soils, the reduction in N leaching can increase availability of soil N, which can lead to a trade-off by enhancing N_2O emissions.

Influences of management, soil and climatic zones on cover crop efficiency to decrease N leaching and increase SOC

Cover crops were most efficient in reducing N leaching when the BD was <1.4 g cm^{-3} and N fertilizer application rate was >200 kg N ha^{-1}. Snapp (2005) found application of more N fertilizer, especially with legume cover crops, can increase the risk of nutrient leaching, if a subsequent primary crop is not planted promptly. Thus, to reduce N leaching from soils under cover crops, judicious quantities of N fertilizer should be applied at appropriate application times, with appropriate methods (Yogesh and Juo, 1982; Fan et al., 2010). Also, to avoid losing the excess N in soils by leaching, the amount of N fertilizer applied should be based on soil and crop requirement tests (Bundy et al., 2005; Defra, 2010).

In this study, we found enough data points for MW and MC climatic zones but not for DW and DC climatic zones. This is obviously because cover crops are rarely grown in dry climates as they use water that could be used to grow a primary crop and reduce water percolation by transpiration (Weinert et al., 2002). Additionally, in such climates, cover crops compete with the primary crop for nutrients (Unger and Vigil, 1998) and consequently, have negative impacts on crop growth and productivity. Wortman et al. (2012) and Tribouillois et al. (2018) reported that the large quantity of soil water used by the cover crops, at the cost of the subsequent primary crop and immobilisation of soil N due to incorporation of low quality cover crop residues into the soil is also a major concern. These problems appear mostly in arid and semiarid environments (< 500 mm annual rainfall) where water storage in soils declines with the establishment of cover crops, and results in reduced crop yields (Cherr et al., 2006; Nielsen and Vigil, 2005). Conservation tillage significantly decreased the efficiency of cover crops to decrease N leaching under control treatment compared to that under conventional tillage. The large pores that can develop under conservation tillage result in high N leaching if present after broadcasting N fertilizer (CTS, 2011), and thereby could also increase GHG emissions (Smeaton et al., 2011). Fraser et al. (2013) found that tillage had some effects on N leaching, though the use of minimum tillage for autumn cultivation resulted in significantly less N leaching than either intensive or no-till. Buchi et al. (2018) reported that cover crop could maintain wheat yield and improve soil fertility and nutrient cycling in a no-till system.

Therefore, a combination of the right type of conservation tillage with cover crops could be the best management to reduce N leaching in dry climates. Water utilization by the cover crops is counterbalanced by the improved infiltration and reduced evaporative losses that occur in conservation tillage systems (Unger and Vigil, 1998; Wang and Ngouajio, 2008). Further, the high soil moisture under conservation tillage positively influences microbial activity (Madejon et al., 2009) and increase bypass flow (CTS, 2011). This could also slow the rate of mineralization, as soils take longer to warm in the spring (Abdalla et al., 2013).

We found no significant effects on the efficiency of cover crops to decrease N leaching between the MW and MC climate zones. Fraser et al. (2013) and Hooker et al. (2008) found that inter-annual weather variability and soil types explain the variability of cover crop effectiveness in the temperate regions. Previous studies found the effectiveness of cover crops to reduce N leaching is highly variable, both across and within different climatic zones (Thorup-Kristensen et al., 2003; Tonitto et al., 2006; Quemada et al., 2013). In this study, soil texture had no significant impacts on N leaching under cover crops. In a review by Valkama et al. (2015) a similar relative reduction (%) in N leaching losses by cover crops, compared to the controls, across different soil textures in the Nordic countries was reported. By contrast, Premrov et al. (2014) concluded that, under mild temperate winter conditions, the risk of N leaching from light textured, freely draining soils is high and therefore, it is important to establish over-winter cover crops. In the driest parts of south-east England, early sown cover crops were found to be most effective on freely drained sandy soils, where the risk of N leaching was high, but were less effective on medium-heavy textured soils with poorer drainage (Macdonald et al., 2005).

Under cover crops, soils with higher BD are the most likely to have higher SOC. The presence of N in soil is important for SOC accumulation as C sequestration requires N (van Groenigen et al., 2017). According to Aula et al. (2016), the use of N fertilizer significantly increases SOC. The difference in SOC (%) between the cover crops and the control treatments was at its highest at low N fertilizer rate. High soil pH decreases the efficiency of cover crops to accumulate SOC. Parfitt et al. (2014) reported that high pH (due to liming) possibly reduces SOC. Both soil texture and tillage had no significant impacts on the efficiency of cover crops to sequester SOC, compared to control treatments. Previous studies showed both beneficial (West and Post, 2002; Gonzalez-Sanchez et al., 2012) and no impact (Dimassi et al., 2014; Powlson et al., 2014) of no-till relative to conventional tillage on SOC. Soil organic matter and organic residues are the two main energy sources of microbial biomass (Brookes et al., 2008). Higher SOC is advantageous for soil fertility, water holding capacity and nutrient retention and therefore, is considered essential for sustainable agriculture (Hoyle, 2013).

Impacts of cover crops (legume, non-legume and legume-non-legume mixed) on grain yield and N content in grain of the primary crop

We found, overall, cover crops decreased grain yields of the primary crop by ≈3.9% compared to the control treatment. Both legume and non-legume cover crops decreased grain yields but legume- non-legume mixed cover crops increased yield significantly. Studies found that grain yields of the primary crop can be improved by incorporation of legume-non-legume mixtures (Doltra and Olesen, 2013) or legume (Campiglia et al., 2011) cover crops. A review by Tonitto et al. (2006) reported a 10% reduction in grain yield of primary crops under legume cover crops. In contrast, Coombs et al. (2017) found alfalfa and red clover (legume) had a positive impact on corn yield in one of two years. Dozier et al. (2017) and Marcillo and Miguez (2017) found non-legume cover crops had no effects on the grain yield of corn, especially in the short term. Noland et al. (2018) found that to reduce soil NO_3 while maintaining corn and subsequent soybean yields, cover crops should be inter-seeded into corn at the seven-leaf collar stage. Nevertheless, a successful termination for the cover crops is crucial to avoid competition with the subsequent soybean crop. The legume cover crop increased N in the grain of the primary crop, while non-legumes decreased it and legume-non-legume mixed cover crops had no significant effect. Wittwer et al. (2017) found higher grain N concentrations and N contents under both legume and legume-non-legume mixed cover. However, there are mixed results concerning the effects of cover crops on N content in grain of the primary crop in the literature (Thomsen, 2005; Olesen et al., 2007; Rinnofner et al., 2008; Kramberger et al., 2009; Doltra and Olesen, 2013).

Impacts of cover crops (legume, non-legume and legume-non-legume mixed) on net greenhouse gas balance

Characterising the effects of cover crops on the NGHGB of cropping systems is complex given that they influence both the carbon balance as well as direct and indirect N_2O emissions. The uncertainty in our results, due to assumptions made, was conservatively estimated by calculating the standard deviations (StDev) for all values. Our study showed that all cover crop types could contribute to ecological intensification and climate change mitigation by improving the NGHGB, compared to the control treatment. Cover crop practices could also contribute to the aspirations of the soil C “4-per-mille” initiative (Minasny et al., 2017), especially in wet regions where C stocks are low and nutrients are available (e.g. North Europe, North China and Canada). The growing cover crops could increase water use, keeping soils dry and thereby reduce rates of SOC decomposition, as well as reducing N_2O loss and soil erosion (Desjardins et al., 2005). In contrast, Negassa et al. (2015) reported that the addition of cover crop inputs to topographic depression areas can increase the priming effect (Guenet et al., 2010), which increases decomposition of native SOC, and thereby increases CO_2 emissions, when stimulated by additions of fresh plant residue inputs. However, Steele et al. (2012) reported no changes in organic matter (OM) content after 13 years of a cover crop experiment. One limitation of our analysis is that the majority of the studies collected were short-term experiments (2-3 years). Berntsen et al. (2006) reported that the effects of cover crops should be evaluated in the long-term rather than considering short-term effects only; however, there is a scarcity of such long-term experiments. We found that incorporating cover crops, specifically legume-non-legume mixed cover crops, into the crop rotation is beneficial for soils, the environment and crop productivity. Tonitto et al. (2006) found that the legume-non-legume mixed cover crops useful for both atmospheric N_2 fixation and for soil residual nitrate recycling. Cover crops influence soil N and C dynamics and N available for the subsequent primary crop. They play an important role in achieving more diverse and multifunctional agricultural systems (Schipanski et al., 2014; Blanco-Canqui et al., 2015), suggesting that further efforts are required to enable farmers to overcome all barriers for their widespread adoption (Roesch-McNally et al., 2017). However, management practices in relation to cover crops will need to be adapted to specific soil, management and regional climatic conditions.

Concluding remarks

This global critical review and systematic analysis reveals that, by adopting cover crops we could decrease N leaching to ground water and increase SOC sequestration without having significant effects on direct N_2O emissions. To avoid the negative impacts of cover crops on grain yield (-3.9%), legume-non-legume mixed cover crops, which increase the yield by ≈13% and had no significant impacts on N in grain, should be selected. Overall, cover crops can mitigate net greenhouse gas balance by 2.06 ±2.10 Mg CO_2-eq ha^{-1} y^{-1}. These effects can be considered important in contributing to the resilience of farming systems to environmental changes, for example from climate change, by being more fertile, productive and have better water quality. However, to increase the effectiveness of cover crops, field management techniques should be optimized to the local climatic conditions, water resources, soil and cropping systems. The genetics of cover crop species could be improved, to provide deeper rooted crops, which have higher N use efficiencies, better nitrate scavenging abilities and lower N leaching potential. Deep rooted species could help with cover crop resilience, e.g. deeper delivery of C in the soil profile. It is also important to adjust timings and dates of the planting and kill dates of the cover crops, to avoid competition with the primary crop, to improve their effectiveness and avoid trying to establish cover crops when soil conditions are sub-optimal (potentially increasing soil erosion losses). Although cover crops increase costs, due to the need to purchase new seeds, management operations and termination costs, these costs can be compensated for if the wider benefits are considered. These include retention and carryover of nutrients between phases of a rotation, and the opportunity for the cover crops to be sold as forage or grazed. A positive return from cover crops for producers is a possibility, especially if they replace a fallow period instead of a primary crop. However, to support the widespread adoption of cover crops, improved policy, education, training and awareness raising of the potential benefits and risks and risk abatement strategies are needed.

Acknowledgements

This work contributes to the UK-China Virtual Joint Centre N-Circle (grant number BB/N013484/1), SuperG (funded under EU Horizon 2020 programme)) and ADVENT (grant number NE/M019691/1). DRC was supported by the UK-China Virtual joint Centre for Agricultural Nitrogen (CINAg, BB/N013468/1) and the UK-Brazil Virtual Joint Centre to deliver enhanced N-use efficiency via an integrated soil-plant systems approach (NUCLEUS), which are jointly supported by Newton fund *via* UK BBSRC and NERC.

References

Abalos, D., Deyn, G. B., Kuyper, T.W. & van Groenigen, J. W. (2014). Plant species identity surpasses species richness as a key driver of N_2O emissions from grassland. *Global Change Biology, 20,* 265- 275.

Abdalla, M., Hastings, A., Chadwick, DR., Jones, DL., Evans, CD., Jones, MB., Rees, RM. & Smith, P. (2018). Critical review of the impacts of grazing intensity on soil organic carbon storage and other soil quality indicators in extensively managed grasslands. *Agriculture Ecosystems & Environment*, *253*, 62-81.

Abdalla, M., Hastings, A., Helmy, M., Prescher, A., Osbourne, B., Lanigan, G., Forristal, D., Killi, D., Maratha, P., Williams, M., Rueangritsarakul, K., Smith, P., Nolan, P. & Jones, M.B. (2014). Assessing the combined use of reduced tillage and cover crops for mitigating greenhouse gas emissions from arable ecosystem. *Geoderma, 223*, 9-20.

Abdalla, M., Osborne, B., Lanigan, G., Forristal, D., Williams, M., Smith, P. & Jones, M. B. (2013). Conservation tillage systems: a review of its consequences for greenhouse gas emissions. *Soil Use and Management, 29,* 199-209.

Allingham, K.D., Cartwright, R., Donaghy, D., Conway, J.S., Goulding, K.W. & Jarvis, S.C. (2002). Nitrate leaching losses and their control in a mixed farm system in the Cotswold Hills, England. *Soil Use and Management, 18,* 421-427.

Aronsson, H., Stenberg, M. & Ulén, B. (2011). Leaching of N, P and glyphosate from two soils after herbicide treatment and incorporation of a ryegrass catch crop. *Soil Use and*

Management, 27, 54-68.

Ascott, M.J., Gooddy, D., Wang, L., Stuart, M.E., Lewis, M.A., Ward, R.S. et al. (2017). Global patterns of nitrate storage in the vadose zone. *Nature Communications, 8,* 1416.

Askegaard, M. & Eriksen, J. (2008). Residual effect and leaching of N and K in cropping systems with clover and ryegrass catch crops on coarse sand. *Agriculture, Ecosystems and Environment, 123,* 99-108.

Askegaard, M., Olesen, J.E., Rasmussen, I.A. & Kristensen, K. (2011). Nitrate leaching from organic arable crop rotations is mostly determined by autumn field management. *Agriculture, Ecosystems and Environment, 142,* 149-160.

Askegaard, M., Olesen, J.E., Rasmussen, I.A. & Kristensen, K. (2005). Nitrate leaching from organic arable crop rotations: effects of location, manure and catch crop. *Soil Use and Management, 21,*181-188.

Aula, L., Macnack, N., Jeremiah, P., Mullock, J. & Raun, W. (2016). Effect of fertilizer nitrogen (N) on soil organic carbon, total N, and soil pH in long-term continuous winter wheat (Triticum Aestivum L.). *Communications in Soil Science and Plant Analysis, 47,* issue 7.

Basche, A.D., Miguez, F.E., Kaspar, T.C. & Castellano, M.J. (2014). Do cover crops increase or decrease nitrous oxide emissions? A meta-analysis. *Journal of Soil and Water Conservation, 69,* 471-482.

Bates, D., Mächler, M., Bolker, B. & Walker, S. (2015). Fitting Linear Mixed-Effects Models Using lme4. *Journal of Statistical Software, 67*(1), 1-48.

Battany, M. & Grismer, M.E. (2000). Rainfall runoff and erosion in Napa Valley vineyards:

effects of slope, cover and surface roughness. *Hydrological Processes, 14,* 1289-1304.

Benoit, M., Garnier, J., Anglade, J. & Billen, G. (2014). Nitrate leaching from organic and conventional arable crop farms in the Seine Basin (France). *Nutrient Cycling in Agroecosystems, 100,* 285-299.

Berntsen, J., Olesen, J.E., Petersen, B.M. & Hansen, E.M. (2006). Algorithms for sensor-based redistribution of nitrogen fertilizer in winter wheat. *Precision Agriculture, 7,* 65-83.

Blanco-Canqui, H., Shaver, T.M., Lundquist, J.L., Shapiro, C.A., Elmore, R.W., Francis, C.A. & Hergert, G.W. (2015). Cover crops and ecosystem services: Insights from studies in temperate regions. *Agronomy Journal, 107,* 2449-2474.

Brookes, P. C., Cayuela, M. L., Contin. M., De Nobili, M., Kemmitt, S. J., & Mondini, C. (2008). The mineralization of fresh and humified soil organic matter by the soil microbial biomass. *Waste Management, 28(4),* 716-722.

Buchi, L., Wendling, M., Amosse, C., Necpalova, M. & Charles, R. (2018). Importance of cover crop in alleviating negative effects of reduced soil tillage and promoting soil fertility in a winter wheat cropping system. *Agriculture, Ecosystems and Environment, 256*, 94-104.

Bundy, L.G. & Andraski, T.W. (2005). Recovery of Fertilizer Nitrogen in Crop Residues and Cover Crops on an Irrigated Sandy Soil. *Soil Science Society of America Journal, 69,* 640-648.

Campiglia, E., Mancinelli, R., Radicetti, E. & Marinari, S. (2011). Legume cover crops and mulches: Effects on nitrate leaching and nitrogen input in a pepper crop. *Nutrient Cycling in Agroecosystems, 89,* 399-412.

Cardenas, L.M., Cuttle, S.P., Crabtree, B., Hopkins, A., Shepherd, A., Scholefield, D., & Del

Prado, A. (2011). Cost effectiveness of nitrate leaching mitigation measures for grassland livestock systems at locations in England and Wales. *Science of the Total Environment*, *409 (3-4),* 1104-1115.

Chambers, B.J., Smith, K.A. & Pain B.F. (2000). Strategies to encourage better use of nitrogen in animal manures. *Soil Use and Management, 16,* 157-166.

Cherr, C.M., Scholberg, J.M.S. & McSorley, R. (2006). Green manure approaches to crop production: A synthesis. *Agronomy Journal, 98,* 302-319.

Coombs, C., Lauzon, J.D., Deen, B. &Van Eerd, L.L. (2017). Legume cover crop management on nitrogen dynamics and yield in grain corn systems. *Field Crops Research, 20,* 75-85.

CTS. (2011). Conservation tillage service. Number 4. Available at: http://cropsoil.psu.edu/extension/ct/uc127.pdf; accessed on 10/01/2012.

Dabney, S.M., Delgado, J.A., Meisinger, J.J., Schomberg, H.H., Liebig, M.A., Kaspar, T., et al. (2011). Using cover crops and cropping systems for nitrogen management. In: J.A. Delgado and R.F. Follet, editors, Advances in nitrogen management for water quality. *Soil and Water Conservation*, Soc., Ankeny, IA. p. 230-281.

Defra (2010). Department for Environment Food and Rural Affairs, 2010. Fertiliser manual (RB209). https://www.gov.uk/government/publications/fertiliser-manual-rb209--2 (accessed on 16/11/2018).

Delgado, J.A., Shaffer, M.J., Lal, H., McKinney, S., Gross, C.M. & Cover, H. (2008). Assessment of nitrogen losses to the environment with a Nitrogen Trading Tool (NTT). *Computer and Electronics in Agriculture, 63,*193-206.

Delignette-Muller, M.L. & Dutang, C. (2015). fitdistrplus: An R package for fitting distributions. *Journal of Statistical Software*, *64*(4), 1-34.

Desjardins, R.L., Smith, W., Grant, B., Campbell, C. & Riznek, R. (2005). Management strategies to sequester carbon in agricultural soils and to mitigate greenhouse gas emissions. *Climatic Change, 70,* 283-297.

Dimassi, B., Mary, B., Wylleman, R., Labreuche, J., Couture, D., Piraux, F., et al. (2014). Long-term effect of contrasted tillage and crop management on soil carbon dynamics during 41 years. *Agriculture, Ecosystems and Environment, 188,*134-46.

Ding, G., Liu, X., Herbert, S., Novak, J., Amarasiriwardena, D. & Xing, B. (2006). Effect of cover crop management on soil organic matter. *Geoderma, 130,* 229-239.

Doltra, J. & Olesen, J. (2013). The role of catch crop in the ecological intensification of spring cereals in organic farming under Nordic climate. *European Journal of Agronomy, 44,* 98-108.

Dozier, I.A., Behnke, G.D., Davis, A.S., Nafziger, E.D. & Villamil, M.B. (2017). Tillage and Cover Cropping Effects on Soil Properties and Crop Production in Illinois. *Agronomy Journal, 109,* 1261-1270.

Drinkwater, L.E. & Snapp, S.S. (2007). Nutrients in agroecosystems: Rethinking the management paradigm. *Advances in Agronomy, 92,* 63-186.

Fan, J., Hao, M. & Malhi, S.S. (2010). Accumulation of nitrate-N in the soil profile and its implications for the environment under dryland agriculture in northern China: A review. *Canadian Journal of Soil Science, 90,* 429-440.

Finney, D. M., White, C. M., & Kaye, J. P. (2016). Biomass Production and Carbon/Nitrogen Ratio Influence Ecosystem Services from Cover Crop Mixtures. *Agronomy Journal, 108(1)*, 39-52.

Fraser, P.M., Curtin, D., Harrison-kirk, T., Meenken, E.D., Beare, M.H., Tabley, F., Gillespie, R.N. & Francis, G.S. (2013). Winter nitrate leaching under different tillage and winter cover crop management practices. *Soil Science Society of America Journal, 77,* 1391-1401.

Gonzalez-Sanchez, E.J., Ordonez-Fernandez, R., Carbonell-Bojollo, R., Veroz-Gonzalez, O. & Gil-Ribes, J.A. (2012). Meta-analysis on atmospheric carbon capture in Spain through the use of conservation agriculture. *Soil and Tillage Research, 122,* 52-60.

Grieser, J., Gommes, R. & Bernardi, M. (2006).The Miami Model of Climatic Net Primary Production of Biomass. The Agromet Group, SDRN, FAO of the UN, Viale delle Terme di Caracalla, 00100 Rome, Italy.

Guardia, G., Abalos, D., Garcia-Marco, S., Quemada, M., Alonso-Ayuso, M., C_ardenas, L. M., et al. (2016). Effect of cover crops on greenhouse gas emissions in an irrigated field under integrated soil fertility management. *Biogeosciences, 13,* 5245-5257.

Guenet, B., Neill, C., Bardoux, G. & Abbadie, L. (2010). Is there a linear relationship between priming effect intensity and the amount of organic matter input? *Applied Soil Ecology, 46,* 432-442.

Guo, L.B. & Gifford, R.M. (2002). Soil carbon stocks and land use change: a meta-analysis. *Global Change Biology, 8*, 345-360.

Halde, C., Gulden, R.H. & Entz, M.H. (2014). Selecting cover crop mulches for organic rotational no-till systems in Manitoba, Canada. *Agronomy Journal, 106,* 1193-1204.

Harunaa, S.I. & Nkongolo, N.V. (2015). Cover Crop Management Effects on Soil Physical and Biological Properties. *Procedia Environmental Sciences, 29*, 13-14.

Hontoria, C., Garcia-Gonzalez, I., Quemada, M., Roldan, A. & Alguacil, M.M. (2019). The cover crop determines the AMF community composition in soil and in roots of maize after a ten-year continuous crop rotation. *Science of The Total Environment, 660*, 913-922.

Hooker, K.V., Coxon, C.E. Hackett, R., Kirwan, L.E., O'Keeffe, E. & Richards, K.G. (2008). Evaluation of cover crop and reduced cultivation for reducing nitrate leaching in Ireland. *Journal of Environmental Quality, 37,* 138-145.

IPCC (2013). Summary for policymakers. In: Stocker, T.F., Qin, D., Plattner, G.K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (eds). Climate change 2013: the physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

IPCC (2006). IPCC guidelines for national greenhouse gas inventories. Institute for Global Environment Strategies, Hayama, Japan.

Jobbágy, E.G. & Jackson, R.B. (2001). The distribution of soil nutrients with depth: global patterns and the imprint of plants. *Biogeochemistry, 53*, 51-77.

Jobbágy, E.G. & Jackson, R.B. (2000). The vertical distribution of soil organic carbon and its relation to climate and vegetation. *Ecological Applications, 10*, 423-436.

Justes, E., Beaudoin, N., Bertuzzi, P., Charles, R., Constantin, J., Dürr, C., Hermon, C., Joannon, A., Le Bas, C., Mary, B., Mignolet, C., Montfort, F., Ruiz, L., Sarthou, J.P., Souchère, V., Tournebize, J., Savini, I. & Réchauchère, O. (2012). The use of cover crops in the reduction of nitrate leaching: Impact on the water and nitrogen balance and other ecosystem services. Summary of the study report, INRA (France), 60 pp.

Känkänen, H. & Eriksson, C. (2007). Effects of undersown crops on soil mineral N and grain yield of spring barley. *European Journal of Agronomy, 27,* 25-34.

Känkänen, H., Eriksson, C., Räkköläinen, M. & Vuorinen, M. (2003). Soil nitrate N as influenced by annually undersown cover crops in spring cereals. *Agricultural and Food Science in Finland, 12 (3-4)*, 165-176.

Känkänen, H., Eriksson, C., Räkköläinen, M. & Vuorinrn, M. (2001). Effect of annually repeated under-sowing on cereal grain yields. *Agricultural and Food Science in Finland*, *10,* 197-208.

Karlsson-Strese, E.M., Rydberg, I., Becker, H.C. & Umaerus, M. (1998). Strategy for catch crop development II. Screening of species undersown in spring barley (Hordeum vulgare L.) with respect to catch crop growth and grain yield. *Acta Agricultrae Scandinavica, 48,* 26-33.

Kaspar, T.C., Jaynes, D.B., Parkin, T.B., Moorman, T.B. & Singer, J.W. (2012). Effectiveness of oat and rye cover crops in reducing nitrate losses in drainage water. *Agricultural Water Management, 110,* 25-33.

Kaspar, T.C. & Singer, J.W. (2011). The use of cover crops to manage soil. In: Hatfield, J.L., Sauer, T.J. (Eds.), Soil Management: Building a Stable Base for Agriculture. American Society of Agronomy and Soil Science Society of America Journal, pp 321-337. Madison, WI.

Kim, Y., Seo, Y., Kraus, D., Klatt, S., Haas, E., Tenhunen, J. & Kiese, R. (2015). Estimation and mitigation of N_2O emission and nitrate leaching from intensive crop cultivation in the Haean catchment, South Korea. *Science of the Total Environment, 529,* 40-53.

Kramberger, B., Gselman, A., Janzekovic, M., Kaligaric, M. & Bracko, B. (2009). Effects of cover crops on soil mineral nitrogen and on the yield and nitrogen content of maize. *European Journal of Agronomy, 31,* 103-109.

Kuznetsova, A., Brockhoff, P.B. & Christensen, R.H.B. (2017). lmerTest package: tests in linear mixed effects models. *Journal of Statistical Software, 82*(13), 1-26.

Lee, J., Six, J., King, A.P., Van kessel, C. & Rolston, D.E. (2006). Tillage and field scale controls on greenhouse gas emissions. *Journal of Environmental Quality, 35,* 714-725.

Leith, H. (2000). Modelling the primary productivity of the world. Nature and Resources VIII. UNESCO, pp 5-10.

Leslie, A.W., Wang, K.H., Meyer, S.L.F., Marahatta, S. & Hooks, C.R.R. (2017). Influence of cover crops on arthropods, free-living nematodes, and yield in a succeeding no-till soybean crop. *Applied Soil Ecology, 117-118*, 21-31

Liebig, M.A., Hendrickson, J.R., Archer, D.W., Schmer, M.A., Nichols, K.A. & Tanaka, D.L. (2015). Short-term soil responses to late-seeded cover crops in a semi-arid environment. *Agronomy Journal, 107,* 2011-2019.

Lotter, D.W., Seidel, R. & Liebhardt, W. (2003). The performance of organic and conventional cropping systems in an extreme climate year. *American Journal of Alternative Agriculture, 18,*146-154.

Lüscher, A., Mueller-Harvey, I., Soussana, J.F., Rees, R.M. & Peyraud, J.L. (2014). Potential of legume-based grassland-livestock systems in Europe: a review. *Grass Forage Science, 69 (2),* 206-228.

Macdonald, A.J., Poulton, P.R., How, M.T., Goulding, K.W.T. & Powlson, D.S. (2005). The use of cover crops in cereal based cropping systems to control nitrate leaching in SE England. *Plant and Soil, 273,* 355-373.

Madejon, E., Murillo, J.M., Moreno, F., L_opez, M.V., Arrue, J.L., Alvaro-Fuentes, J. & Cantero, C. (2009). Effect of long-term conservation tillage on soil biochemical properties in Mediterranean Spanish areas. *Soil and Tillage Research, 105*, 55-62.

Marcillo, G.S. & Miguez, F.E. (2017). Corn yield response to winter cover crops: An updated meta-analysis. *Journal of Soil and Water Conservation, 72 (3),* 226-239

Min, J., Zhao, X., Shi, W., Xing, G. & Zhu, Z. (2011). Nitrogen Balance and Loss in a Greenhouse Vegetable System in Southeastern China. *Pedosphere, 21 (4),* 464-472.

Minasny, B., et al. (2017). Soil carbon 4 per mille. *Geoderma, 292,* 59-86.

Mitchell, D.C., Castellano, M.J., Sawyer, J.E. & Pantoja, J. (2013). Cover crop effects on nitrous oxide emissions: Role of mineralizable carbon. *Soil Science Society of America Journal, 77,* 1765-1773.

Negassa, W., Price, R.F., Basir, A., Snapp, S.S. & Kravchenko, A. (2015). Cover crop and tillage systems effect on soil CO_2 and N_2O fluxes in contrasting topographic positions. *Soil and Tillage Research, 154,* 64-74.

Nielsen, D.C. & Vigil, M.F. (2005). Legume green fallow effect on soil water content at wheat planting and wheat yield. *Agronomy Journal, 97,* 684-689.

Noland, R.L., Wells, M.S., Sheaffer, C.C., Baker, J.M., Martinson, K.L. & Coulter, J.A. (2018). Establishment and Function of Cover Crops Inter-seeded into Corn. Crop Science, 58, 863-873.

Olson, K., Ebelhar, S.A. & Lang, J.M. (2014). Long-term effects of cover crops on crop yields, soil organic carbon stocks and sequestration. *Open Journal of Soil Science, 4,* 284-292.

Olesen, J.E., Hansen, E.M., Askegaard, M. & Rasmussen, I.A. (2007). The value of catch crops and organic manure for spring barley in organic arable farming. *Field Crop Research, 100,* 168-178.

Parfitt, J.M.B., Timm, L.C., Reichardt, K. & Pauletto, E.A. (2014). Impacts of land levelling on lowland soil physical properties. *Revista Brasileira de Ciência do Solo, 38,* 315-326.

Parkin, T.B., Kaspar, T.C., Jaynes, D.B. & Moorman, T.B. (2016). Rye cover crop effects on direct and indirect nitrous oxide emissions. *Soil Science Society of America Journal, 80,* 1551-1559.

Poeplau, C. & Don, A. (2015). Carbon sequestration in agricultural soils via cultivation of cover crops-A meta-analysis. *Agriculture, Ecosystems and Environment, 200,* 33-41.

Powlson, D.S., Stirling, C.M., Jat, M., Gerard, B.G., Palm, C.A., Sanchez, P.A., et al. (2014). Limited potential of no-till agriculture for climate change mitigation. *Nature Climate Change, 4(8),* 678-83.

Premrov, A., Coxon, C., Hackett, R., Kirwan, L. & Richards, K. (2014). Effects of over-winter green cover on soil solution nitrate concentrations beneath tillage land. *Science of the Total Environment, 470-471,* 967-974.

Quemada, M., Baranski, M., Nobel-de Lange, M.N.J., Vallejo, A. & Cooper, J.M. (2013). Meta-analysis of strategies to control nitrate leaching in irrigated agricultural systems and their effects on crop yield. *Agriculture, Ecosystems and Environment, 174,* 1-10.

Rinnofner, T., Friedel, J.K., de Kruijff, R., Pietsch, G. & Freyer, B. (2008). Effect of catch crops on N dynamics and following crops in organic farming. *Agronomy for Sustainable Development, 28,* 551-558.

Roesch-McNally, G.E., Basche, A.D., Arbuckle, J.G., Tyndall, J.C., Miguez, F.E., Bowman, T. & Clay, R. (2017). The trouble with cover crops: Farmers' experiences with overcoming barriers to adoption. *Renewable Agriculture and Food Systems,* 1-12.

Schipanski, M.E., Barbercheck, M., Douglas, M.R., Finney, D.M., Haider, K., Kaye, J.P., Kemanian, A.R., Mortensen, D.A., Ryan, M.R., Tooker, J. & White, C. (2014). A framework for evaluating ecosystem services provided by cover crops in agroecosystems. *Agricultural Systems, 125,* 12-22.

Smeaton, D.C., Cox, T., Kerr, S. & Dynes, R. (2011). Relationships between farm productivity, profitability, N leaching and GHG emissions: a modelling approach. *New Zealand Grasslands Association, 73,* 57-62.

Smith, P., Goulding, K.W.T., Smith, K.A., Powlson, D.S., Smith, J.U., Falloon, P. & Coleman, K. (2000). Including trace gas fluxes in estimates of the carbon mitigation potential of UK agricultural land. *Soil Use and Management, 16,* 251-259.

Smith, E. G., Peters, T.L., Blackshaw, R.E., Lindwall, C.W. & Larney, F.J. (1996). Economics of reduced tillage in crop-fallow systems. *Canadian Journal of Soil Science, 76,* 411-416.

Snapp, S.S., Swinton, S.W., Labarta, R., Mutch, D., Black, J.R., Leep, R., Nyiraneza, J. & O'Neil, K. (2005). Evaluating cover crops for benefits, costs and performance within cropping system niches. *Agronomy Journal, 97,* 322-332.

Steele, M.K., Coale, F.J. & Hill, R.L. (2012). Winter annual cover crop impacts on no-till soil physical properties and organic matter. *Soil Science Society of America Journal, 76,* 2164-2173.

Steenwerth, K. & Belina, K.M. (2008). Cover crops and cultivation: Impacts on soil N dynamics and Micro-biological function in a Mediterranean vineyard agroecosystem. *Applied Soil Ecology, 40,* 370-380.

Stevenson, F.J. (1982). Humus Chemistry: Genesis, Composition, Reactions. Wiley-Interscience, New York.

Thomsen, I.K. & Hansen, E.M. (2014). Cover crop growth and impact on N leaching as affected by pre- and postharvest sowing and time of incorporation. *Soil Use and Management, 30,* 48-57.

Thomsen, I.K. (2005). Nitrate leaching under spring barley is influenced by the presence of a ryegrass catch crop: results from a lysimeter experiment. *Agriculture Ecosystems, and Environment, 111,* 21-29.

Thorup-Kristensen, K., Magid, J. & Jensen, L.S. (2003). Catch crops and green manures as biological tools in nitrogen management in temperate zone. *Advances in Agronomy, 79,* 227-302.

Tonitto, C., David, M.B. & Drinkwater, L.E. (2006). Replacing bare fallow with cover crops in fertilizer-intensive cropping systems: a meta-analysis of crop yield and N dynamics. *Agriculture Ecosystems, and Environment, 112,* 58-72.

Torstensson, G. & Aronsson, H. (2000). Nitrogen leaching and crop availability in manured catch crop systems in Sweden. *Nutrient Cycling in Agroecosystems, 56,* 139-152.

Tribouillois, H., Constantin, J. & Justes, E. (2018). Cover crops mitigate direct greenhouse gases balance but reduce drainage under climate change scenarios in temperate climate with dry summers. *Global Change Biology, 24 (6),* 2513-2529.

Unger, P.W. & Vigil, M.F. (1998). Cover crop effects on soil water relationships. *Journal of Soil and Water Conservation*, 53, 200-207

Valkama, E., Lemola, R., Känkänen, H. & Turtola, E. (2015). Meta-analysis of the effects of under-sown catch crops on nitrogen leaching loss and grain yields in the Nordic countries. *Agriculture Ecosystems, and Environment, 203,* 93-101.

Van Groenigen, J.W, van Kessel, C., Hungate, B.A., Oenema, O., Powlson, D.S. & Van Groenigen, K.J. (2017). Sequestering Soil Organic Carbon: a Nitrogen Dilemma. *Environmental Science and Technology, 51*(9), 4738-4739.

Villamil, M.B., Bollero, G.A., Darmody, R.G., Simmons, F.W. & Bullock, D.G. (2006). No-till corn/soybean systems including winter cover crops. *Soil Science Society of America Journal, 70,* 1936.

Wallgren, B. & Lindén, B. (1994). Effect of catch crops and ploughing times on soil mineral nitrogen. *Swedish Journal of Agricultural Research, 24,* 67-75.

Wang, G. & Ngouajio, M. (2008). Integration of cover crop, conservation tillage, and low herbicide rate for machine-harvested pickling cucumbers. *HortScience, 43(6),* 1770-1774.

Webb, J., Harrison, R. & Ellis, S. (2000). Nitrogen fluxes in three arable soils in the UK. *European Journal of Agronomy, 13,* 207-223.

Weinert, T.L., Pan, W.L., Moneymaker, M.R., Santo, G.S. & Stevens, R.G. (2002). Nitrogen recycling by non-leguminous winter cover crops to reduce leaching in potato rotations. *Agronomy Journal, 94,* 365-372.

West, T.O. & Post, W.M. (2002). Soil organic carbon sequestration rates by tillage and crop rotation. *Soil Science Society of America Journal, 66(6),* 1930-46.

White, C. M., Finney, D. M., Kemanian, A. R., & Kaye, J. P. (2016). A Model-Data Fusion Approach for Predicting Cover Crop Nitrogen Supply to Corn. *Agronomy Journal, 108,* 2527-2540.

Wittwer, R.A., Dorn, B., Jossi, W. & van der Heijden, M.G.A. (2017). Cover crops support ecological intensification of arable cropping systems. *Scientific Reports, 7,* 41911.

Wortman, S.E., Francis, C.A., Bernards, M.L., Drijber, R.A. & Lindquist, J.L. (2012). Optimizing cover crop benefits with diverse mixtures and an alternative termination method. *Agronomy Journal, 104,* 1425-1435.

Yogesh, A. & Juo, A.S.R. (1982). Leaching of fertilizer ions in a Kaolinitic Ultisol in the high rain fall tropics: Leaching of nitrate in field plots under cropping and bare fallow. *Soil Science Society of America Journal, 46,* 1212-1217.

Zhou, M. & Butterbach-Bahl, K. (2013). Assessment of nitrate leaching loss on a yield-scaled basis from maize and wheat cropping systems. *Plant and Soil, 374,* 977-991.