RESEARCH ARTICLE

Conversion to No-Till Improves Maize Nitrogen Use Efficiency in a Continuous Cover Cropping System

Hazzar Habbib[1]*, Julien Verzeaux[1], Elodie Nivelle[1], David Roger[1], Jérôme Lacoux[1], Manuella Catterou[1], Bertrand Hirel[2], Frédéric Dubois[1], Thierry Tétu[1]

1 Ecologie et Dynamique des Systèmes Anthropisés (EDYSAN, FRE 3498 CNRS UPJV), Laboratoire d'Agroécologie, Ecophysiologie et Biologie intégrative, Université de Picardie Jules Verne, 33 rue St Leu, 80039 Amiens, Cedex, France, 2 Adaptation des Plantes à leur Environnement, Unité Mixte de Recherche 1318, Institut Jean-Pierre Bourgin, Institut National de la Recherche Agronomique, Centre de Versailles-Grignon, R.D. 10, F-78026 Versailles Cedex, France

* hazzar.habbib@u-picardie.fr

Abstract

A two-year experiment was conducted in the field to measure the combined impact of tilling and N fertilization on various agronomic traits related to nitrogen (N) use efficiency and to grain yield in maize cultivated in the presence of a cover crop. Four years after conversion to no-till, a significant increase in N use efficiency N harvest index, N remobilization and N remobilization efficiency was observed both under no and high N fertilization conditions. Moreover, we observed that grain yield and grain N content were higher under no-till conditions only when N fertilizers were applied. Thus, agronomic practices based on continuous no-till appear to be a promising for increasing N use efficiency in maize.

1. Introduction

Maize (*Zea mays* L.), also known as corn, is an essential dual-use food and energy crop, both in terms of cultivated area and production of harvestable material. The yearly increase in maize productivity worldwide has been much higher compared to other cereals, being on average 60 kg per ha every year since 1960 [1]. The total world production of maize reached a record of 877×10^9 kg in the 2011–2012 fiscal year [2]. Maize requires large amounts of nitrogen (N) inputs for optimum grain and silage production, due mainly to the ability of the crop to produce large quantities of dry matter [3–5]. However, in several studies it has been shown that increasing N fertilization above a certain threshold, neither leads to an increase in plant uptake nor in grain production [6–8]. N use efficiency (NUE), originally defined by Moll et al. [9] as the grain yield or biomass production yield obtained per unit of N available in the soil (already present and originating from fertilizer application), is inversely proportional to the amount of N fertilizer applied [10]. When the rate of N fertilization is too high, nitrate leaching occurs, leading to multiple damaging effects on the diversity and functioning of non-agricultural bacterial, animal and plant ecosystems [11,12]. In addition, fertilizer-derived N oxide emissions into the atmosphere contribute to the depletion of the ozone layer [13], whilst volatilized ammonia

is returned as wet or dry deposition, which can cause acidification and eutrophication. Moreover it has been reported than an excessive application of N fertilizers can even lead to a decrease in grain yield [14,15]. Thus, improving NUE is particularly relevant for maize, for which global NUE has been estimated to be less than 50% [16,17].

Both from a physiological and agronomic point of view, NUE is the result of two main biological processes: N uptake efficiency (NUpE) which corresponds to the amount of N taken up per unit of available N, and N utilization efficiency (NUtE) which corresponds to the increase in biomass or yield per unit of N taken up [18,19]. During the plant developmental cycle, a number of complex physiological processes are involved in the control of plant NUE notably N uptake, N assimilation and N translocation [9,18–20]. Cereals in general and maize in particular, need to remobilize the N accumulated in proteins in vegetative tissues and at the same time take up and assimilate N after anthesis, in order to ensure storage protein deposition in the grain. In maize, both N uptake and N remobilization processes contribute equally to NUE [21], measurement of these two components was a major part of this study, which aimed at optimizing tillage practices for optimal soil N recovery.

It is well known that on top of mineral N fertilization, intensive mechanical cultivation practices such as tillage generally alters soil biological activity [22–24]. These intensive cultivation practices create compaction zones in the soil [25–27], expose the soil surface to wind and water erosion [28,29] and alter the soil organic matter (SOM) decomposition rate. Reicosky and Archer [30] reported that larger amounts of CO_2 were released into the atmosphere as the result of tillage, which, in turn reduced the soil carbon (C) content. In contrast, conservation tillage practices under continuous cropping systems are known to improve SOM content [31–36], notably by enhancing C accumulation in soil aggregates. Hence, compared to conventional tillage, agricultural practices based on the use of conservation tillage are in many cases beneficial in terms of crop yield improvement [37–39].

Moreover, it has been shown that both under tilling and no-till cultivation conditions, the use of cover crops captures the excess mineral N remaining in the soil during winter and early spring periods, thus limiting the amount of mineral N that can leach into ground water [40–42]. Furthermore, several studies have demonstrated that due to their ability to fix atmospheric N, legume cover crops have a beneficial impact on crop production [43–46] by increasing soil fertility, notably by increasing the N content [47].

A large number of studies have focused on improving N fertilizer management practices in order to increase both NUE and yield in many crops, including maize [48–51]. Among these management practices no-till has been increasingly used. However, its impact remains to be thoroughly characterized both in terms of plant NUE and plant productivity.

In the present study, maize plants were grown over four years in the presence of cover crops under tillage and no-till conditions to evaluate the combined effect of tilling and N fertilization on NUE and NUE-related traits. In the absence of mineral N fertilization, an increase in NUE and NUE-related traits including nitrogen remobilization (NRem), nitrogen remobilization efficiency (NRE) and nitrogen harvest index (NHI) under no-till conditions was observed. Thus, no-till appears to be a promising strategy for maintaining maize productivity without additional N fertilizers inputs.

2. Materials and Methods

2.1. Site Description and Experimental Design

The field experiment was conducted at the experimental site of La Woestyne, in North France (50°44′N, 2°22′E, 40 m a.s.l.). The owner of the land "Bonduelle company" gave permission to conduct the study on this site. The field studies did not involve endangered or protected

species. Physical and chemical soil characteristics are presented in Table 1. Weather-related parameters for this area are as follows: average annual rainfall 675 mm, average annual temperature 10.5°C.

The field was managed under a chisel plough and rotary power system until 2010, when the experiment was initiated. The field experiment was split into four treatments with three replicated plots placed randomly for each of the four treatments including: no-till with (NTN1) or without (NTN0) N fertilization; conventional tillage with (CTN1) or without (CTN0) N fertilization. The individual plot size was 7m×8m for each treatment. Since the beginning of the experiment in 2010, the conventional tillage in CT plots was performed using the moldboard plowing technique followed by the passing of a rotating harrow (Kuhn, France) for shallow tillage (30 cm tillage depth). In 2013 (3 years after the beginning of the field experiment) and in 2014 (4 years after the beginning of the field experiment), maize samples were collected in each plot in 2013 and in 2014. The crop rotation preceding maize cultivation in 2013 consisted of green bean (*Phaseolus vulgaris* L.) in 2010, followed by wheat (*Triticum aestivum*) in 2011, pea (*Pisum sativum*) in 2012. In the maize culture performed in 2014, the crop rotation consisted of wheat (*Triticum aestivum*) in 2010, followed by green bean (*Phaseolus vulgaris* L.) in 2011, wheat (*Triticum aestivum*) in 2012, pea (*Pisum sativum*) in 2013 (S1 Fig).

Before sowing the main crop, cover crop residues were buried in CT plots and left on the soil surface in NT plots. This cover crop consisted of a mixture of legume and non-legume species which were sown as follow: 12 kg ha^{-1} of Egyptian clover (*Trifolium alexandrinum* L.), 100 kg ha^{-1} of faba bean (*Vicia faba* L.), 20 kg ha^{-1} of vetch (*Vicia sativa* L.), 5 kg ha^{-1} of flax (*Linum usitatissimum* L.), 4 kg ha^{-1} of phacelia (*Phacelia tanacetifolia* Benth.), 10 kg ha^{-1} of oats (*Avena sativa* L.). To evaluate N inputs from cover crops residues, in each of the four plots,

Table 1. Characteristics of the soil used for evaluating the impact of no-till and N fertilization on maize NUE at the beginning of the experiment in 2010.

Parameters (units)	Depth range (cm)	Value
Clay <2 μm (g kg^{-1})	0–30	211.6
Silt 2–20 μm (g kg^{-1})	0–30	232.3
Silt 20–50 μm (g kg^{-1})	0–30	436.3
Fine sand 50–200 μm (g kg^{-1})	0–30	95.2
Coarse sand (200–2000 μm) (g kg^{-1})	0–30	24.6
pH in H_2O	0–15	6.9
CEC[a] (cmol$^+$ kg^{-1})	0–15	12
P[b] (mg kg^{-1})	0–15	24
Organic Carbon (g kg^{-1})	0–15	11.6
Exchangeable cations (cmol$^+$ kg^{-1})		
Ca^{2+}	0–15	17.5
Mg^{2+}	0–15	0.83
Na^+	0–15	<0.43
K^+	0–15	0.77
Penetration Resistance (MPa)		
With a soil moisture of 33%	0–15	0.7
	15–30	1.1
	30–45	1.7
	45–60	2.2

[a] Cation-exchange capacity (Metson method)

[b] Available phosphorus (Olsen method)

doi:10.1371/journal.pone.0164234.t001

$3 \times 1 \text{ m}^2$ of cover crops were sampled each year. Samples were dried in an oven at 65°C for three days and then weighed. The total aboveground biomass of cover crops was ground into powder prior total N measurements. From the beginning of the experiment in 2010, means of N input originating from the cover crops residues in each of the four treatments were (123 kg ha^{-1}, 127 kg ha^{-1}, 125 kg ha^{-1} and 128 kg ha^{-1}) under NTN0, NTN1, CTN0 and CTN1 conditions respectively.

The amount of N fertilizer applied under N1 conditions was determined according to the N budget method for maize [52], based on the predictive balance-sheet method (Software Azobil, INRA, Laon, France) using the following formula:

$$B + Rf = (Ri - L) + Mn + X$$

Where B is the N requirement of the crop, Rf is the residual soil mineral nitrogen content at harvest, Ri is the readily available soil mineral nitrogen in a determined depth of soil before maize planting, L is the soil mineral nitrogen potential loss during the period from analysis of soil N to N-fertilizer application, X is N the fertilizer rate and Mn is the net supply of soil mineral nitrogen during the growing season. Mn results from the sum of the net mineralization from SOM, the mineral N supply from previous crop residues and the mineral N supply from organic manures. All the terms are expressed in kg N ha^{-1}.

The final amounts of N fertilizer applied under N1 conditions were 97 kg N ha^{-1} in 2013 and 80 kg N ha^{-1} in 2014. The N fertilizer was composed of 50% urea, 25% ammonium, 25% nitrate applied in a liquid form on the soil surface through broadcast applications at daybreak or at nightfall. Under these conditions of application, it was assumed that N volatilization was negligible.

2.2. Soil Sampling and Chemical Analyses

In March 2013 and 2014, six 30-cm deep soil cores were randomly collected using a 2-cm diameter auger in each of the three replicated plots for the four treatments (NTN1, NTN0, CTN1 and CTN0). Six soil cores from each replicate plot were collected and pooled, thus forming a single sample in each of the three replicates. Soils were then sieved using a 2 mm mesh and divided into two parts, for soil total N and soil residual N analysis. For soil total N measurements, the sieved soil was dried in an oven at 45°C for 48 h and ball milled ground (MM 400, Retsch, Germany). Soil total N (expressed as % of dry soil) was quantified using the combustion method of Dumas [53] using a Flash EA 1112 elemental analyzer, Thermo Electron, Germany.

Residual N (expressed in kg N ha^{-1}) corresponds to the N originating from nitrate and ammonium present in the soil. Nitrate and ammonium were extracted using 20 g of fresh soil mixed with 100 mL of 1 M KCl. After shaking for 1 h, the soil extracts were centrifuged for 10 min at 4,000 g and the supernatant was analyzed using a continuous flow analytical system (San^{++} system, Skalar, Holland). The measured amounts of total N and residual N present in the soil before maize sowing in April 2013 and 2014 are shown in Table 2.

Soil water content (%) at sowing in April (SWC.s) and at crop harvest (SWC.h) in October were determined by using a moisture meter connected to a Penetrologger (Eijkelkamp, The Netherlands).

2.3. Crop Sampling and Plant Analysis

Maize (*Zea mays*, var. SY Cookie, Syngenta, Switzerland) was sown in 75 cm spaced rows using a Kuhn Maxima drill (Kuhn, France). At anthesis and at crop maturity when both stover and grains were dried [54], 6 rows of 1m length were sampled in 2013 and 2014 in each of the four

Table 2. Soil total N (%) and Soil residual N (kg ha^{-1}) under two tillage systems and N fertilizer rates in the two studied years.

Year		2013		2014	
N fertilizer	Tillage	Soil total N (%)	Soil residual N (kg ha^{-1})	Soil total N (%)	Soil residual N (kg ha^{-1})
N0	NT	0.26	50.07	0.26	44.66
	CT	0.25	64.40	0.24	64.29
N1	NT	0.27	79.55	0.26	52.98
	CT	0.28	63.80	0.27	48.21

NT = No-till with cover crops, CT = Conventional tillage with cover crops, N0 = no fertilization, N1 = N fertilization

treatments (NTN1, NTN0, CTN1 and CTN0). The shoots were clipped at ground level and threshed to separate the grain for yield per m^2 measurements. Shoots and grain were dried in an oven at 60°C for 3 days, weighed and finally ground in a Retsch mill (Retsch zm200, Haan, Germany) to obtain a fine powder (0.75 mm particles). Grain and stover N contents were quantified using the same elemental analyzer as that used for soil N content analysis.

Traits related to NUE were calculated according to Moll et al. [9], Huggins and Pan [55] and López-Bellido et al.[49] using the following equations:-

$$\text{NUE (kg kg}^{-1}) = \text{Gy/Nsupply} \tag{1}$$

$$\text{NUtE (kg kg}^{-1}) = \text{Gy/Nt} \tag{2}$$

$$\text{NHI } (\%) = (\text{Ng/Nt}) \times 100 \tag{3}$$

where, Gy corresponds to grain yield (kg ha^{-1}), Nt to total plant N at maturity (kg ha^{-1}), Ng is the grain N (kg ha^{-1}) and N supply, the soil N available to the crop (expressed in kg kg^{-1}).The available N corresponds to the sum of applied N fertilizer and of total plant N uptake in non-fertilized plots in the tilled and no-tilled cultivation systems [6]. To measure the amount of N remobilized from vegetative to reproductive organs after anthesis (NRem), the following equations were used according to the method described by Cox et al. [56], Beheshti and Behboodi [57] and Masoni et al. [58]:

NRem (g plant^{-1})
$$= \text{N content of the whole plant at anthesis } - \text{ N content of leaves, stem and chaff at maturity.} \tag{4}$$

$$\text{NRE } (\%) = (\text{NRem/N content of the whole plant at anthesis}) \times 100. \tag{5}$$

2.4. Statistical Analyses

All statistical analyses were performed in R Statistical Software version 3.2.3 [59]. Data were subjected to variance analysis (Two-way ANOVA), using tillage practices (CT, NT) as the main parameters and the level of N application (N0, N1) as the second parameters. All explanatory variables were examined for normality using the Shapiro-Wilk test [60] and for homogeneity of variances with the Bartlett test [61]. Means of each of the four treatments (NTN1, NTN0, CTN1 and CTN0) were compared using Duncan's new multiple range test at a 95% family-wise confidence level (Agricolae package) [62]. Correlations between agronomical variables (grain yield, plant N, soil N, soil water content) and NUE-related traits (NUE, NUtE, NRem, NRE and NHI) were computed using a Pearson product-moment correlation

coefficient at $P<0.05$ (Hmisc package) [63]. Principal component analysis (PCA) (ade4 package) [64] was also carried out to visualize relationships existing between NUE-related traits (NUE, NUtE, NRem, NRE and NHI) and agronomic traits (Grain yield, soil N total, plant N, SWC.s and SWC.h).

3. Results

3.1. Effect of Tillage on Agronomic and NUE-Related Traits

Grain yield over the two years of experimentation ranged from 8060.00 to 12757.33 kg ha^{-1} (Table 3). In 2013 and in 2014, grain yield was not significantly different between tillage and no-till conditions, whereas N fertilization significantly increased grain production both under NT and CT conditions ($P < 0.001$, $P < 0.05$ in 2013 and 2014 respectively).

Total biomass production was not significantly modified under CT or NT conditions over the two years of experimentation. In 2013, N application increased the total biomass production significantly, irrespective of the tilling conditions (Table 3).

Both in 2013 and 2014, total N uptake was not significantly modified under CT and NT conditions. However, N uptake was higher when N fertilizers were applied (N1 treatment) both in the tilling and no-till system (Table 3).

Tillage did not modify grain N content both in 2013 and in 2014. In contrast, when N fertilizers were applied, a significant increase ($P < 0.001$) in the grain N content was observed, only in 2013 (Table 3).

The ANOVA statistical analysis indicated that SWC.s and SWC.h were not significantly different between N0 and N1 (Table 4). In contrast, tillage had a significant effect on SWC both at

Table 3. Impact of tilling and nitrogen fertilization on maize agronomic traits (mean ± standard error).

Source of variance			Agronomic trait			
Year	N fertilizer	Tillage	Total biomass (kg ha^{-1})	Total plant N uptake (kg ha^{-1})	Grain yield (kg ha^{-1})	N grain (kg ha^{-1})
2013	N0	NT	17817 ± 1534 b	166.53 ± 22.94 b	8060.0 ± 1064.7 b	108.02 ± 17.98 b
		CT	19833 ± 748 b	212.49 ± 6.08 b	9458.0 ± 517.4 b	118.44 ± 6.40 b
	N1	NT	24513 ± 1059 a	298.76 ± 29.86 a	12757 ± 895 a	186.06 ± 19.16 a
		CT	23919 ± 480 a	301.26 ± 11.74 a	11846 ± 315 a	159.59 ± 3.10 a
2014	N0	NT	24578 ± 1891	252.22 ± 37.90 c	9676.4 ± 972.0 b	107.51 ± 14.68
		CT	30822 ± 1791	305.53 ± 22.34 bc	10408 ± 282 b	112.32 ± 5.43
	N1	NT	29400 ± 2002	366.39 ± 37.74 ab	10074 ± 592 a	122.03 ± 7.71
		CT	32200 ± 1225	431.49 ± 17.67 a	10829 ± 582 a	130.82 ± 11.00
	Analyse of variance			$P>F$ (n = 6)		
2013	Tillage		ns	ns	ns	ns
	N fertilizer		<0.001 ***	<0.001 ***	<0.001***	<0.001***
	Tillage×N fertilizer		ns	ns	ns	ns
2014	Tillage		ns	ns	ns	ns
	N fertilizer		ns	<0.001 ***	<0.05*	ns
	Tillage×N fertilizer		ns	ns	ns	ns

NT = No-till with cover crops, CT = Conventional tillage with cover crops, N0 = no fertilization, N1 = N fertilization. Data for each parameter were subjected to variance analysis (Two-way ANOVA). Treatment means were compared using Duncan's new multiple range test at a 95% family-wise confidence level. Means with the same letter are not significantly different. (*, *** = significant at 0.05 and 0.001 probability level, respectively). ns = not significant.

doi:10.1371/journal.pone.0164234.t003

Table 4. Impact of tilling and nitrogen fertilization on soil water content (%) at sowing and at crop harvest (mean ± standard error).

Source of variance		2013		2014	
N fertilizer	Tillage	SWC.s (%)	SWC.h (%)	SWC.s (%)	SWC.h (%)
N0	NT	38.83 ± 0.47 *a*	40.83 ± 0.94 *a*	39.33 ± 0.33 *a*	41.50 ± 0.76 *a*
	CT	37.00 ± 0.57 *b*	37.66 ± 0.49 *b*	34.50 ± 0.99 *c*	37.31 ± 0.66 *b*
N1	NT	38.16 ± 0.47 *ab*	39.66 ± 0.66 *ab*	38.16 ± 0.47*ab*	39.33 ± 0.80 *b*
	CT	36.66 ± 0.21 *b*	38.00 ± 0.36 *b*	36.66 ± 0.21 *b*	38.00 ± 0.36 *b*
Analyse of variance		*P>F* (n = 6)			
Tillage		<0.01**	<0.01**	<0.001***	<0.001***
N fertilizer		ns	ns	ns	ns
Tillage×N fertilizer		ns	ns	<0.01**	<0.05*

NT = No-till with cover crops, CT = Conventional tillage with cover crops, N0 = no fertilization, N1 = N fertilization, SWC.s = soil water content at sowing, SWC.h = soil water content at harvest. Data for each parameter were subjected to variance analysis (Two-way ANOVA). Treatment means were compared using Duncan's new multiple range test at a 95% family-wise confidence level. Means with the same letter are not significantly different. (*, **, *** = significant at 0.05, 0.01, 0.001 probability level, respectively). ns = not significant.

doi:10.1371/journal.pone.0164234.t004

sowing and at harvest both in 2013 and in 2014. A significant increase in SWC.s and SWC.h was also observed in NT compared to CT, only under N1 conditions.

In 2013 and in 2014, tillage had a significant and negative impact on NRE compared to the NT conditions ($P < 0.001$ in both years) (Fig 1A). The application of N fertilizer increased NRE under NT conditions. However, N application did not increase NRE under CT conditions.
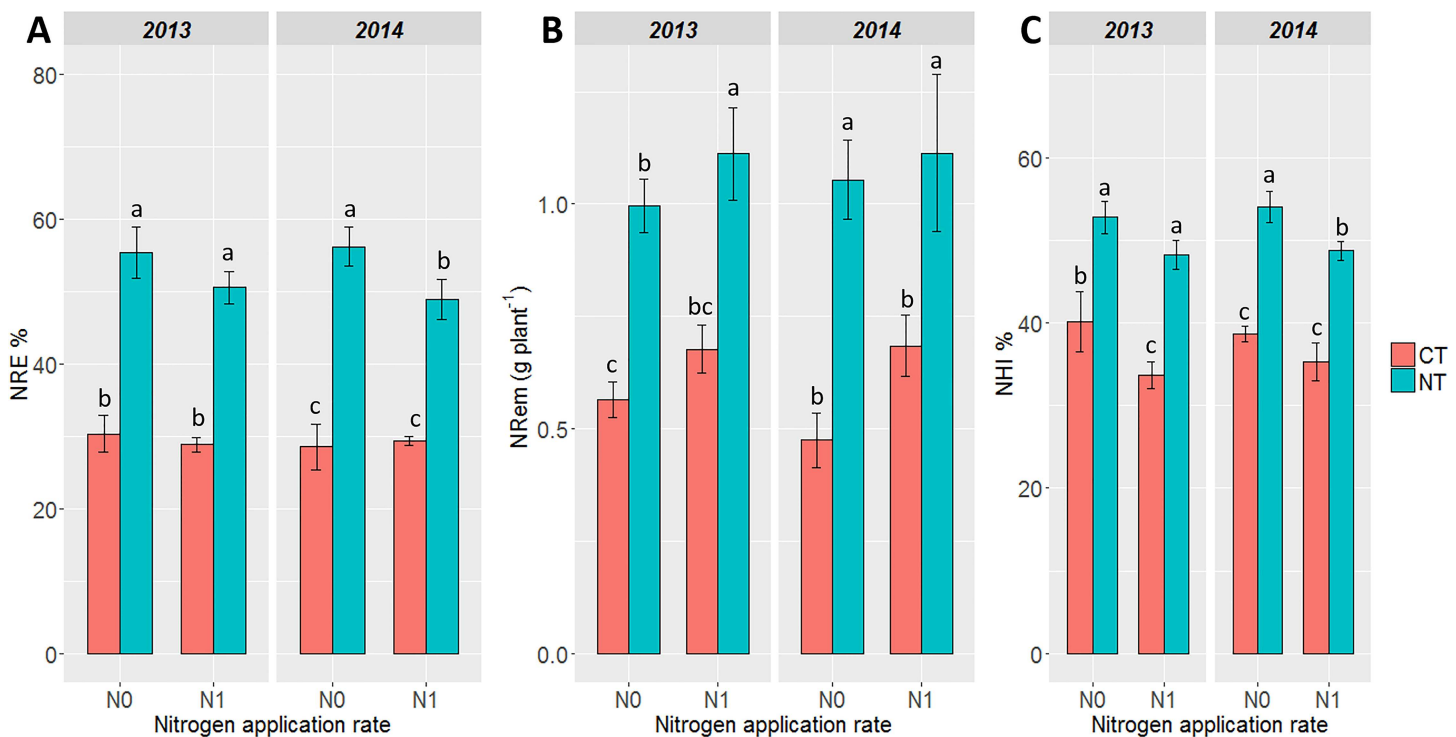

Fig 1. Impact of tillage practice and N application on (A) NRE; (B) NRem and (C) NHI, according to the soil tillage treatment in 2013 and 2014. (NT) No-till with cover crops, (CT) Conventional tillage with cover crops. N0 = no fertilization, N1 = N fertilization. Data for each parameter were subjected to variance analysis (two-way ANOVA). Treatment means were compared using Duncan's new multiple range test at a 95% family-wise confidence level. Means with the same letter are not significantly different.
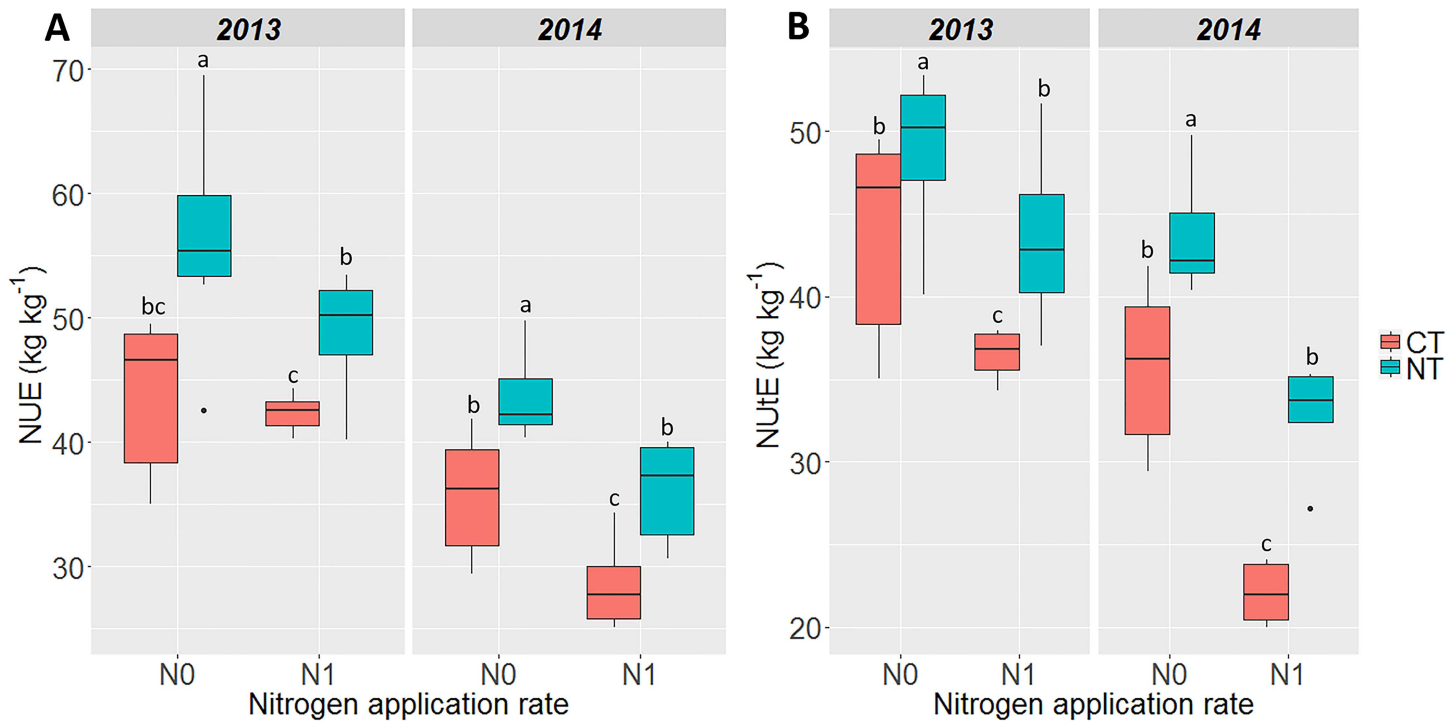
doi:10.1371/journal.pone.0164234.g001

Fig 2. Impact of tillage practice and N application on (A) NUE of maize grain (kg kg⁻¹) and (B) NUtE of maize grain (kg kg⁻¹) according to the soil tillage treatment in 2013 and 2014. (NT) No-till with cover crops, (CT) Conventional tillage with cover crops. N0 = no fertilization, N1 = N fertilization. Box plots are represented with the median and the 25th-75th percentile with the minimum and the maximum. Data for each parameter were subjected to analysis of variance (two-way ANOVA). Treatment means were compared using Duncan's new multiple range test at a 95% family-wise confidence level. Means with the same letter are not significantly different.

doi:10.1371/journal.pone.0164234.g002

The tillage system had a significant effect on NRem. This positive effect was significantly higher ($P < 0.001$) under NT compared to CT (Fig 1B) in both years, whereas Nrem was not modified whatever the N the fertilization conditions.

In 2013, the N fertilization did not significantly modify NHI, either under NT or CT conditions. However, both in N0 or N1, tillage had a negative effect on NHI compared to the NT cultivation system over the two years of experimentation ($P < 0.001$, $P < 0.05$ in 2013 and 2014 respectively) (Fig 1C). The N fertilization significantly modified NHI under CT conditions in 2013 and under NT conditions in 2014.

Both in 2013 and 2014, CT and N application had a significant negative impact on NUE and its component NUtE ($P < 0.001$). Under N0 and N1, both NUE and NUtE were significantly higher in NT compared to CT conditions (Fig 2). A significant decrease in NUE and NUtE was also observed when N fertilizers were applied both under NT and CT conditions.

3.2. Correlation Analyses

Pearson correlations between NUE, NUtE, yield, soil N, total plant N, NRem, NRE, SWC.s, SWC.h and NHI over the two years of experimentation are presented in Fig 3. NUE and NUtE were significantly and positively correlated with NRem, NRE, NHI, soil N, SWC.s and SWC.h. Similarly, NRE, NRem and NHI were significantly correlated with the soil N content, SWC.s and SWC.h. Conversely, NUE, NUtE, NRE and NHI were significantly and negatively correlated with the plant N content. A PCA analysis was then performed to obtain a visual
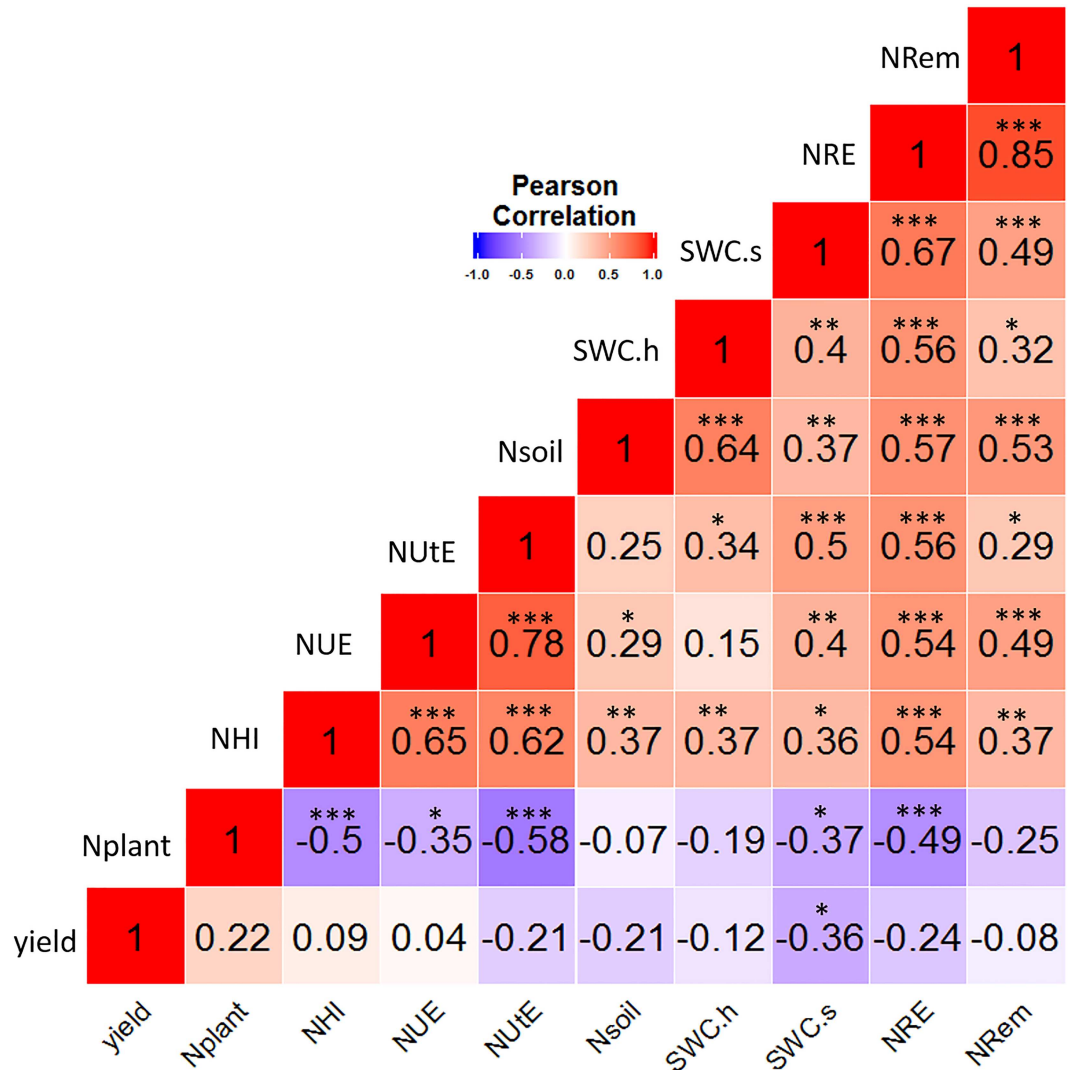
Fig 3. Pearson correlation coefficient *r* between NUE and NUE-related traits. (*, **, *** = significant at 0.05, 0.01, 0.001 probability level, respectively.).

representation of the correlations between agronomic and NUE-related traits, according to the tillage system and the level of N fertilization (Fig 4). The first two axes of a PCA using NUE traits explained 61.59% of the variation in the data set. The variables were separated into four groups corresponding to tillage system and fertilizer application rate. Axis.1 (46.94% of variance explained) was positively correlated with plant N and yield, and negatively correlated with soil N, SWC.s, SWC.h, NRem, NRE, NHI, NUE and NUtE, which matches the Pearson correlation test. NRem, NRE, soil N, SWC.s and SWC.h were strongly correlated and positively grouped along Axis.2 (14.65% of variance explained). Similarly, NUE, NUtE and NHI were strongly correlated and negatively grouped along Axis.2. The first axis clearly separated the CT treatment from the NT treatment. The N0 and N1 fertilization conditions were separated along the second axis. NUE and NUtE related traits were markedly higher under NT conditions compared to the CT treatment.
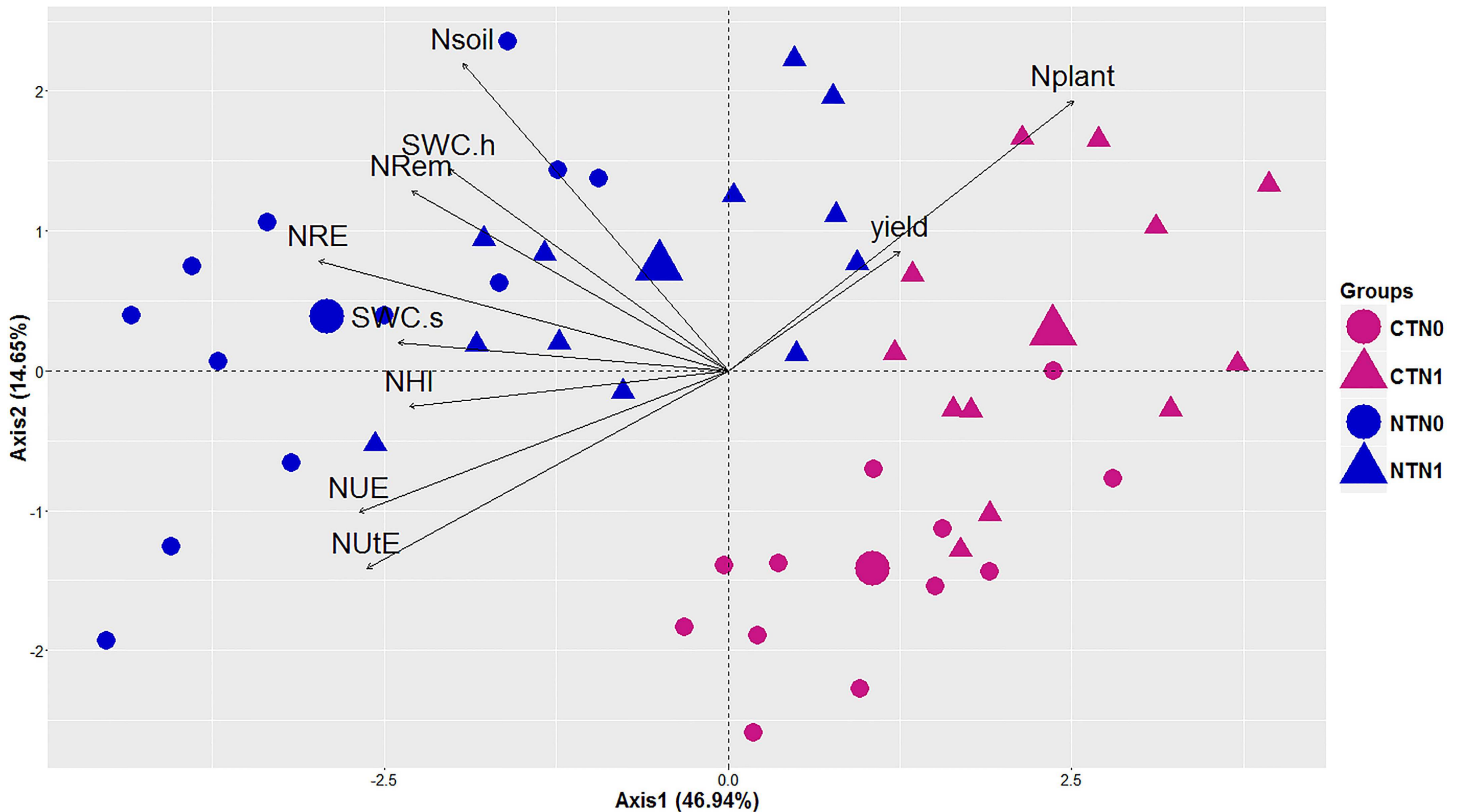
Fig 4. PCA analysis showing the correlations between tilling conditions, N fertilization and NUE-related traits. Diagrams were defined by the first two axes of the PCA of the variables (n = 12). Axis.1 (46.94% of variance explained) and Axis.2 (14.65% of variance explained). NTN0 = No-till without N fertilization, CTN0 = Conventional tillage without N fertilization, NTN1 = No-till with N fertilization, CTN1 = Conventional tillage with N fertilization.

4. Discussion

The field experiment performed over two consecutive years showed that conversion to no-till under a continuous cover cropping system significantly increased maize NUE and NUtE, in comparison to a cultivation system based on continuous till. Moreover, such an increase occurred both under low and high N fertilization conditions (Fig 2). These results are in agreement with those obtained with wheat by Soon et al. [65], who showed that NUE was increased under no-till conditions. In contrast, Brennan et al. [6] and López-Bellido and López-Bellido [7] found that in wheat, NUE was lower under reduced or no-till conditions respectively, likely because under their experimental conditions, crop N uptake was reduced. Another survey conducted by Dalal et al. [34] over 40 years of experimentation, led to the conclusion that wheat NUE remained constant, irrespective of the tilling practices employed. These contrasting results can be explained by the fact that in conservation systems, there is often an inefficient mobilization of N generated by plant residues left at the soil surface, thus leading to a decrease in NUE [66,67]. The originality of our study was to show that in maize, a crop rarely tested for its ability to valorize N under continuous till conditions, NUE is higher when the soil is not plowed, irrespective of the N fertilization regime.

In agreement with Burgess et al. [66] and Torbert et al. [68], grain yield, remained similar either under low or high N fertilization, regardless of the tilling conditions. In other studies, it has been reported that maize yields decrease slightly when no-till is used instead of conventional tilling, likely because the soil N availability is lower leading to a reduction in crop productivity

[69,70]. In spring cereals such as barley, oats and wheat, it was generally observed that under no-till conditions, grain yield was substantially reduced [71–73]. Under the experimental conditions employed in these studies, the combined effect of tillage and of the level of N fertilization did not markedly modify N uptake, as slightly more N was taken up by the maize plants under CT conditions. Moreover, in agreement with Al-Kaisi and Kwaw-Mensah [74], we observed that such a small increase in N uptake did not lead to an increase in the grain N content (Table 3).

NUE is a complex agronomic traits depending on soil N availability, resulting from the efficiency of N uptake by the roots and N utilization and N remobilization by the plant [75]. Among the various traits representative of NUE, NHI was higher under NT conditions compared to CT, irrespective of the level of N fertilization. Similarly, other NUE-related traits such as NRem and NRE were significantly higher under NT compared to CT, whether or not N fertilizers were applied (Fig 1A and 1B). In addition, NHI and NRE were positively and significantly correlated with NUE and NUtE (Fig 3). Although the leaf N content at maturity was higher in CT than in NT, the grain N content was similar irrespective of the tillage practice (Table 3).

In this study, tillage had a negative impact on the amount of water stored in the soil. In particular, without additional N fertilization (N0), SWC.s and SWC.h were significantly lower following CT under N0 conditions in comparison to NT over the two years of experimentation (Table 4). The absence of tillage is known to preserve soil moisture [65,76] by maintaining total soil pore space while keeping the exchanges between the macro- and micro-pores in the soil [77]. It has been shown that soil water retention under NT conditions is beneficial to the crop, notably during the grain filling period after anthesis [78]. During this period, N remobilization largely depends on soil water availability [79–81]. In line with these observations, it has been reported that in wheat both N uptake and N remobilization and thus NUE were reduced when there was a shortage of water [82,83]. It is likely that in the NT system, soil water retention was one of the components that favored post-anthesis N uptake and thus NUE.

PCA analysis allowed a refinement of the correlations observed between NUE, and the various NUE-related traits such as NUtE, NRE and NHI and their relationship with the tillage system according to the level of N fertilization (Fig 4). The first axis clearly separated CT plots from NT plots. The second axis mainly separated N0 from N1 plots. Remarkably, NUE and NUtE were the two traits that contributed the most to the increase in NUE under NT conditions. Such an analysis thus confirmed that the no-till system had a positive impact both on NUE and NUE-related traits.

5. Conclusion

In the present study, a field experiment was conducted over a 4-year period to ensure that the impact of the conversion to a no-till system on NUE and NUE-related traits was rapidly and accurately monitored. Both NUE and NUE-related traits, which could not have been accurately measured using longer-term experiments, were used as markers in order to investigate the benefit of the no-till cultivation system. As in a number of previous studies [74,84–86], measurements of these traits were performed using short-term experiments in order to detect the effect of no-till at any time during the entire field experiment. Over two years of experimentation, the results showed that the use of a continuous no-till system with a cover crop is a promising way to increase the NUE of maize, and consequently to reduce both the use and the loss of N fertilizers without any yield penalty.

Supporting Information

S1 Fig. Chronological representation of crop rotation over the 4-year experiment. (NT) no-till, (CT) conventional tillage, (N0) no fertilization, (N1) N fertilization, (Ø) no cover crops. (TIF)

References

1. Leveau V, Lorgeou J, Prioul JL. Maize in the world economy: a challenge for scientific research–how to produce more cheaper! In: Prioul JL, Thévenot C, Molnar C, editors. Advances in Maize. London: Society for Experimental Biology; 2011. pp. 509–534.

2. International Grains Council; 2013. Report for fiscal year 2011/12. International Grains Council, London.

3. Moser SB, Feil B, Jampatong S, Stamp P. Effects of pre-anthesis drought, nitrogen fertilizer rate, and variety on grain yield, yield components, and harvest index of tropical maize. Agric Water Manag. 2006; 81(1–2):41–58. doi: 10.1016/j.agwat.2005.04.005

4. Robertson MJ, Sakala W, Benson T, Shamudzarira Z. Simulating response of maize to previous velvet bean (*Mucuna pruriens*) crop and nitrogen fertiliser in Malawi. Field Crops Res. 2005; 91(1):91–105. doi: 10.1016/j.fcr.2004.06.009

5. Zhou J Bin, Wang CY, Zhang H, Dong F, Zheng XF, Gale W, et al. Effect of water saving management practices and nitrogen fertilizer rate on crop yield and water use efficiency in a winter wheat-summer maize cropping system. Field Crops Res. 2011; 122(2):157–63. doi: 10.1016/j.fcr.2011.03.009

6. Brennan J, Hackett R, McCabe T, Grant J, Fortune RA, Forristal PD. The effect of tillage system and residue management on grain yield and nitrogen use efficiency in winter wheat in a cool Atlantic climate. Eur J Agron. 2014; 54:61–9. doi: 10.1016/j.eja.2013.11.009

7. López-Bellido RJ, López-Bellido L. Efficiency of nitrogen in wheat under mediterranean conditions: effect of tillage, crop rotation and N fertilization. Field Crops Res. 2001; 71(1):31–46. doi: 10.1016/s0378-4290(01)00146-0

8. Staggenborg SA, Whitney DA, Fjell DL, Shroyer JP. Seeding and nitrogen rates required to optimize winter wheat yields following grain sorghum and soybean. Agron J. 2003; 95(2):253–9. doi: 10.2134/agronj2003.0253

9. Moll RH, Kamprath EJ, Jackson WA. Analysis and interpretation of factors which contribute to efficiency of nitrogen utilization. Agron J. 1982; 74(3):562–4. doi: 10.2134/agronj1982.00021962007400030037x

10. Hirel B, Lemaire G. From agronomy and ecophysiology to molecular genetics for improving nitrogen use efficiency in crops. In: Goyal SS, Tischner R, Basra AS, editors. Enhancing the efficiency of nitrogen utilisation in plants. Food Product Press, the Haworth Press Inc. 2005. pp. 213–57.

11. Erisman JW, Galloway JN, Seitzinger S, Bleeker A, Dise NB, Petrescu AMR, et al. Consequences of human modification of the global nitrogen cycle. Philos Trans R Soc Lond B Biol Sci. 2013; 368 (1621):20130116. doi: 10.1098/rstb.2013.0116 PMID: 23713116

12. Galloway JN, Leach AM, Bleeker A, Erisman JW. A chronology of human understanding of the nitrogen cycle. Philos Trans R Soc Lond B Biol Sci. 2013; 368(1621):20130120. doi: 10.1098/rstb.2013.0120 PMID: 23713118

13. Ravishankara AR, Daniel JS, Portmann RW, Wuebbles DJ, Crutzen PJ, Johnston H, et al. Nitrous oxide (N_2O): the dominant ozone-depleting substance emitted in the 21st century. Science. 2009; 326 (5949):123–5. doi: 10.1126/science.1176985 PMID: 19713491

14. Lü P, Zhang JW, Liu W, Yang JS, Su K, Liu P, et al. Effects of nitrogen application on yield and nitrogen use efficiency of summer maize under super-high yield conditions. Plant Nutr Fertil Sci. 2011; 852–60.

15. Saiz-Fernandez I, De Diego N, Sampedro MC, Mena-Petite A, Ortiz-Barredo A, Lacuesta M. High nitrate supply reduces growth in maize, from cell to whole plant. J Plant Physiol. 2015; 173:120–9. doi: 10.1016/j.jplph.2014.06.018 PMID: 25462086

16. Raun WR, Johnson GV. Improving Nitrogen Use Efficiency for Cereal Production. Agron J. 1999; 91 (3):357–63. doi: 10.2134/agronj1999.00021962009100030001x

17. Edmonds DE, Tubaña BS, Kelly JP, Crain JL, Edmonds MD, Solie JB, et al. Maize grain yield response to variable row nitrogen fertilization. J Plant Nutr. 2013; 36(7):1013–24. doi: 10.1080/01904167.2011.585198

18. Masclaux-Daubresse C, Daniel-Vedele F, Dechorgnat J, Chardon F, Gaufichon L, Suzuki A. Nitrogen uptake, assimilation and remobilization in plants: challenges for sustainable and productive agriculture. Ann Bot. 2010; 105(7):1141–57. doi: 10.1093/aob/mcq028 PMID: 20299346

19. Paponov I, Aufhammer W, Kaul HP, Ehmele FP. Nitrogen efficiency components of winter cereals. Eur J Agron. 1996; 5(1–2):115–24. doi: 10.1016/s1161-0301(96)02015-1

20. Sinclair TR, Purcell LC, Sneller CH. Crop transformation and the challenge to increase yield potential. Trends Plant Sci. 2004; 9(2):70–5. doi: 10.1016/j.tplants.2003.12.008 PMID: 15102372

21. Fageria NK. Nitrogen Management in Crop Production. CRC Press; 2014. p.436.

22. Alvear M, Rosas A, Rouanet JL, Borie F. Effects of three soil tillage systems on some biological activities in an Ultisol from southern Chile. Soil Tillage Res. 2005; 82(2):195–202. doi: 10.1016/j.still.2004.06.002

23. Green V, Stott D, Cruz J, Curi N. Tillage impacts on soil biological activity and aggregation in a Brazilian Cerrado Oxisol. Soil Tillage Res. 2007; 92(1–2):114–21. doi: 10.1016/j.still.2006.01.004

24. Pandey D, Agrawal M, Bohra JS. Effects of conventional tillage and no tillage permutations on extracellular soil enzyme activities and microbial biomass under rice cultivation. Soil Tillage Res. 2014; 136:51–60. doi: 10.1016/j.still.2013.09.013

25. Birkás M, Jolánkai M, Gyuricza C, Percze A. Tillage effects on compaction, earthworms and other soil quality indicators in Hungary. Soil Tillage Res. 2004; 78(2):185–96. doi: 10.1016/j.still.2004.02.006

26. Botta GF, Jorajuria D, Balbuena R, Ressia M, Ferrero C, Rosatto H, et al. Deep tillage and traffic effects on subsoil compaction and sunflower (Helianthus annus L.) yields. Soil Tillage Res. 2006; 91 (1–2):164–72. doi: 10.1016/j.still.2005.12.011

27. Filipovic D, Husnjak S, Kosutic S, Gospodaric Z. Effects of tillage systems on compaction and crop yield of Albic Luvisol in Croatia. J Terramechanics. 2006; 43(2):177–89. doi: 10.1016/j.jterra.2005.04.002

28. Meijer AD, Heitman JL, White JG, Austin RE. Measuring erosion in long-term tillage plots using ground-based lidar. Soil Tillage Res. 2013; 126:1–10. doi: 10.1016/j.still.2012.07.002

29. Wang Y, Zhang JH, Zhang ZH. Influences of intensive tillage on water-stable aggregate distribution on a steep hillslope. Soil Tillage Res [Internet]. 2015 Aug; 151:82–92. Available: http://www.sciencedirect.com/science/article/pii/S0167198715000604. Accessed 24 March 2015. doi: 10.1016/j.still.2015.03.003

30. Reicosky DC, Archer DW. Moldboard plow tillage depth and short-term carbon dioxide release. Soil Tillage Res. 2007; 94(1):109–21. doi: 10.1016/j.still.2006.07.004

31. Awale R, Chatterjee A, Franzen D. Tillage and N-fertilizer influences on selected organic carbon fractions in a North Dakota silty clay soil. Soil Tillage Res. 2013; 134:213–22. doi: 10.1016/j.still.2013.08.006

32. Dimassi B, Cohan JP, Labreuche J, Mary B. Changes in soil carbon and nitrogen following tillage conversion in a long-term experiment in Northern France. Agric Ecosyst Environ [Internet]. 2013 Apr; 169:12–20. Available: http://linkinghub.elsevier.com/retrieve/pii/S0167880913000248. Accessed 5 November 2014. doi: 10.1016/j.agee.2013.01.012

33. Kahlon MS, Lal R, Ann-Varughese M. Twenty two years of tillage and mulching impacts on soil physical characteristics and carbon sequestration in Central Ohio. Soil Tillage Res. 2013; 126:151–8. doi: 10.1016/j.still.2012.08.001

34. Dalal RC, Wang W, Allen DE, Reeves S, Menzies NW. Soil nitrogen and nitrogen use efficiency under long-term no-till practice. Soil Sci Soc Am J. 2011; 75(6):2251–61. doi: 10.2136/sssaj2010.0398

35. Lal R. Challenges and opportunities in soil organic matter research. Eur J Soil Sci. 2009; 60(2):158–69. doi: 10.1111/j.1365-2389.2008.01114.x

36. Christopher SF, Lal R, Mishra U. Regional study of no-till effects on carbon sequestration in the mid-western United States. Soil Sci Soc Am J. 2009; 73(1):207–16. doi: 10.2136/sssaj2007.0336

37. Nyakudya IW, Stroosnijder L. Conservation tillage of rainfed maize in semi-arid Zimbabwe: A review. Soil Tillage Res. 2015; 145:184–97. doi: 10.1016/j.still.2014.09.003

38. Šíp V, Růžek P, Chrpová J, Vavera R, Kusá H. The effect of tillage practice, input level and environment on the grain yield of winter wheat in the Czech Republic. Field Crops Res. 2009; 113(2):131–7. doi: 10.1016/j.fcr.2009.04.013

39. Aulakh MS, Manchanda JS, Garg AK, Kumar S, Dercon G, Nguyen ML. Crop production and nutrient use efficiency of conservation agriculture for soybean–wheat rotation in the Indo-Gangetic Plains of Northwestern India. Soil Tillage Res. 2012; 120:50–60. doi: 10.1016/j.still.2011.11.001

40. Vos J, Van Der Putten PEL. Nutrient cycling in a cropping system with potato, spring wheat, sugar beet, oats and nitrogen catch crops. II. Effect of catch crops on nitrate leaching in autumn and winter. Nutr Cycl Agroecosystems. 2004; 70(1):23–31. doi: 10.1023/b:fres.0000049358.24431.0d

41. Gselman A, Kramberger B. Benefits of winter legume cover crops require early sowing. Aust J Agric Res. 2008; 59(12):1156–63. doi: 10.1071/ar08015

42. Thorup-Kristensen K. Are differences in root growth of nitrogen catch crops important for their ability to reduce soil nitrate-N content, and how can this be measured? Plant Soil. 2001; 230(2):185–95.

43. Hirel B, Tétu T, Lea PJ, Dubois F. Improving nitrogen use efficiency in crops for sustainable agriculture. Sustainability. 2011; 3(12):1452–85. doi: 10.3390/su3091452

44. Giller KE. Nitrogen fixation in tropical cropping systems. CABI Publishing, Wallingford, UK; 2001. p.423.

45. Njarui DMG, Mureithi JG. Evaluation of lablab and velvet bean fallows in a maize production system for improved livestock feed supply in semiarid tropical Kenya. Anim Prod Sci. 2010; 50(3):193–202. doi: 10.1071/an09137

46. Nyambati EM, Sollenberger LE, Hiebsch CK, Rono SC. On-Farm Productivity of Relay-Cropped Mucuna and Lablab in Smallholder Crop-Livestock Systems in Northwestern Kenya. J Sustain Agric. 2006; 28(1):97–116. doi: 10.1300/j064v28n01_09

47. Tonitto C, David MB, Drinkwater LE. Replacing bare fallows with cover crops in fertilizer-intensive cropping systems: A meta-analysis of crop yield and N dynamics. Agric Ecosyst Environ. 2006; 112(1):58–72. doi: 10.1016/j.agee.2005.07.003

48. Caviglia OP, Melchiori RJM, Sadras VO. Nitrogen utilization efficiency in maize as affected by hybrid and N rate in late-sown crops. Field Crops Res. 2014; 168:27–37. doi: 10.1016/j.fcr.2014.08.005

49. López-Bellido L, López-Bellido RJ, Redondo R. Nitrogen efficiency in wheat under rainfed Mediterranean conditions as affected by split nitrogen application. Field Crops Res. 2005 Oct; 94(1):86–97. doi: 10.1016/j.fcr.2004.11.004

50. Lü P, Zhang JW, Jin LB, Liu W, Dong ST, Liu P. Effects of nitrogen application stage on grain yield and nitrogen use efficiency of high-yield summer maize. Plant, Soil Environ. 2012; 58(5):211–6.

51. Setiyono TD, Yang H, Walters DT, Dobermann A, Ferguson RB, Roberts DF, et al. Maize-N: A decision tool for nitrogen management in maize. Agron. J. 2011; 103(4):1276–83. doi: 10.2134/agronj2011.0053

52. Machet, Dubrulle, Louis. AZOBIL: a computer program for fertilizer N recommandations based on a predictive balance sheet method. In: Proceedings of the First Congress of the European Society of Agronomy. 1990. p. 21.

53. Dumas JBA. Procédés de l'analyse organique. Ann Chem Phys. 1831; 47(2):198–213.

54. Bertin P, Gallais A. Genetic variation for nitrogen use efficiency in a set of recombinant maize inbred lines I. Agrophysiological results. Maydica. 2000; 45(1):53–66.

55. Huggins DR, Pan WL. Nitrogen efficiency component analysis: an evaluation of cropping system differences in productivity. Agron J. 1993; 85(4):898–905. doi: 10.2134/agronj1993.00021962008500040022x

56. Cox MC, Qualset CO, Rains DW. Genetic variation for nitrogen assimilation and translocation in wheat. II. Nitrogen assimilation in relation to grain yield and protein. Crop Sci. 1985; 25(3):435–40. doi: 10.2135/cropsci1985.0011183x002500030003x

57. Beheshti AR, Behboodi-frad B. Dry matter accumulation and remobilization in grain sorghum genotypes (Sorghum bicolor L. Moench) under drought stress. Aust J Crop Sci. 2010; 4(3):185–9.

58. Masoni A, Ercoli L, Mariotti M, Arduini I. Post-anthesis accumulation and remobilization of dry matter, nitrogen and phosphorus in durum wheat as affected by soil type. Eur J Agron. 2007; 26(3):179–86. doi: 10.1016/j.eja.2006.09.006

59. R Development Core Team. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. 2015. Available: http://www.R-project.org/.

60. Royston P. An extension of Shapiro and Wilk's W test for normality to large samples. Appl Stat. 1982; 31:115–24. doi: 10.2307/2347973

61. Bartlett MS. Properties of sufficiency and statistical tests. Proc R Soc Lond A Math Phys Sci. 1937; 160:268–82. doi: 10.1098/rspa.1937.0109

62. De Mendiburu F. Agricolae: Statistical Procedures for Agricultural Research Version 1.2–3. [Internet]. 2015. Available: http://cran.r-project.org/.

63. Harrell F. Hmisc: Harrell Miscellaneous Version 3.17–1. [Internet]. 2015. Available: http://cran.r-project.org/

64. Dray S, Dufour AB, Thioulouse J. Ade4: Analysis of Ecological Data: Exploratory and Euclidean Methods in Environmental Sciences Version 1.7–3. [Internet]. 2015. Available: http://cran.r-project.org/.

65. Soon YK, Malhi SS, Wang ZH, Brandt S, Schoenau JJ. Effect of seasonal rainfall, N fertilizer and tillage on N utilization by dryland wheat in a semi-arid environment. Nutr Cycl Agroecosys. 2008; 82:149–60. doi: 10.1007/s10705-008-9176-0

66. Burgess MS, Mehuys GR, Madramootoo CA. Decomposition of grain-corn residues (Zea mays): a litter bag study under three tillage systems. Can J Soil Sci.2002; 82:127–38. doi: 10.4141/s01-013

67. Verachtert E, Govaerts B, Lichter K, Sayre KD, Ceballos-Ramirez JM, Luna-Guido ML, et al. Short term changes in dynamics of C and N in soil when crops are cultivated on permanent raised beds. Plant Soil. 2009; 320(1–2):281–93. doi: 10.1007/s11104-009-9893-4

68. Torbert HA, Potter KN, Morrison JE. Tillage system, fertilizer nitrogen rate, and timing effect on corn yields in the Texas Blackland Prairie. Agron J. 2001; 93(5):1119–24. doi: 10.2134/agronj2001.9351119x

69. Karlen DL, Berry EC, Colvin TS, Kanwar RS. Twelve-year tillage and crop rotation effects on yields and soil chemical properties in northeast Iowa 1. Commun Soil Sci Plant Anal. 1991; 22(19–20):1985–2003. doi: 10.1080/00103629109368552

70. Mallarino AP, Bordoli JM, Borges R. Phosphorus and potassium placement effects on early growth and nutrient uptake of no-till corn and relationships with grain yield. Agron J. 1999; 91:37–45. doi: 10.2134/agronj1999.00021962009100010007x

71. Känkänen H, Alakukku L, Salo Y, Pitkänen T. Growth and yield of spring cereals during transition to zero tillage on clay soils. Eur J Agron. 2011; 34(1):35–45. doi: 10.1016/j.eja.2010.10.002

72. Machado S, Petrie S, Rhinhart K, Qu A. Long-term continuous cropping in the Pacific Northwest: Tillage and fertilizer effects on winter wheat, spring wheat, and spring barley production. Soil Tillage Res. 2007; 94(2):473–81. doi: 10.1016/j.still.2006.09.007

73. Tørresen KS, Skuterud R, Tandsæther HJ, Hagemo MB. Long-term experiments with reduced tillage in spring cereals. I. Effects on weed flora, weed seedbank and grain yield. Crop Prot. 2003; 22(1):185–200. doi: 10.1016/s0261-2194(02)00145-x

74. Al-Kaisi MM, Kwaw-Mensah D. Effect of Tillage and Nitrogen Rate on Corn Yield and Nitrogen and Phosphorus Uptake in a Corn-Soybean Rotation. Agron J. 2007; 99(1):1548–58. doi: 10.2134/agronj2007.0012

75. Abdin MA, Dwivedi RK, Abrol Y. Nitrogen in agriculture. In: Singh RP, Shankar N, Jaiwal PK, eds Nitrogen Nutrition and Plant Productivity. Houston, Tex, USA: Studium Press LLC. 2005: 1–41.

76. Arshad MA, Franzluebbers AJ, Azooz RH. Components of surface soil structure under conventional and no-tillage in northwestern Canada. Soil Tillage Res. 1999; 53(1):41–7. doi: 10.1016/s0167-1987(99)00075-6

77. Josa R, Ginovart M, Solé A. Effects of two tillage techniques on soil macroporosity in sub-humid environment. Int Agrophysics. 2010; 24(2):139–47.

78. Thomas G, Dalal R, Standley J. No-till effects on organic matter, pH, cation exchange capacity and nutrient distribution in a Luvisol in the semi-arid subtropics. Soil Tillage Res. 2007; 94(2):295–304. doi: 10.1016/j.still.2006.08.005

79. Ercoli L, Lulli L, Mariotti M, Masoni A, Arduini I. Post-anthesis dry matter and nitrogen dynamics in durum wheat as affected by nitrogen supply and soil water availability. Eur J Agron. 2008; 28(2):138–47. doi: 10.1016/j.eja.2007.06.002

80. Plaut Z, Butow B., Blumenthal C., Wrigley C. Transport of dry matter into developing wheat kernels and its contribution to grain yield under post-anthesis water deficit and elevated temperature. Field Crops Res. 2004; 86(2–3):185–98. doi: 10.1016/j.fcr.2003.08.005

81. Sarvestani T, Jenner CF, Donald M. Dry Matter and Nitrogen Remobilization of Two Wheat Genotypes under Post—anthesis Water Stress Conditions. J Agric Sci Technol. 2003; 5:21–29.

82. Bahrani A, Heidari H, Abad S, Aynehband A. Nitrogen remobilization in wheat as influenced by nitrogen application and post-anthesis water deficit during grain filling. African J Biotechnol. 2011; 10 (52):10585–94.

83. Pampana S, Mariotti M, Ercoli L, Masoni A. Remobilization of dry matter, nitrogen and phosphorus in durum wheat as affected by genotype and environment. Ital J Agron. 2007; 3:3–14.

84. Gürsoy S, Sessiz A, Malhi SS. Short-term effects of tillage and residue management following cotton on grain yield and quality of wheat. Field Crops Res. 2010; 119(2–3):260–8. doi: 10.1016/j.fcr.2010.07.016

85. Salem HM, Valero C, Muñoz MÁ, Rodríguez MG, Silva LL. Short-term effects of four tillage practices on soil physical properties, soil water potential, and maize yield. Geoderma [Internet]. 2015; 237–238:60–70. Available: doi: 10.1016/j.geoderma.2014.08.014

86. Kristensen HL, Debosz K, McCarty GW. Short-term effects of tillage on mineralization of nitrogen and carbon in soil. Soil Biol Biochem. 2003; 35(7):979–86. doi: 10.1016/s0038-0717(03)00159-7