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The effect of reduced tillage on nitrogen dynamics in silt loam soils

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Abstract

Crop rotations in Western Europe contain crops that seem not suitable for reduced tillage (RT) agriculture because they often include beets and potatoes, resulting in a high disturbance of the soil at the formation of the ridges and at harvest. Therefore, the short- and long-term effects of RT on the stratification and stock of total nitrogen (TN) in the 0–40 cm depth layer and the nitrogen (N) mineralization in the upper 15 cm depth layer of silt loam soils was evaluated. For doing so, 10 fields at seven locations representing the important types of RT systems in Belgium, applied for a different number of years, and eight fields under conventional tillage (CT) with comparable soil type and crop rotation were selected. Despite the presence of root and tuber crops in these rotations, the stratification of the percentage of TN and of the carbon to nitrogen ratio was more pronounced under RT than CT fields. The TN stock in the RT fields worked with a cultivator or soil loosener was comparable to CT fields, even after 20 years. No trend could be found in the change in TN stock of reduced tillage by direct drilling compared to CT. The N mineralization rate in undisturbed soil cores under controlled conditions in the laboratory was on average 0.20 ± 0.08 mg N kg^{-1} dry soil day^{-1} for RT fields compared to an average of 0.13 ± 0.05 mg N kg^{-1} dry soil day^{-1} for CT fields. This increase in N mineralization rate was correlated with a higher microbial biomass nitrogen content.

Keywords: Reduced tillage; Total nitrogen; Nitrogen mineralization; Incubation; Undisturbed soil; Microbial biomass nitrogen

1. Introduction

Since the nitrogen (N) released by mineralization is often a major source of N for plant growth and strongly depends on soil factors, extensive data has been collected in the past on the N mineralization rate under controlled circumstances in the laboratory (e.g. Coppens et al., 2002) and in the field (e.g. Hofman, 1988). However, all these data were pertaining to conventionally tilled (CT) soils. While reduced tillage (RT) is gaining momentum, the research on RT in Western Europe was focused on the effects of the change of management on soil erosion and soil organic carbon (SOC) stock changes. The change of N dynamics under a temperate climate due to the shift to RT has mainly received attention in the large arable regions in USA, Latin America and Australia with crop rotations including mainly cereals, maize and soybean. The arable crop rotations in Western Europe are somewhat particular because of the large share of root and tuber crops. However, no research has been carried out on the effect of RT on the N dynamics of soils with crop rotations including beet and potatoes, with heavy soil disturbance at harvest, that seem less suitable for RT.

In general, the TN stock of experimental fields with a cereal, maize and soybean crop rotation under a temperate climate seemed to remain unchanged or to decrease under short- and long-term RT compared to CT. No significant differences in the TN stock compared to CT were measured of two sandy loam soils after 4 or 5 years reduced tillage by direct drilling (RT_{DD}) and one loam soil after 8 years reduced tillage working the soil with a cultivator or soil loosener (RT_C) in eastern Canada (Angers et al., 1997), of a silty clay loam soil after 8 years RT_{DD} or RT_C in central Ohio (Puget and Lal, 2005) and of a silt loam soil after 21 years of RT_C in Germany (Stockfisch et al., 1999). However, Etana et al. (1999) measured a decreased TN stock compared to CT after 17 years RT_C of a silt loam soil in Sweden.

Next to the change in TN stock, it is important to know the N mineralization rate. Kandeler and Böhm (1996) and Kandeler

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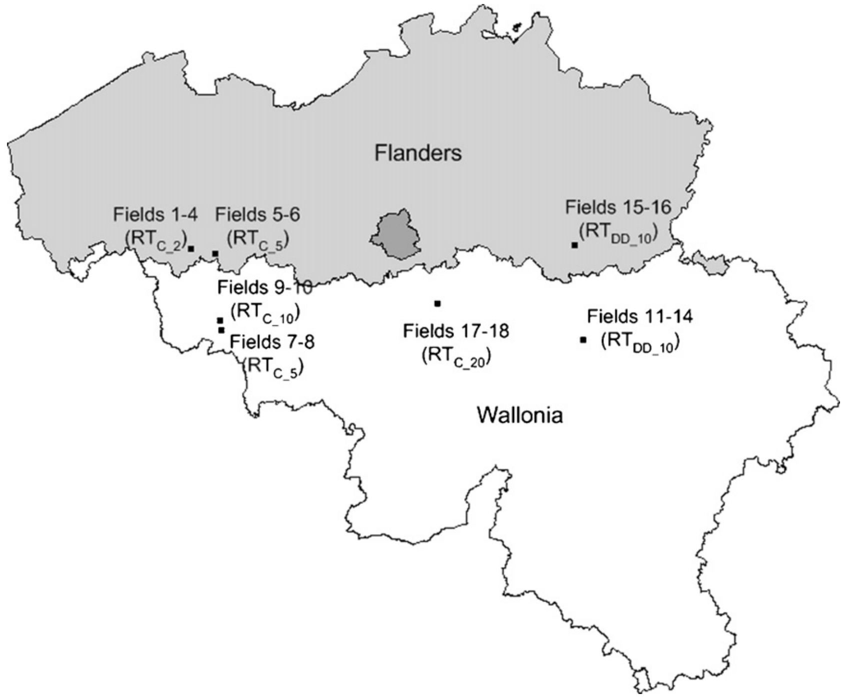

Fig. 1. Location of the selected fields in Belgium (■) with between brackets period (years) and type of reduced tillage (RT) (RT with cultivator or soil loosener [RT_C] or direct drilling [RT_{DD}]).

et al. (1999b) measured the N mineralization rate of a clay field from Austria 2 to 8 years after changing to RT_{DD} and RT_C. The N mineralization rate of the upper depth layer showed a decreasing trend in the order: $RT_{DD} > RT_C > CT$. Deeper in the soil profile a significant decrease in N mineralization was found under RT compared to CT. Doran (1987) found a (significant) increase of potentially mineralizable N in the upper depth layer of silt and silt loam fields under 5–11 years RT_{DD} compared to CT. The same trend was observed by Friedel et al. (1996) after 14 years RT_C in Germany and by Kristensen et al. (2000) after 20 years RT_{DD} in Maryland.

The objective of this study was to look into the short- and long-term effects of RT on the stratification of %N, the N stock and the N mineralization of the top soil for these specific Western European climatic and soil conditions, with crop rotations containing crops that are less common under RT agriculture (including an important share of root and tuber crops).

2. Materials and methods

2.1. Selection of the fields

Belgium has a temperate maritime climate with mild winters and cool summers. Our research sites were situated in the silt loam belt of central Belgium with an average precipitation of 757 mm year^{-1} and average yearly temperature of 9.7 °C (KMI, 2005).

The soils under CT are in general tilled to a depth of 25–30 cm with a mouldboard plough which inverts the soil and buries crop residues. Depending on the crop rotation, crop residues and the application of organic manure the plough is combined with cultivator and/or harrow. Basically, two types of non-inversion tillage are practised, namely reduced tillage with a cultivator or soil loosener (RT_C) and direct drilling (RT_{DD}). However, many variants exist in these two main RT types. Different types of cultivators and soil looseners in combination with harrows are used under RT.

Eighteen fields with a silt loam soil texture were selected (Fig. 1 and Table 1). They include the different types of RT running for a different number of years, and were paired to fields under CT with comparable soil type and crop rotation. Particular care was taken so that the texture of the paired RT–CT fields were similar, because of the major influence of texture on C and N dynamics in soil. The tillage operations of the selected fields of 2002–2004 are given in Table 2. The amount of effective organic carbon (EOC), i.e. the amount of organic carbon that is still in the soil 1 year after application of the organic material (Hénin and Dupuis, 1945; Vleeshouwers and Verhagen, 2002; De Neve et al., 2003), and TN of main crops, green manure and organic manure of the selected fields of 2002–2004 were determined based on Hofman et al. (1995), Sleutel et al. (2007) and measurements of organic manure composition of the Soil Service of Belgium (Table 3). The period of RT (in years) is indicated in subscript.

In Heestert (50°48′ N; 3°25′ E), an experiment was started in 2003 to investigate the influence of RT on soil losses by erosion, where different types of RT were compared to CT. Before sowing the main crop, the soil of fields 1–4 was first worked with a cultivator to a depth of 10–15 cm. The cultivator had three rows with five small bend tines ending in a sweep. The seedbed of RT_{C_2} field 1 was prepared by harrowing (Table 2). RT_{C_2} fields 2 and 3 were worked to a depth of 15–20 cm with a soil loosener

Table 1
Management (reduced with cultivator or soil loosener (RT_C), reduced tillage with direct drilling (RT_{DD}) or conventional (CT) tillage), period of RT, granulometric composition, slope, soil organic carbon (SOC), pH_{KCl} of the 0–10 cm depth layer and bulk density (BD) of 5–10 and 25–30 cm depth layer (with standard deviation between brackets), crop at sampling and sampling date of the selected fields

Field	Management	Period of RT (years)	Clay (%)	Loam (%)	Sand (%)	Slope (%)	SOC (%)	pH_{KCl}	BD 5–10 cm ($g\,cm^3$)	BD 25–30 cm ($g\,cm^3$)	Crop at sampling	Sampling date
1	RT_C	2	13.5	52.6	33.9	3	1.05 (0.03) *a*	7.0 (0.3) *a*	1.38 (0.10) *a*	1.51 (0.03) *a*	Mustard[a]	December 3 2004
2	RT_C	2	12.4	53.7	33.9	3	1.08 (0.08) *a*	6.5 (0.2) *a*	1.49 (0.08) *a*	1.47 (0.14) *a*	Mustard[a]	December 3 2004
3	RT_C	2	12.1	59.9	28.0	3	1.08 (0.06) *a*	6.6 (0.5) *a*	1.46 (0.02) *a*	1.50 (0.04) *a*	Mustard[a]	December 3 2004
4	CT	/	12.7	54.4	32.9	3	1.08 (0.10) *a*	6.5 (0.8) *a*	1.48 (0.08) *a*	1.48 (0.03) *a*	Mustard[a]	December 3 2004
5	RT_C	5	18.1	51.6	30.3	10	1.22 (0.06) *a*	6.5 (0.1) *a*	1.37 (0.04) *a*	1.52 (0.05) *a*	Fallow	December 10 2004
6	CT	/	16.4	56.0	27.6	10	0.89 (0.10) *b*	5.5 (0.3) *b*	1.43 (0.04) *a*	1.53 (0.02) *a*	Fallow	December 10 2004
7	RT_C	5	10.6	59.0	30.4	0	1.15 (0.06) *a*	7.3 (0.2) *a*	1.46 (0.10) *a*	1.54 (0.02) *a*	Winter oat[a]	December 20 2004
8	CT	/	11.1	59.6	29.3	0	1.00 (0.03) *b*	6.7 (0.2) *b*	1.24 (0.07) *b*	1.51 (0.03) *a*	Fallow	December 20 2004
9	RT_C	10	20.6	70.9	8.5	2	1.25 (0.03) *a*	6.1 (0.1) *a*	1.43 (0.04) *a*	1.55 (0.05) *a*	Mustard[a]	March 17 2005
10	CT	/	13.9	77.6	8.5	2	1.08 (0.03) *b*	5.7 (0.1) *b*	1.49 (0.04) *a*	1.51 (0.01) *a*	Fallow	March 17 2005
11	RT_{DD}	10[b]	19.8	72.2	7.9	0	1.61 (0.15) *a*	6.5 (0.2) *a*	1.37 (0.04) *b*	1.50 (0.05) *a*	Winter wheat	March 9 2005
12	CT	/	18.9	75.4	5.7	0	1.11 (0.04) *a*	6.6 (0.1) *a*	1.40 (0.03) *b*	1.54 (0.03) *a*	Phacelia[a]	March 9 2005
13	RT_{DD}	10[b]	16.7	77.2	6.1	0	1.39 (0.14) *ab*	6.5 (0.1) *a*	1.47 (0.03) *a*	1.53 (0.04) *a*	Winter wheat	March 10 2005
14	CT	/	16.2	74.6	9.4	0	0.94 (0.02) *b*	5.8 (0.1) *b*	1.49 (0.04) *a*	1.50 (0.06) *a*	Winter wheat	March 10 2005
15	RT_{DD}	10[b]	15.5	71.7	12.8	0	1.30 (0.08) *a*	5.8 (0.1) *b*	1.47 (0.01) *b*	1.50 (0.02) *b*	Rapeseed[a]	March 11 2005
16	CT	/	17.4	71.5	11.1	0	0.97 (0.02) *b*	6.4 (0.2) *a*	1.51 (0.02) *a*	1.56 (0.01) *a*	Fallow	March 11 2005
17	RT_C	20	14.7	71.5	13.8	0	1.13 (0.13) *a*	6.3 (0.2) *a*	1.35 (0.08) *a*	1.58 (0.03) *a*	Winter wheat	December 15 2004
18	CT	/	16.0	75.7	8.2	0	0.92 (0.04) *a*	6.0 (0.3) *a*	1.47 (0. 08) *a*	1.59 (0.06) *a*	Winter wheat	December 15 2004

Same italic letters indicate no significant differences between tillage treatments per location ($P = 0.05$) (one way ANOVA/Duncan post hoc test, Welch/Games–Howell post hoc test or *t*-test).
Mustard, *Sinapis alba* L.; winter oat, *Avena sativa* L.; winter wheat, *Triticum aestivum* L.; phacelia, *Phacelia* L.; rapeseed, *Brassica rapa* L.

[a] Green manure.

[b] 6 years RT_C + last 4 years RT_{DD}.

Table 2
Type and depth of successive tillage operations of 2002–2004 of the selected fields

	Field	Tillage	Depth (cm)	Tillage	Depth (cm)	Tillage	Depth (cm)	Tillage	Depth (cm)	Time		
1	RT_{C_2}	Cultivator	10–15	Tine harrow	5	Tine harrow	5			2002_S	2003_S	2003_A
		Cultivator	10–15	Tine harrow	5					2004_A[a]		
2	RT_{C_2}	Cultivator	10–15	Soil loosener	15–20	Tine harrow	5	Tine harrow	5	2002_S	2003_S	2003_A
		Cultivator	10–15	Tine harrow	5					2004_A[a]		
3	RT_{C_2}	Cultivator	10–15	Soil loosener	15–20	Tine harrow	5	Tine harrow	5	2002_S	2003_S	2003_A
		Cultivator	10–15	Tine harrow	5					2004_A[a]		
4	CT	Cultivator	10–15	Plough	25–30	Tine harrow	5	Tine harrow	5	2002_S	2003_S	2003_A
		Cultivator	10–15	Tine harrow	5					2004_A[a]		
5	RT_{C_5}	Cultivator	10	Soil loosener	35	Cultivator	10	Rotary harrow	5	2002_S	2003_S	
		Cultivator	10	Soil loosener	25	Rotary harrow	5			2004_S	2005_S	
6	CT	Cultivator	10	Plough	25–30	Cultivator	10	Rotary harrow	5	2002_S	2003_S	
		Plough	25–30	Cultivator	10	Rotary harrow	5			2004_S		
7	RT_{C_5}	Cultivator	25	Cultivator	25	Rotary harrow	5			2002_S		
		Cultivator	10	Cultivator	35	Rotary harrow	5			2002_A[a]		
		Cultivator	5	Cultivator	12	Rotary harrow	5			2003_S		
		Cultivator	15	Cultivator	15					2003_A		
		Cultivator	25	Rotary harrow	5					2004_A[a]		
8	CT	Cultivator	10	Plough	30	Cultivator	10	Rotary harrow	5	2002_A	2003_A	2004_A
9	RT_{C_10}	Cultivator	10	Rotary harrow	5					2002_S	2004_A[a]	2005_S
		Cultivator	10	Soil loosener	20	Rotary harrow	5			2002_A		
		Soil loosener	20	Rotary harrow	5					2003_A		
10	CT	Cultivator	10	Plough	25–30	Cultivator	10	Rotary harrow	5	2002_S	2003_S	2004_S
11	RT_{DD_10}	Rotary harrow	5							2002_A	2003_A[a]	
12	CT	Plough	25–30	Rotary harrow	5					2002_A[a]	2003_S	2003_A
		Soil loosener	25–30	Rotary harrow	5					2004_A[a]		
13	RT_{DD_10}	Rotary harrow	5							2002_A	2003_A[a]	
14	CT	Plough	25–30	Cultivator	10	Rotary harrow	5			2002_A	2004_A	
		Cultivator	10	Plough	25–30	Cultivator	10	Rotary harrow	5	2004_S		
15	RT_{DD_10}	Rotary harrow	5							2003_A	2004_A[a]	
16	CT	Plough	20–25	Cultivator	10	Tine harrow	5			2002_W	2005_W	
		Plough	20–25	Tine harrow	5					2002_A	2003_A	
		Cultivator	10							2004_A[a]		
17	RT_{C_20}	Rotary harrow	5							2002_S	2004_S	
		Soil loosener	25	Rotary harrow	5					2002_A	2004_A	
		Cultivator	10	Cultivator	10	Soil loosener	25	Rotary harrow		2003_A[a]		
18	CT	Plough	25	Rotary harrow	5	Rotary harrow	5			2002_S	2004_S	
		Soil loosener	25	Rotary harrow	5					2002_A	2004_A	
		Cultivator	10	Cultivator	10					2003_A[a]		

RT_C, reduced tillage with cultivator or soil loosener; RT_{DD}, by direct drilling with in subscript the period in years; CT, conventional tillage.
S, spring (Marsh–May) tillage operation; A, autumn (August–November) tillage operation; W, winter (December–February) tillage operation.
[a] Tillage operation before green manure.

Table 3
Amount of dry matter (DM), effective organic carbon (EOC) and total nitrogen (TN) content of crop residues and organic manure application of 2002–2004 of the selected fields

	Field	2002				2003				2004			
		Crop (type of residue)/manure	Amount DM (tonne ha^{-1})	EOC[a,b] (kg ha^{-1})	TN[b] (kg ha^{-1})	Crop (type of residue)/manure	Amount DM (tonne ha^{-1})	EOC[a,b] (kg ha^{-1})	TN[b] (kg ha^{-1})	Crop (type of residue)/manure	Amount DM (tonne ha^{-1})	EOC[a,b] (kg ha^{-1})	TN[b] (kg ha^{-1})
1	$RT_{C,2}$	Maize (fodder) (stubble)	3.4	350	25	Maize (fodder) (stubble)	3.4	350	25	Winter wheat (stubble)	5.4	750	30
		Pig slurry (25 tonne ha^{-1})	2.3	340	195	Pig slurry (25 tonne ha^{-1})	2.3	340	195	Pig slurry (25 tonne ha^{-1})	2.3	340	195
2	$RT_{C,2}$	Maize (fodder) (stubble)	3.4	350	25	Maize (fodder) (stubble)	3.4	350	25	Winter wheat (stubble)	5.4	750	30
		Pig slurry (25 tonne ha^{-1})	2.3	340	195	Pig slurry (25 tonne ha^{-1})	2.3	340	195	Pig slurry (25 tonne ha^{-1})	2.3	340	195
3	$RT_{C,2}$	Maize (fodder) (stubble)	3.4	350	25	Maize (fodder) (stubble)	3.4	350	25	Winter wheat (stubble)	5.4	750	30
		Pig slurry (25 tonne ha^{-1})	2.3	340	195	Pig slurry (25 tonne ha^{-1})	2.3	340	195	Pig slurry (25 tonne ha^{-1})	2.3	340	195
4	CT	Maize (fodder) (stubble)	3.4	350	25	Maize (fodder) (stubble)	3.4	350	25	Winter wheat (stubble)	5.4	750	30
		Pig slurry (25 tonne ha^{-1})	2.3	340	195	pig slurry (25 tonne ha^{-1})	2.3	340	195	Pig slurry (25 tonne ha^{-1})	2.3	340	195
5	$RT_{C,5}$	Maize (grain) (stubble)	8.0	1225	135	Maize (grain) (stubble)	8.0	1225	135	Maize (grain) (stubble)	8.0	1225	135
		Pig slurry (20 tonne ha^{-1})	1.8	270	155	Pig slurry (20 tonne ha^{-1})	1.8	270	155	Pig slurry (20 tonne ha^{-1})	1.8	270	155
6	CT	Maize (fodder) (stubble)	3.4	350	25	Maize (fodder) (stubble)	3.4	350	25	Potatoes (leaves)	2.1	440	20
		Pig slurry (25 tonne ha^{-1})	2.3	340	195	Pig slurry (25 tonne ha^{-1})	2.3	340	195	Pig slurry (25 tonne ha^{-1})	2.3	340	195
7	$RT_{C,5}$	Maize (fodder) (stubble)	3.4	350	25	Winter rye[c]	1.9	325	80	Winter wheat (stubble)	5.4	750	30
						Sugar beet (heads + leaves)	7.0	575	160				
		Cattle horse compost (20 tonne ha^{-1})	10.0	1710	165	Green compost (15 tonne ha^{-1})	7.5	1280	70	Cattle horse manure (25 tonne ha^{-1})	6.0	960	210
8	CT	Winter wheat (stubble)	5.4	750	30	Triticale (stubble)	5.4	750	30	Winter barley (stubble)	5.4	750	30
		Cattle manure (20 tonne ha^{-1})	4.8	770	155	Cattle manure (20 tonne ha^{-1})	4.8	770	155	Cattle manure (15 tonne ha^{-1})	3.6	580	115
9	$RT_{C,10}$	Peas (stubble + straw)	6.0	500	180	Winter wheat (stubble)	5.4	750	30	Winter wheat (stubble)	5.4	750	30
						Winter wheat (straw)	4.7	650	40	Winter wheat (straw)	4.7	650	40
10	CT	Sugar beet (heads + leaves)	7.0	575	160	Maize (fodder) (stubble)	3.4	350	25	Maize (fodder) (stubble)	3.4	350	25
										Cattle stable manure (45 tonne ha^{-1})	10.8	1730	375
11	$RT_{DD,10}$	Winter wheat (stubble)	5.4	750	30	Winter barley (stubble)	5.4	750	30	Rapeseed[c]	4.1	425	90
		Winter wheat (straw)	4.7	650	40	Winter barley (straw)	4.7	650	40	Sugar beet (heads + leaves)	7.0	575	160
										Cattle stable manure (25 tonne ha^{-1})	6.0	950	210
12	CT	Winter wheat (stubble)	5.4	750	30	Phacelia[c]	4.1	350	90	Winter wheat (stubble)	5.4	750	30
						Sugar beet (heads + leaves)	7.0	575	160				
13	$RT_{DD,10}$	Winter wheat (stubble)	5.4	750	30	Winter barley (stubble)	5.4	750	30	Rapeseed[c]	4.1	425	90
		Winter wheat (straw)	4.7	650	40	Winter barley (straw)	4.7	650	40	Potatoes (leaves)	2.1	440	20
										Cattle stable manure 25 tonne ha^{-1})	6.0	960	210
14	CT	Winter wheat (stubble)	5.4	750	30	Winter barley (stubble)	5.4	750	30	Potatoes (leaves)	2.1	440	20
										Cattle stable manure (25 tonne ha^{-1})	6.0	960	210
15	$RT_{DD,10}$	Rapeseed[c]	4.1	425	90	Winter wheat (stubble)	5.4	750	30	Winter barley (stubble)	5.4	750	30
		Sugar beet (heads + leaves)	7.0	575	160	Winter wheat (straw)	4.7	650	40	Winter barley (straw)	4.7	650	40
		Cattle stable manure (25 tonne ha^{-1})	6.0	960	210								
16	CT	Mustard[c]	4.1	425	90	Winter wheat (stubble)	5.4	750	30	Winter barley (stubble)	5.4	750	30
		Sugar beet (heads + leaves)	7.0	575	160								
		Cattle stable manure (25 tonne ha^{-1})	6.0	960	210								
17	$RT_{C,20}$	Mustard[c]	4.1	425	90	Winter wheat (stubble)	5.4	750	30	Mustard[c]	4.1	425	90
		Sugar beet (heads + leaves)	7.0	575	160	Winter wheat (straw)	4.7	650	40	Sugar beet (heads + leaves)	7.0	575	160
						Cattle stable manure (30 tonne ha^{-1})	7.2	1160	250				
18	CT	Mustard[c]	4.1	425	90	Winter wheat (stubble)	5.4	750	30	Mustard[c]	4.1	425	90
		Sugar beet (heads + leaves)	7.0	575	160	Cattle stable manure (40 tonne ha^{-1})	9.6	1540	330	Sugar beet (head + leaves)	7.0	575	160

RT_C, reduced tillage with cultivator or soil loosener; RT_{DD}, by direct drilling with in subscript the period in years; CT, conventional tillage; Maize, *Zea mays* ssp. *Mays* L.; winter wheat, *Triticum aestivum* L.; mustard, *Sinapsis alba* L.; potatoes, *Solanum tuberosum* L.; winter rye, *Secale cereale* L.; winter oat, *Avena sativa* L.; sugar beet, *Beta vulgaris* L.; triticale, *X Triticosecale*; winter barley, *Hordeum vulgare* L.; peas, *Pisum sativum* L.; rapeseed, *Brassica rapa* L.; phacelia, *Phacalia tanacetifolia* L.

[a] Effective organic carbon (EOC) is the organic carbon that remains in the soil 1 year after the application (Hénin and Dupuis, 1945; Vleeshouwers and Verhagen, 2002; De Neve et al., 2003).

[b] Calculations of EOC and TN are based on Hofman et al. (1995), Sleutel et al. (2007) and measurements of organic manure composition of the Soil Service of Belgium.

[c] Green manure.

with one row of four tines ending in a sweep and in a five-pronged horizontal fork, respectively, followed by a secondary tillage with a tine harrow. The solid tines of the soil loosener are spaced apart, more solid and longer than the cultivator making a deeper soil loosening possible. Field 4 was conventionally ploughed to a depth of 25–30 cm, followed by a secondary tillage with a tine harrow.

The main tillage operation of RT_{C_5} field 5 with monoculture maize in Kluisbergen (50°46′ N; 3°29′ E) was done in the spring with a soil loosener with one row of four tines ending in a chisel (to a depth of 30–35 cm). The main tillage operation of the adjacent field 6 before sowing was ploughing to a depth of 25–30 cm. Fields 7 and 8 were located in Baugnies (50°33′ N; 3°33′ E). The tillage operations of RT_{C_5} field 7 depended on the preceding and following crop. The deepest tillage operation of 2002–2004 was done with a cultivator with three rows of three tines ending in a chisel to a depth of 35 cm. The main yearly tillage operation of field 8 was ploughing in the autumn to a depth of 30 cm.

Fields 9 and 10 were located in Maulde (50°37′ N; 3°32′ E). The main tillage operation of RT_{C_10} field 9 and CT field 10 were done with a soil loosener and plough, respectively. Fields 11–14 are located in Villers-le-Bouillet (50°34′ N; 5°15′ E) and fields 15–16 in Kuttekoven (50°47′ N; 5°20′ E). Fields 11, 13 and 15 had not been ploughed since 1994. In 1995–2000 these fields were worked with a cultivator (chisel) and from 2001 onwards they were managed under RT_{DD} (RT_{DD_10}). The main tillage operation of fields 12, 14 and 16 was ploughing.

Fields 17 and 18, with a 2 year sugar beet—winter wheat/yellow mustard crop rotation, were located in Court-Saint-Etienne (50°38′ N; 4°34′ E). The deepest tillage operation of RT_{C_20} field 17 was done in the autumn with a soil loosener with one row of four tines to a depth of 25 cm. Field 18 was conventionally ploughed every 2 years in the winter before the sugar beets to a depth of 25 cm.

In each field three plots of 150 m^2 (10 m × 15 m), each spaced 10 m apart, were selected. To avoid edge effects, the plots were located more than 20 m from the edges of the fields. On sloping fields the plots on the RT and CT field were located on the same position on the slope. The sampling dates are given in Table 1.

2.2. pH_{KCl}, total nitrogen, soil organic carbon, soil texture and bulk density

Five subsamples per plot were taken from the 0–10, 10–20, 20–30 and 30–40 cm depth layers. The subsamples were bulked per plot and per depth layer into one composite sample, thoroughly mixed and air-dried in the laboratory. The pH_{KCl} of air-dried soil samples was measured in a 1 M KCl (1:2.5 soil weight (g): extractant volume (ml)) suspension using a glass electrode. The percentage of TN was measured with an elemental analyser (Vario Max, Elementar, Germany) whereas SOC content was analysed according to the method of Walkley and Black (1934). Soil texture of each field was determined per depth layer on a mixed soil sample of the three plots by the combined sieve and pipette method (De Leenheer, 1959).

Two replicate undisturbed soil cores with a volume of 98 cm^3 were taken per plot from the 5–10 and 25–30 cm depth layers for the determination of soil bulk density (BD). Oven dry weight at 105 °C was determined after 24 h. The BD was based on the soil dry weight and volume of the soil core.

2.3. Nitrogen mineralization

N mineralization was measured under controlled conditions in the laboratory on undisturbed soil samples. PVC tubes with a 0.046 m inner diameter and 0.18 m height were used as incubation containers. On each field, visible crop residues were removed at the sampling locations, and tubes were then pushed 15 cm into the soil. The soil core was carefully dug out, excess soil from the bottom of the core was removed, and the bottom was covered with a PVC cap. Seven tubes were taken from each plot and incubated undisturbed. The moisture content of fields 1–8 and 17–18 at the time of sampling was 50 ± 5% 'water filled pore space' (WFPS), which is considered to be within the optimum soil moisture content range for N mineralization (De Neve and Hofman, 2002). It was therefore not necessary to dry or moisten the soil. The moisture content of fields 9–16 was significantly higher than 50% WFPS and therefore the soil from those fields was dried to 50 ± 5% WFPS to avoid N losses through denitrification during the incubation. The tubes were incubated at a constant temperature of 15 °C. Every 2 weeks soils were sampled destructively by removing the soil from one tube for each plot. The soil was mixed thoroughly and 30 g moist soil was analysed for mineral N (NO_3^-–N and NH_4^-–N) by extraction with a 1 M KCl (1:2 soil weight (g):extractant volume (ml)) solution. The mineral N concentration in the extract was measured colorimetrically with a 'continuous flow auto-analyser' (Chemlab System 4, Skalar, the Netherlands).

The N mineralization rates were calculated using zero-order kinetics: $N_t = N_0 + kt$, where t is the time (in days), N_t is the amount of mineral N at time t, N_0 is the initial amount of mineral N (mg N kg^{-1} dry soil), and k is the mineralization rate (mg N kg^{-1} dry soil day^{-1}).

2.4. Microbial biomass carbon and nitrogen

Eight weeks after the start of the incubation, the microbial biomass C (MB-C) was measured with a chloroform fumigation extraction using a 0.1 M KCl extractant (1:2 soil weight (g):extractant volume (ml)) (Voroney et al., 1993). The OC in the extracts was analysed with a TOC analyser (TOC-V CPN, Shimadzu, Japan). To correct for the incomplete release and extraction of MB-C an extraction efficiency factor (K_{EC}) is needed (Voroney et al., 1993). As suggested by Voroney et al. (1993) a K_{EC} value of 0.25 was used. The MB-N was obtained assuming a C:N ratio of 6 for microbial biomass (Chaves et al., 2006).

Table 4
Percentage of total nitrogen (with standard deviation between brackets) of the 0–40 cm depth layer of the selected fields

	Field	0–10 cm			10–20 cm			20–30 cm			30–40 cm		
1	RT_{C_2}	0.109	(0.011)	a	0.099	(0.011)	a	0.084	(0.019)	a	0.077	(0.018)	a
2	RT_{C_2}	0.104	(0.015)	a	0.100	(0.006)	a	0.089	(0.011)	a	0.074	(0.018)	a
3	RT_{C_2}	0.112	(0.013)	a	0.108	(0.013)	a	0.096	(0.018)	a	0.084	(0.009)	a
4	CT	0.101	(0.005)	a	0.097	(0.008)	a	0.093	(0.013)	a	0.092	(0.016)	a
5	RT_{C_5}	0.116	(0.002)	a	0.111	(0.004)	a	0.079	(0.006)	a	0.114	(0.055)	a
6	CT	0.091	(0.012)	b	0.091	(0.009)	b	0.048	(0.025)	a	0.052	(0.021)	a
7	RT_{C_5}	0.115	(0.007)	a	0.087	(0.003)	a	0.067	(0.006)	a	0.061	(0.006)	a
8	CT	0.095	(0.005)	b	0.100	(0.017)	a	0.082	(0.009)	a	0.067	(0.007)	a
9	RT_{C_10}	0.127	(0.010)	a	0.093	(0.001)	b	0.070	(0.006)	b	0.076	(0.017)	a
10	CT	0.112	(0.002)	a	0.111	(0.001)	a	0.100	(0.007)	a	0.082	(0.007)	a
11	RT_{DD_10}	0.155	(0.011)	a	0.113	(0.004)	a	0.074	(0.007)	a	0.085	(0.003)	a
12	CT	0.128	(0.008)	b	0.113	(0.009)	ab	0.087	(0.015)	a	0.086	(0.010)	a
13	RT_{DD_10}	0.139	(0.002)	b	0.101	(0.003)	ab	0.073	(0.004)	a	0.076	(0.005)	a
14	CT	0.097	(0.002)	c	0.094	(0.001)	b	0.079	(0.011)	a	0.077	(0.007)	a
15	RT_{DD_10}	0.118	(0.010)	a	0.090	(0.006)	b	0.062	(0.006)	b	0.076	(0.010)	a
16	CT	0.110	(0.000)	a	0.117	(0.005)	a	0.089	(0.014)	a	0.087	(0.004)	a
17	RT_{C_20}	0.117	(0.007)	a	0.090	(0.003)	b	0.065	(0.004)	a	0.063	(0.003)	a
18	CT	0.099	(0.002)	b	0.098	(0.003)	a	0.072	(0.008)	a	0.067	(0.007)	a

RT_C, reduced tillage with cultivator or soil loosener; RT_{DD}, by direct drilling with in subscript the period in years; CT, conventional tillage.
Same letters indicate no significant differences per location and per depth ($P = 0.05$) (one way ANOVA/Duncan post hoc test or Welch/Games–Howell post hoc test and *t*-test).

2.5. Statistical analysis

The homogeneity of variances was tested with the Levene's test ($P < 0.05$). A *t*-test was used to find statistically significant differences in %TN and C:N ratio per depth layer and TN stock for locations with only two fields. One way ANOVA with field as factor/post hoc Duncan test and Welch/post hoc Games–Howell test were used to determine statistically significant differences for the locations with more than two fields for homogeneous and heterogeneous variances, respectively.

Table 5
The C:N ratio (with standard deviation between brackets) of the 0–40 cm depth layer of the selected fields

	Field	0–10 cm			10–20 cm			20–30 cm			30–40 cm		
1	RT_{C_2}	9.7	(0.9)	a	9.3	(0.4)	a	9.3	(0.8)	a	9.0	(0.1)	a
2	RT_{C_2}	10.5	(0.9)	a	9.6	(0.4)	a	9.4	(0.3)	a	9.0	(0.7)	a
3	RT_{C_2}	9.7	(1.0)	a	8.9	(1.2)	a	9.4	(1.2)	a	9.4	(0.6)	a
4	CT	10.7	(1.3)	a	9.6	(0.4)	a	9.0	(0.8)	a	9.3	(0.2)	a
5	RT_{C_5}	10.6	(0.5)	a	9.4	(0.5)	a	8.2	(1.4)	a	6.6	(2.8)	a
6	CT	9.8	(0.3)	a	10.1	(0.5)	a	10.6	(2.0)	a	6.2	(1.9)	a
7	RT_{C_5}	10.1	(1.1)	a	10.1	(0.1)	a	8.6	(0.7)	a	6.2	(2.3)	a
8	CT	10.5	(0.6)	a	9.2	(1.4)	a	8.6	(2.3)	a	9.2	(0.4)	a
9	RT_{C_10}	9.9	(1.0)	a	9.0	(0.3)	a	8.3	(0.4)	b	8.6	(0.4)	a
10	CT	9.7	(0.3)	a	10.0	(0.7)	a	9.6	(0.2)	a	8.1	(2.6)	a
11	RT_{DD_10}	10.4	(0.6)	a	8.3	(0.6)	a	6.6	(0.7)	a	6.6	(0.1)	b
12	CT	8.7	(0.2)	b	9.2	(0.8)	a	8.2	(0.0)	a	8.4	(0.4)	a
13	RT_{DD_10}	10.0	(1.0)	a	9.2	(0.5)	a	8.6	(0.2)	a	8.1	(0.4)	a
14	CT	9.7	(0.1)	ab	9.5	(0.1)	a	8.6	(0.1)	a	8.2	(0.2)	a
15	RT_{DD_10}	11.1	(0.7)	a	9.6	(0.6)	a	7.8	(0.4)	a	7.8	(0.1)	a
16	CT	8.8	(0.1)	b	8.7	(0.6)	a	8.4	(0.2)	a	8.2	(0.8)	a
17	RT_{C_20}	9.7	(0.7)	a	9.7	(0.6)	a	7.9	(0.9)	a	7.8	(1.1)	a
18	CT	9.3	(0.5)	a	8.8	(0.1)	a	8.5	(0.2)	a	7.4	(0.3)	a

RT_C, reduced tillage with cultivator or soil loosener; RT_{DD}, by direct drilling with in subscript the period in years; CT, conventional tillage.
Same letters indicate no significant differences per location and per depth ($P = 0.05$) (one way ANOVA/Duncan post hoc test or Welch/Games–Howell post hoc test and *t*-test).

The N mineralization was calculated with linear regression in SPSS. A correlation analysis was done using a Pearson's correlation matrix in SPSS (SPSS version 12.0, SPSS Inc., USA).

3. Results

3.1. Percentage and stock of total nitrogen

There were no significant differences in %TN in the different depth layers of fields 1–4 (Table 4). However, the %TN decreased more gradually with depth in CT field 4. The %TN in the 0–10 and 10–20 cm depth layer in RT_{C_5} field 5 was significantly higher than field 6 under CT ($P = 0.05$) but not significantly higher deeper in the soil profile. The %TN in the 0–10 cm depth layer in RT_{C_5} field 7 was significantly higher than in CT field 8 ($P = 0.05$) and lower deeper in the soil profile. A (significant) increase in %TN in the 0–10 cm depth layer was observed after 10 years RT. The %TN of the 10–20 cm depth layer was significantly decreased in RT_{C_10} field 9 compared to CT field 10 and in RT_{DD_10} field 15 compared to CT field 16 ($P = 0.05$), while the %TN of the 10–20 cm depth layer was lower in CT field 14 compared to fields 11–13. In the 20–30 cm depth layer, the %TN after 10 years RT was (significantly) lower than under CT. The %TN in the 30–40 cm depth layer after 10 years RT was comparable to CT. The %TN in RT_{C_20} field 17 was significantly higher in the 0–10 cm depth layer and significantly lower in the 10–20 cm depth layer compared to CT field 18 ($P = 0.05$). The %TN in the 20–30 and 30–40 cm depth layer was lower in RT_{C_20} field 17 than in CT field 18.

There was no difference in C:N ratio in fields 1–8 between ≤5 years RT_C and CT (Table 5). After 10 years RT, the C:N ratio was (significantly) higher in the 0–10 cm depth layer ($P = 0.05$) and mostly lower in the 10–20 and 20–30 cm depth layer than under CT. RT_{C_20} field 17 had a slightly higher C:N ratio (not significant) in the 0–10 and 10–20 cm depth layer and a lower C:N ratio in the 20–30 cm depth layer compared to CT field 18.

The BD of RT and CT fields was similar in fields 1–6 (≤5 years RT) ($P = 0.05$) (Table 1). However, the BD of RT_{C_5} field 7 was higher in the upper depth layer compared to CT field 8 and similar deeper in the soil profile. The BD of the RT_{DD_10} fields 9, 11, 13 and 15 with a higher %SOC was lower than the CT fields in the upper depth layer and comparable deeper in the soil profile. The BD of RT_{C_20} field 17 and CT field 18 were comparable.

The TN stock of the 0–40 cm depth layer calculated with the measured BD was on average 5.4 ± 0.6 tonne TN ha^{-1} for the 18 fields. The TN stock was similar for RT_{C_2} fields 1–3 and CT field 4 (Fig. 2). An increased TN stock was measured after 5 years RT_C ($P = 0.05$). The TN stock, however, decreased after 10 years RT, namely RT_{C_10} field 9 compared to field 10 and RT_{DD_10} field 15 compared field 16. Conversely, CT field 14 had a significantly lower TN stock compared to the RT_{DD_10} fields 11 and 13 ($P = 0.05$). The TN stock of RT_{C_20} field 17 was lower (but not significantly) than CT field 18.

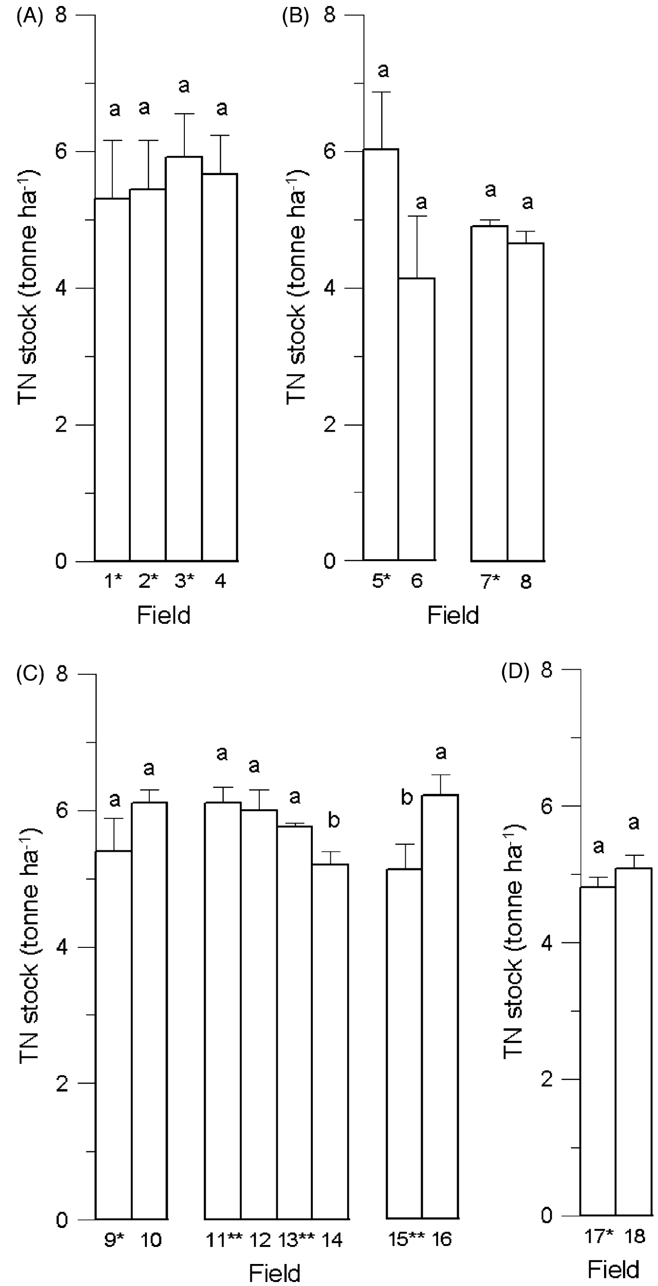

Fig. 2. Total nitrogen stock (tonne TN ha^{-1}) in the 0–40 cm depth layer (line = standard deviation) of the selected fields (A: 2 years reduced tillage (RT), B: 5 years RT; C: 10 years RT and C: 20 years RT) (same letters indicate no significant differences per location ($P = 0.05$) (one way ANOVA/Duncan post hoc test and *t*-test); (*): reduced tillage field with cultivator or soil loosener; (**): reduced tillage with direct drilling field).

3.2. Nitrogen mineralization and microbial biomass nitrogen

The amount of NH_4^+–N increased until week 4 and then decreased but was low in general (data not shown). As an example in Fig. 3 the evolution of mineral N (NO_3^-–N + NH_4^+–N) in the undisturbed soil cores of RT_{C_10} field 9 and CT field 10 is given. The amount of mineral N (NO_3^-–N + NH_4^+–N) increased linearly with time. However, a very large variability between replicates was observed. The N mineralization

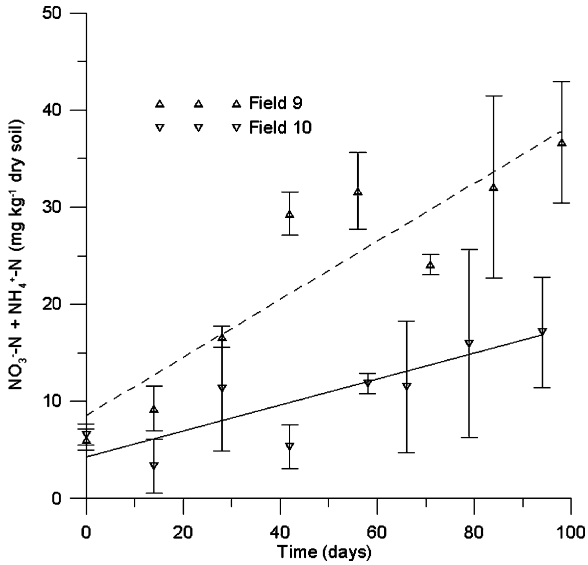

Fig. 3. Evolution of mineral N (mg NH_4^+–N + NO_3^-–N kg^{-1} dry soil) (line = standard deviation) of undisturbed soil cores of reduced tillage field 9 (10 years) and conventionally tilled field 10.

rate of the undisturbed soil samples varied from 0.032 to 0.329 mg N kg^{-1} dry soil day^{-1} (Table 6). At each location, the N mineralization rate of the fields under RT was higher than under CT, with the exception of RT_{C_5} field 5 compared to CT 6. The N mineralization rates of the RT_C fields and RT_{DD} fields was on average 1.55 and 1.76 times larger than the N mineralization rate of the CT fields, respectively. The N mineralization rates per ha were calculated with the measured BD and varied from 0.066 to 0.708 kg N ha^{-1} day^{-1}. The N mineralization rates per ha were 1.53 and 1.69 times higher for the RT_C and RT_{DD} fields than for the CT fields, respectively.

The MB-N content in the undisturbed soils after 8 weeks of incubation was higher in the RT fields (≥5 years) (33.4 ± 16.8 mg MB-N kg^{-1} dry soil) than in the CT fields (28.1 ± 13.2 mg MB-N kg^{-1} dry soil), but the differences were not significant (Table 6).

4. Discussion

4.1. Total nitrogen percentage and stock

At present, RT is being promoted strongly in Western Europe, because of its proven effects on reduction of soil erosion by water. However, very little information is available on the evolution of important soil properties related to N dynamics in RT under the specific Western European climatic and soil conditions and with rotations containing crops that seem less suitable because they often include beets and potatoes, resulting in a high disturbance of the soil at the formation of the ridges and at harvest. In the study area, very little experimental sites exist where CT practices are compared to RT practices. Therefore, we had to include farmers' fields, where inevitably there is no perfect match between CT and RT fields. However, in the selec-

Table 6

Nitrogen mineralization rate k and microbial biomass nitrogen (MB-N) (with standard deviation between brackets) of the undisturbed soil of the 0–15 cm depth layer of the selected fields to be compared per location

	Field	Nitrogen mineralization rate[a]				MB-N (mg N kg^{-1} dry soil)	
		k (mg N kg^{-1} dry soil day^{-1})		R^2	Significance		
1	RT_{C_2}	0.108	(0.028)	0.395	0.001	13.5	(0.1)
2	RT_{C_2}	0.107	(0.015)	0.705	0.000	11.2	(2.0)
3	RT_{C_2}	0.082	(0.032)	0.235	0.016	10.1	(3.5)
4	CT	0.084	(0.027)	0.308	0.005	14.6	(4.6)
5	RT_{C_5}	0.032	(0.024)	0.065	0.229	26.3	(11.6)
6	CT	0.069	(0.020)	0.364	0.002	15.7	(0.5)
7	RT_{C_5}	0.177	(0.036)	0.525	0.000	12.2	(5.8)
8	CT	0.131	(0.088)	0.094	0.145	9.3	(4.7)
9	RT_{C_10}	0.275	(0.056)	0.606	0.000	35.6	(6.3)
10	CT	0.109	(0.034)	0.187	0.035	28.7	(4.4)
11	RT_{DD_10}	0.095	(0.038)	0.218	0.021	56.7	(7.7)
12	CT	0.242	(0.031)	0.741	0.000	48.4	(5.0)
13	RT_{DD_10}	0.224	(0.069)	0.325	0.004	47.1	(11.8)
14	CT	0.178	(0.018)	0.817	0.000	31.8	(7.5)
15	RT_{DD_10}	0.329	(0.027)	0.872	0.000	42.0	(17.5)
16	CT	0.091	(0.022)	0.427	0.001	38.1	(8.7)
17	RT_{C_20}	0.099	(0.030)	0.330	0.003	13.9	(4.3)
18	CT	0.033	(0.018)	0.129	0.085	24.7	(11.9)

RT_C, reduced tillage with cultivator or soil loosener; RT_{DD}, by direct drilling with in subscript the period in years; CT, conventional tillage.

[a] The N mineralization rate k was calculated using zero-order kinetics: $N_t = N_0 + kt$, where t is the time (in days), N_t is the amount of mineral N at time t, N_0 is the initial amount of mineral N (mg N kg^{-1} dry soil), and k the mineralization rate (mg N kg^{-1} dry soil day^{-1}). The R^2 of the regression and significance of N mineralization rate k are given.

tion of the fields much care was taken to select paired fields which were similar from a soil type and management point of view. However, since one of the most important objectives of RT farmers is to reduce erosion, crop residues are maintained on the soil surface (e.g. RT_{C_5} field 5) and/or green manures are sown (e.g. RT_{C_5} field 7). Therefore, when assessing the effect of the change of management to RT not only the change in tillage intensity but also the differences in EOC and TN applied by organic manure, crop and green manure have to be considered.

The experimental plots on fields 5 and 6, both with a slope of 10%, were located on the same position on the slope. Their potential erosion loss calculated with the Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1991) is more than 20 tonne soil ha^{-1} $year^{-1}$ (Van Rompaey et al., 2000). However, next to the potential erosion the actual erosion loss also depends on the crop and tillage operations. The cultivation of grain maize on RT_{C_5} field 5 not only resulted in a higher amount of crop residues and as a consequence EOC and TN compared to fodder maize and potatoes of CT field 6 but the maize residues on RT_{C_5} field 5 also prevented soil losses through erosion during winter, while CT field 6 was often left fallow during winter. The low TN stock of CT field 6 can be related to erosion losses resulting in a serious loss of fertile top soil and TN in combination with the lower amount of crop residues and higher tillage intensity compared to RT_{C_5} field 5 (Fig. 2).

Application of composted manure and green waste compost, resulted in a high amount of the EOC and TN in RT_{C_5} field 7 (Table 3), but has not resulted in a higher TN stock in RT_{C_5} field 7 compared to CT field 8. A negative aspect of sowing green manure is, however, extra tillage and soil disturbance times in RT_{C_5} field 7 compared to CT field 8 (Table 2).

Results from experiments under temperate climate with cereal, maize and soybean rotations indicated that TN stocks tend to be similar under RT compared to CT (e.g. Doran, 1987; Angers et al., 1997; Etana et al., 1999; Stockfisch et al., 1999; Puget and Lal, 2005). We did not find a change in TN stock under RT_C, even after 20 years (Fig. 2), although the amount of EOC and TN of the manure and crop residues of the beet–winter wheat/mustard rotation of fields 17 and 18 was comparable, namely 1780 kg EOC ha^{-1} $year^{-1}$ and 285 kg TN ha^{-1} $year^{-1}$ in RT_{C_20} field 17 compared to 1645 kg EOC ha^{-1} $year^{-1}$ and 305 kg TN ha^{-1} $year^{-1}$ in CT field 18 (Table 3). The amount of EOC and TN applied with the manure was lower in RT_{C_20} field 17 (30 tonne cattle manure ha^{-1}) compared to CT field 18 (40 tonne cattle manure ha^{-1}) in 2003. However, this was compensated with the EOC and TN of the straw that was left on the soil surface of RT_{C_20} field 17. No trend could be found in the change in TN stock of RT_{DD} fields. The significant increase in TN stock of RT_{DD_10} fields 11 and 13 compared to CT field 14 suggests an increase in TN stock after long-term RT_{DD} compared to CT, but the TN stock of RT_{DD_10} field 15 was significantly lower compared to CT field 16. Measuring the TN stock after a longer period of direct drilling will possibly indicate a trend for the RT_{DD} fields with crop rotations including root and tuber crops.

In our study, the C:N ratio of the upper depth layer of RT_{DD} fields was higher compared to CT fields (Table 5). The higher %TN and C:N ratio in the upper depth layer of RT fields is attributed to the higher amount of crop residues remaining on the surface (RT_{DD}) or in the upper depth layer (RT_C) and a slower decomposition of crop residues at the soil surface because of the limited contact between the soil microflora, crop residues and nutrients (Stemmer et al., 1999). Faster mineralization results in a lower C:N ratio in CT fields compared to CT fields (Van Hove, 1969).

Higher C:N ratios were also measured in the upper depth layer in Nebraska under 5–11 years RT_{DD} (Doran, 1987) and in Ohio after 8 years RT_{DD} compared to CT and RT_C (Puget and Lal, 2005). In most cases, the C:N ratio of the upper depth layer of RT_C fields remained unchanged or increased compared to CT. A comparable C:N ratio in the upper depth layer was measured under CT and after 8–17 years of RT_C in eastern Canada by Angers et al. (1997), in Sweden by Etana et al. (1999), in central Ohio by Puget and Lal (2005) while an increased C:N ratio was measured after 9 and 21 years RT_C in Germany by Ahl et al. (1998) and Stockfisch et al. (1999), respectively. These results indicate that the changes in C:N ratio compared to CT become apparent after short-term RT_{DD} but only after long-term RT_C.

4.2. Nitrogen mineralization

Comparison of the N mineralization in this study with N mineralization data from other research is hampered by the fact that N mineralization experiments are carried out at different temperatures and moisture contents, with or without drying and sieving the soil and for different periods. N mineralization research is most often measured with sieved soil. Sieving results in the destruction of both macro- and micro-aggregates and the release of large amounts of physically protected soil organic matter. Due to the sampling protocol adapted here (undisturbed tubes), the variability in N mineralization between the plots was generally high. However, homogenizing the soil before the incubation in order to reduce the variability would have removed the inherent differences in soil structure between the RT and CT fields, hence invalidating the comparison that we intended to make. In a literature review Balesdent et al. (2000) mostly found an increased N mineralization after sieving the soil of virgin, RT_{DD} and CT fields. The largest differences were found for RT_{DD} fields with high %clay.

Independent of the measuring method, an increased N mineralization rate of the upper depth layer was measured under RT compared to CT, which was correlated with an increased %TN (Friedel et al., 1996; Kandeler et al., 1999b; Kristensen et al., 2000).

Soils under RT often have a lower temperature and higher moisture content (Balesdent et al., 2000; Six et al., 2004). In general these differences in soil temperature and moisture content slow down the N mineralization of RT compared to CT fields. After 7 years RT_C and RT_{DD} of a clay soil in Pennsylvania the N mineralization rate in the laboratory was highest under RT_{DD} and lowest under CT. In the field, however, the highest amount of NO_3^-–N in the 0–5 and 5–20 cm depth layer was measured under RT_C and the lowest under RT_{DD}. The highest differences in the amount of NO_3^-–N in the field were found in spring (Drinkwater et al., 2000). However, lower NO_3^-–N concentrations can also be an indication of increased gaseous N losses as a result of higher moisture content rather than a lower N mineralization rate under RT in field conditions.

We used a temperature correction function for Flemish CT soils determined by De Neve et al. (1996) to recalculate the N mineralization rate obtained in the laboratory to N mineralization per hectare and per year using the monthly average temperatures. This resulted in an estimated in situ N mineralization of an average 52, 73 and 114 kg N ha^{-1} $year^{-1}$ 15 cm^{-1} for CT, RT_C and RT_{DD} fields, respectively, if the soil temperature and moisture content are assumed to be equal for both CT and RT fields. However, under field conditions the differences in N mineralization will be smaller due to the less favourable soil temperature and moisture conditions of the RT fields. Moreover, the low stratification of N under CT fields due to the mixing of the soil at ploughing results in a comparable N mineralization in the entire plough layer. The N mineralization of the upper 30 cm depth layer of the CT field can be assumed to be roughly twice the N mineralization of the 15 cm depth layer, namely 104 kg N ha^{-1} $year^{-1}$. However, the N mineralization of RT_{DD} fields in the 15–30 cm depth layer will be much lower due to the high stratification of the %TN and the overall N mineralization rate in the entire 0–30 cm depth layer will probably be not much higher than the estimated 114 kg N ha^{-1} $year^{-1}$. The N mineralization of RT_C fields in the 15–30 cm depth layer will be in between N mineralization of the CT and RT_{DD} fields. This indicates that the differences in N mineralization in the upper 30 cm between CT and RT fields are probably too small to require an adjustment of the N fertilization for RT fields.

A higher N mineralization rate was correlated with a higher MB-N content. The higher MB-N content under RT compared to CT fields is similar with the results of other researches. After only 3 years RT_C in a clay loam soil in Germany, the MB-N was increased in the 0–10 cm depth layer compared to CT (Hoffmann et al., 1997). The MB-N of a sandy loam field from Austria was increased in the 0–10 cm depth layer 7 years after changing to RT_C and RT_{DD} (Kandeler et al., 1999a). The MB-N in the upper 15 cm of a silt loam soil was significantly increased 20 years after changing to RT_C compared to CT field in Maryland (McCarty et al., 1995).

The sampling method of undisturbed tubes resulted in a high variability of N mineralization rates (kg N ha^{-1} day^{-1} 15 cm^{-1}) making the detection of correlations with soil parameters more difficult. No significant correlations of the N mineralization rate could be found with texture, %TN and C:N ratio. The N mineralization rate of RT fields was significantly correlated with MB-N content ($P = 0.01$).

5. Conclusion

Crop rotations in Western Europe often include beets or potatoes. Despite the soil disturbance at the harvest of these crops, an increased stratification of %TN in the soil profile was found under RT compared to CT. The TN stock of the 0–40 cm depth layer of the RT_C fields was comparable to CT fields, even after 20 years RT_C. No trend could be found in the change in TN stock of RT_{DD} compared to CT fields. The higher %TN in the upper 0–15 cm depth layer of fields under RT resulted in a higher N mineralization rate and MB-N content in undisturbed soil cores under controlled conditions in the laboratory. Recalculation of the N mineralization rate obtained in the laboratory to N mineralization per hectare and per year using the monthly average temperatures and considering the higher stratification of %TN of RT compared to CT fields indicated that the differences in N mineralization in the upper 30 cm between CT and RT fields are too small to adapt the N fertilization for RT fields.

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