

The potential of reduced tillage agriculture in Flanders

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THE POTENTIAL OF REDUCED TILLAGE AGRICULTURE IN FLANDERS

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Woord vooraf

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ANOVA	:	analysis of variances
$BaCl_2$	:	barium dichloride
BD	:	bulk density
C	:	carbon / koolstof
$CaCO_3$	:	calcium carbonate
CAP	:	Common Agricultural Policy
CH_4	:	methane
CO_2	:	carbon dioxide
ConsL	:	conserveringslandbouw
Conv	:	conventioneel
CsT	:	conservation tillage
CT	:	conventional tillage
D	:	disturbed
DM	:	dry matter
ECAF	:	European Conservation Agriculture Federation
EOC	:	effective organic matter
EU	:	European Union
fPOM	:	free particulate organic matter
GWP	:	global warming potential
IC	:	inorganic carbon
iPOM	:	intra-micro-aggregate particulate organic matter
k_C	:	carbon mineralization rate
KCl	:	potassium chloride
K_{EC}	:	extraction efficiency of carbon
K_{EN}	:	extraction efficiency of nitrogen
K_{fs}	:	field-saturated hydraulic conductivity
k_N	:	nitrogen mineralization rate
MB	:	microbial biomass
MB-C	:	microbial biomass carbon
MB-N	:	microbial biomass nitrogen
MTR	:	Mid Term Review
MWD	:	mean weight diameter
MWD_{fast}	:	mean weight diameter after heavy shower
MWD_{slow}	:	mean weight diameter after slow wetting
MWD_{stir}	:	mean weight diameter after stirring after prewetting
N	:	nitrogen / stikstof
N_2	:	dinitrogen
NaOH	:	natrium hydroxide
NH_3	:	ammonia

NH_4^+ : ammonium
NO_x : nitrogen oxide
NO : nitrogen monooxide
NO_2^- : nitrite
NO_3^- : nitrate
N_2O : nitrous oxide
NT : no-tillage
O_2 : dioxygen
OC : organic carbon / organische koolstof
OM : organic matter
OS : organische stof
PASW : plant available soil water
POM : particulate organic matter
PR : penetration resistance
RPASW : readily plant available soil water
Red : gereduceerde bodembewerkingen
Red_{C} : gereduceerde bodembewerkingen met cultivator of woeler
Red_{DI} : gereduceerde bodembewerkingen met directe inzaai
RT : reduced tillage
RT_{C} : reduced tillage with cultivator or soil loosener
$\text{RT}_{\text{C\_n}}$: reduced tillage with cultivator or soil loosener for n years
RT_{DD} : reduced tillage by direct drilling
$\text{RT}_{\text{DD\_n}}$: reduced tillage by direct drilling for n years
SI : stability index
SOC : soil organic carbon
SOM : soil organic matter
TC : total carbon
TOC : total organic carbon
TN : total nitrogen
TPASW : total plant available soil water
U : undisturbed
WFPS : water filled pore space
WRC : water retention curve
θ_r : residual soil water content
θ_s : saturated soil water content

Chapter 1:

Introduction

KUTTEKOVEN: DECEMBER 2005
WINTER WHEAT AFTER SUGAR BEETS

LEFT: CONVENTIONNAL TILLAGE AGRICULTURE
RIGHT: REDUCED TILLAGE AGRICULTURE

1.1. MODERN AGRICULTURE AND DETERIORATION OF SOIL QUALITY

1.1.1. Modern agriculture

The explosive population growth in the 20th century resulted in a high food demand in industrialised societies. Therefore the arable as well as animal production needed to increase through an intensification of agriculture. Until recently, modern agriculture was based on mechanization, intensive use of agrochemicals and organic manure and was focused on maximum food production without considering the long term impact on soil fertility or environment. As a consequence modern agriculture is nowadays confronted with a number of pressing problems. There is an intense debate about the role of agriculture in the diffuse pollution of the environment by the intensive use of agrochemicals and organic manure. These problems reflect negatively on agriculture because they are directly sensed by the society. Farmers themselves are also facing several direct negative consequences of the modern production methods. Agriculture in industrialised societies has to address the degradation of physical soil structure resulting in erosion and soil compaction, decline in soil organic matter (SOM) and nitrogen (N) losses.

1.1.2. Deterioration of physical soil quality

The erosion process is a physical phenomenon resulting from the removal of soil particles by water or wind, transporting them elsewhere. Erosion is a natural process triggered by a combination of factors such as steep slopes, climate (e.g. long dry periods followed by heavy rainfall), inappropriate land use, land cover patterns (e.g. sparse vegetation) and ecological disasters (e.g. forests fires). Moreover, some intrinsic features of a soil can make it more prone to erosion (e.g. a thin layer of topsoil, low SOM content) (EAA, 2003; Esteve *et al.*, 2004).

Erosion causes financial damage on the farm through the formation of rills and gullies and the washing away of fertile soil, seeds, manure and fertilizers. The loss of fertile soil by erosion not only has serious effects on crop yields but also negatively affects the soil functions, as it reduces plant rooting depth, removes nutrients and SOM, reduces infiltration rates and plant available soil water (PASW). Decrease in soil biodiversity is another and very important on-site impact of erosion. Decline in soil biodiversity affects nutrient turnover, decreases aggregate stability, increases crusting, reduces infiltration rates and exacerbates erosion (Pimentel *et al.*, 1995; Lupwayi *et al.*, 2001; OECD, 2003; Anonymous, 2007b; Feller, 2007; MESAM, 2007).

There are also important off-site problems caused by erosion like pollution of drinking water resources, the accelerated silting up of water reservoirs and mud on the roads and in housing properties of densely populated areas. Next to the offsite costs for the society for dredging waterways and cleaning the roads, the muddy floods also result in financial costs for the private households and have an emotional impact on the inhabitants (Pimentel *et al.*, 1995; Uri, 1999; Verstraeten & Poesen, 1999; Verstraeten *et al.*, 2003a; Dorren *et al.*, 2004; Schiettecatte, 2006; Verstraeten *et al.*, 2006; MESAM, 2007).

In Europe, the Mediterranean region is particularly prone to erosion because it is subject to long dry periods, followed by heavy bursts of erosive rain, falling on steep slopes with fragile soils. This contrasts with Western Europe where soil erosion is less severe, because rain falling on mainly gentle slopes is more evenly distributed throughout the year and consequently, the area affected by erosion is less extensive than in Southern Europe. However, erosion is still a serious and increasing problem in Western Europe. It is clear that erosion by water and wind is irreversibly degrading the soils in many parts of Europe. Approximately 10% of European land is strongly or extremely degraded by water erosion (Jones *et al.*, 2004).

Erosion in Belgium mainly occurs in the loess belt, which stretches from east to west across the central part of the country, i.e. in the south of Flanders, and in the north of Wallonia (Verstraeten & Poesen, 1999; Anonymous, 2000; Gobin & Govers, 2003; Verstraeten *et al.*, 2006). The major erosion problems are found with root and tuber crops and maize (*Zea mays* ssp. *Mays* L.) (Anonymous, 2000; Esteve *et al.*, 2004; Geelen, 2006). The yearly erosion from silt loam soils in the hilly areas in Belgium varies between a few to 100 Mg soil ha^{-1} y^{-1} (Verstraeten *et al.*, 2003b).

Next to erosion, soil compaction also seriously threatens the agricultural production in some areas in Europe. Soil compaction essentially reduces the pore space between soil particles and can occur both at the surface and in subsurface soil horizons. The worst effects of surface soil compaction can be rectified relatively easily by soil tillage, root growth and biological activity in general and, hence, it is perceived to be a less serious problem in the medium to long term. On the contrary, once subsoil compaction occurs, it can be extremely difficult and expensive to alleviate. Furthermore, remedial treatments usually need to be repeated. Deep soil compaction decreases the growth of plants by a reduction of the plant rooting depth and PASW (capacity) and often results in a decrease of crop yield (Figure 1.1) (Ide *et al.*, 1984 & 1987; Ide & Hofman, 1990; Crescimanno *et al.*, 2004; Jones *et al.*, 2004). More than a third of European subsoils are classified as having high or very high susceptibility to subsoil compaction (Dorren *et al.*, 2004).

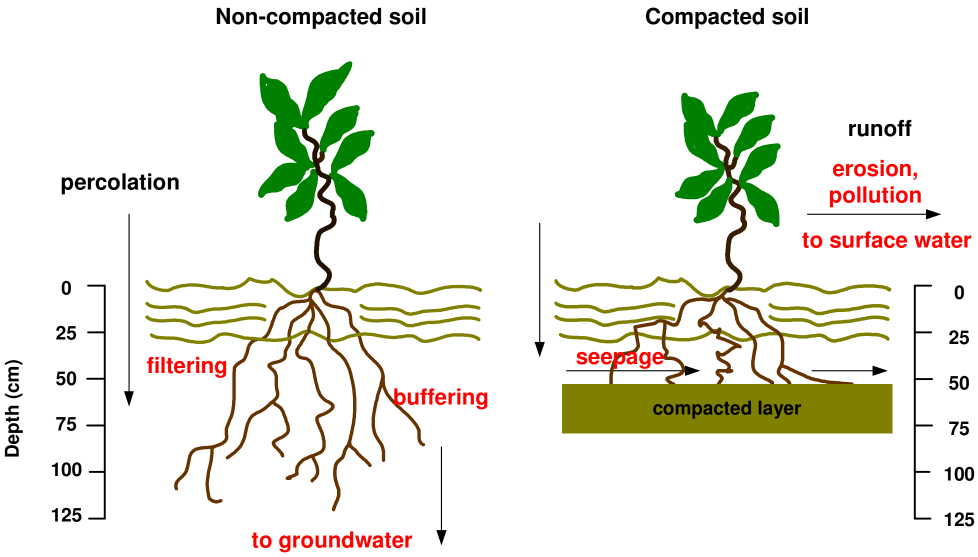


Figure 1.1 Reduction of rooting depth and increase of erosion due to deep soil compaction (after Jones *et al.*, 2004)

As a result of human induced erosion and soil compaction the soil fertility of arable land is diminishing continuously. Erosion and soil compaction strongly depend on management. The main human causes for the degradation of the physical soil structure are increased farm and field sizes, limited crop rotations, intensification of crops with lower crop cover density, the frequent passages of the fields with heavy farming equipment, also under unfavourable circumstances, and ploughing and intensive soil tillage in general causing a disruption of aggregates and a decline in SOM. After all, farmer's management decisions are determined by market conditions, technological development and changes in the global economy, particularly the rising relative cost of labour (Esteve *et al.*, 2004; Jones *et al.*, 2004; Bronick & Lal, 2005; Hamza & Anderson, 2005).

1.1.3. Deterioration of chemical soil quality

Decline of soil organic matter

SOM plays a major part in maintaining soil fertility. There are many soil properties, in particular related to soil physical structure, which are influenced by the presence of SOM. The retention and release of water, the ability to provide charged surfaces (variable with pH) where cations may be retained in a form available to plants are vitally important for a fertile soil. The simple mixture of SOM with the mineral fraction lowers the soil bulk density (BD) (and influences workability), but SOM also affects the stability of soil aggregates which determine several associated pore related properties, such as aeration and water infiltration rate (Tisdall & Oades, 1982; Holland, 2004; Robert *et al.*, 2004).

A higher amount of SOM results in more energy being available for heterotrophic bacteria and fungi and as a consequence in a higher amount and activity of soil micro-organisms. Microbial biomass (MB) is but a small portion of the total SOM content, but its activity is absolutely crucial for all soil functions. Micro-organisms are the main decomposers of litter, are crucial in the process of humification and make the parent mineral material into a habitat conducive for other forms of soil life, including plant growth and have a positive effect on the aggregate stability (Allison, 1968; Andrén *et al.*, 2004; Bronick & Lal, 2005).

SOM, erosion and soil compaction are strongly interrelated. Since a higher amount of SOM and microbial biomass result in a better aggregate stability and a reduction of the risk of erosion, it is essential to maintain high SOM contents in the upper depth layer. Although the importance of a high amount of SOM in the upper depth layer is acknowledged by scientists and farmers, a decrease of the soil organic carbon (SOC) content of European agricultural soils during the 1990's was calculated (Vleeshouwers & Verhagen, 2002; Janssens *et al.*, 2005; Goidts & Van Wesemael, 2007). Recent studies of the evolution of SOC in arable fields (0-24 cm depth layer) in Flanders, in the northern part of Belgium, showed a decrease of 354 x 10^3 Mg SOC y^{-1} during the 1990's (Sleutel *et al.*, 2003a & b). The decrease in SOC stock could be correlated with the decrease in livestock and by consequence a lower organic carbon (OC) input from manure applications (Sleutel *et al.*, 2003b). Sleutel *et al.* (2006b & 2007a) found that next to the reduced manure application, a reduction in cereal straw and crop incorporation and a higher carbon (C) mineralization rate due to the observed temperature increase had attributed to the SOC stock decrease. As a consequence of the decrease of SOC stock in the upper depth layer, it looks as if erosion and soil compaction will become more problematic in Europe the following years.

Next to the necessity of a high amount of SOC in the upper depth layer to reduce erosion and soil compaction, maintaining or increasing the SOC stock is important in the framework of "global change" and the decrease of carbon dioxide (CO_2) emissions from soils. A lot of attention is given to the possible role of agricultural soils as a C sink because increasing the SOC stock removes the greenhouse gas CO_2 from the atmosphere and this can help in the reduction of the greenhouse effect. Art. 3.4 of the Kyoto Protocol allows C sequestration due to human-induced agricultural activities, which have started after 1990, to be accounted for during the 2008-2012 commitment period (IPCC, 2000).

Nitrogen losses

The loss of fertile soil through erosion and the decrease in SOM have not directly endangered the chemical soil fertility due to the abundant use of fertilizers. However, high nutrient inputs not only have adverse effects on the arable production by decreasing the quality e.g. lodging of cereals by over fertilization of N and making crops more susceptible to diseases and pests (Vos & MacKerron, 2000), the excessive use of agrochemicals and organic manure in agriculture results in a diffuse pollution of the environment that disrupts the ecological processes and nutrient cycles (IFA, 1992; De Clercq *et al.*, 2001).

The N cycle is the most intensively studied nutrient cycle from the point of view of nutrient management, since N is the most important nutrient for obtaining a good crop production and quality, but also because N has a major impact on the quality of the environment through the various pathways of N losses (Figure 1.2) (Franco & Munns, 1982; Mengel & Kirkby, 1982; De Clercq *et al.*, 2001; Hofman *et al.*, 2003; Salomez, 2004).

N losses can be categorized in gaseous losses (dinitrogen (N_2), nitrous oxide (N_2O), nitrogen oxide (NO_x) and ammonia (NH_3)), leaching losses (nitrate (NO_3^-)), run-off and erosion. Nitrous oxide is a powerful greenhouse gas that can contribute to the depletion of the stratospheric ozone layer and the global warming, with the most extreme effects being the melting of the ice caps and the related increase of the sea level (Peoples *et al.*, 1995; Van Cleemput, 1998). Nitrogen monooxide (NO) causes acid rain and the formation of ozone in the troposphere (Bogaert *et al.*, 1998). Ammonia reacts in the air with acid gases and particles. Their return to the soil through deposition can diminish biodiversity and cause acidification and eutrophication (Hofman *et al.*, 2000). Leaching of NO_3^-, which mainly occurs during winter and early spring in Europe, can also cause eutrophication. Eutrophication involves the abundant growth of algae and rooted vegetation. As algae dies and decays, it uses oxygen from the surrounding water, lowering the dissolved oxygen levels and altering the size and composition of commercial and recreational sport fisheries. Floating algae blooms can restrict light penetration to surface waters and can affect the health, safety and enjoyment of people using water for recreation. Floating algae can clog intake pipes and filtration systems, increasing the cost of water treatment and drinking water production. Rooted plants can become a nuisance around marinas and shorelines (Bogaert *et al.*, 1998; Uri *et al.*, 1999; Mulier *et al.*, 2001).

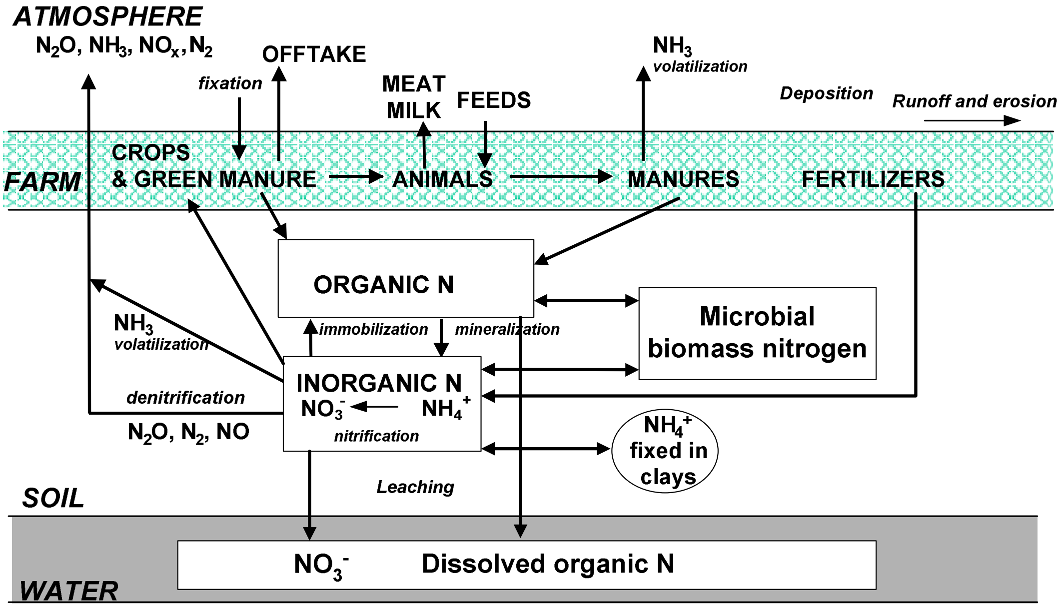


Figure 1.2 A simplified nitrogen cycle at the field scale (after De Clercq *et al.*, 2001)

To protect waters against pollution caused by NO_3^- from agricultural sources, the European Union (EU) Nitrate Directive (91/676/EEC), has imposed a maximum concentration level of 50 mg NO_3^- L^{-1} in ground and surface water (Anonymous, 1991a). To meet this provision set in the EU Nitrate Directive, Flanders has issued the so-called Manure Decree (Anonymous, 1991b) which has been amended afterwards 19 times and was replaced by a new Manure Decree in 2006 (Anonymous, 2006c). The Flemish farmers, stimulated by the

Manure Decree, have reduced their N losses for many years by using less chemical fertilizers, a decrease in livestock and switching over to concentrates with a low N content (Stuykens, 2002; Wustenberghs *et al.*, 2004).

The C and N dynamics and losses not only depend on the crop rotation and fertilization practice but also the tillage operations.

1.2. CONSERVATION TILLAGE AGRICULTURE

1.2.1. Definition

There is confusion in the literature concerning the terminology of agriculture because many of the terms used are very general and a variety of implements are used together with different tillage intensity. Furthermore, different authors often use the same terms for different systems (Barber, 2000).

Conventional tillage (CT) agriculture involves inversion of the soil, normally with a mouldboard as the primary tillage operation, followed by secondary tillage. The main objective of the primary tillage is weed control through underploughing, and the main objective of the secondary tillage is seedbed preparation. Subsequent weed control may be carried out either mechanically, or with herbicides. The negative aspect of this system is that the soil lacks a protective residue cover and is left practically bare, hence susceptible to soil and water losses through erosion.

Conservation tillage (CsT) agriculture is a general term which has been defined as “whichever tillage or sowing system which maintains at least 30% of the soil surface covered with residues after sowing so as to reduce erosion by water” (IPCC, 2000). Another definition of CsT agriculture used is “whatever sequence of tillage operations that reduces the losses of soil and water, when compared to conventional tillage agriculture” (Lal, 1989). Normally this refers to a tillage system which does not invert the soil and which retains crop residues on the surface. However, in some situations, there are insufficient residues or other materials to provide a protective cover to the soil. These definitions show that CsT agriculture was first introduced as an erosion control measure.

1.2.2. Types of conservation tillage agriculture

Using the definition "whatever sequence of tillage operations that reduces the losses of soil and water, when compared to conventional tillage agriculture", CsT agriculture includes the following systems (Derpsch, 2007):

- *Direct drilling* (synonymous with *zero tillage* and *no-tillage* (*NT*)) *agriculture* refers to planting the seed into the stubble of the previous crop without any previous tillage or soil disturbance, except that which is necessary to place the seed at the desired depth. Weed control relies on the use of herbicides.
- *Strip tillage* or *zonal tillage agriculture* refers to a system where strips 5 to 20 cm in width are prepared to receive the seed whilst the soil along the intervening bands is not disturbed and remains covered with residues. The system causes more soil disturbance and provides less cover along the rows than direct drilling.
- *Tined tillage* or *vertical tillage agriculture* refers to a system where the land is prepared with implements which do not invert the soil and which cause little soil compaction. For this reason, the surface normally remains with a good cover of residues on the surface in excess of 30%.
- *Ridge tillage agriculture* is a system where the crops are grown on ridges and furrows. The ridges may be narrow or wide and the furrows can be parallel to the contour lines or constructed with a slight slope, depending on whether the objective is to conserve water or to drain excess water. The ridges can be semi-permanent or be constructed each year, which will govern the amount of residue material that remains on the surface. In the semi-permanent systems which have a good residue cover between the ridges, there will still be more soil disturbance and less overall cover than for the no-tillage system.
- *Reduced tillage* (*RT*) *agriculture* refers to tilling the whole soil surface but eliminating one or more of the operations that would otherwise be done in a CT system. This definition is extremely broad and it follows that tillage systems which vary as regards the implements used, the frequency and the intensity of operations, can all be considered as RT agriculture. The type of implement and the number of passes also vary. The result is that some systems leave very little residue at the surface and in others, this may be in excess of 30%. Generally, RT agriculture does not use either mouldboard or disc ploughs. Owing to the great variation in RT systems, it is difficult to generalize over the advantages and limitations. However, all the systems have the advantage of

reducing fuel consumption, work time and the equipment required as compared to CT agrivulture. RT systems are thus more flexible than CT systems. Germination conditions tend to be generally better than for NT agriculture due to the break-up of the soil. There is also comparatively more flexibility for weed control using cultivators or herbicides.

1.2.3. Positive and negative effects of conservation tillage agriculture

CsT agriculture is a very effective measure to reduce erosion and store water into the soil (Arshad, 1999; Six *et al.*, 2002b; Bautista *et al.*, 2004; Derpsch, 2007). CsT agriculture can theoretically be expected to increase the SOC stock in the soil profile for several reasons. Leaving crop residues at the soil surface under CsT agriculture results in a lower rate and extent of decomposition because the residues are physically separated from the soil nutrients and decomposers and are in an environment with less favourable temperature and moisture conditions than under CT agriculture. The crop residues at the soil surface can reduce soil temperature and increase soil moisture content, which decreases C mineralization rates in the soil. The aggregates and soil structure are much less disrupted under CsT than CT agriculture where ploughing results in decomposition of physically protected SOM (Drury *et al.*, 1999; Stockfisch *et al.*, 1999; Balesdent *et al.*, 2000; Six *et al.*, 2000c; Larney *et al.*, 2003; Baritz *et al.*, 2004; Six *et al.*, 2004a; McLauchlan, 2006). The build-up of SOM results in an improved soil structure that enhances gas fluxes and water infiltration rate and in an increased population of micro-organisms and earthworms under CsT compared to CT agriculture (Höflich *et al.*, 1999; Uri *et al.*, 1999; Holland, 2004; Van den Bossche *et al.*, 2007).

However, CsT agriculture may also have negative effects. Due to the higher soil moisture content and higher amounts of easily available C in the upper layer under CsT compared to CT agriculture higher emissions of the greenhouse gas N_2O may occur under CsT agriculture (Holland, 2004; Six, 2007). The presence of crop or green manure residues as mulch on the soil surface and higher soil moisture content can increase the bacterial and fungal infections of the following main crop (Sturz *et al.*, 1997; Carter & Sanderson, 2001; D'Emden & Llewellyn, 2004).

CsT agriculture was first introduced on a large scale in the USA, Latin America and Australia. Therefore research on the positive and negative effect of CsT compared to CT agriculture mainly focussed on the crop rotations and the specific climatic and soil conditions of the USA, Latin America and Australia. In these large arable areas mainly cereals, soybean (*Glycine max*) and sunflower (*Helianthus annuus*) are grown under a warm and dry climate (Arshad, 1999; Uri, 1999; Six *et al.*, 2002b; D'Emden & Llewellyn, 2004; Derpsch, 2007). The climatic and soil conditions and crop rotations in Western Europe are, however, very different. Western Europe has a maritime temperate climate and the crop rotations contain crops that seem less suitable under RT agriculture because they often include beets (*Beta vulgaris* L.) and potatoes (*Solanum tuberosum* L.), resulting in a high disturbance of the soil at the formation of the ridges and at harvest. In Belgium 20% of the cropped area is cultivated with beets and potatoes (Anonymous, 2006d; KMI, 2007). Next to crop rotations and climatic conditions, the effect of CsT agriculture also depends on the type and chemical composition of the organic additions and type and properties of the soil (Vigil & Kissel, 1991; Breland & Hansen, 1996; Robert *et al.*, 2004; Ogle *et al.*, 2005).

1.2.4. Area of conservation tillage agriculture

One big push for the development of NT agriculture trials in the USA, UK and elsewhere was the significant progress in herbicide technology with the introduction of atrazine in the late 1950’s and paraquat in the early 1960’s (Six *et al.*, 2002b; Derpsch, 2007; Lal *et al.*, 2007). Adoption of NT agriculture by farmers started in the early 1960’s in the USA and in the 1980’s in Latin America, mainly Brazil. NT agriculture was introduced on a large scale in the USA and Latin America as an effective measure against erosion, to stock water in the soil and to increase the SOM content (Arshad, 1999; Six *et al.*, 2002b; Derpsch, 2007). Compared to the Americas, NT practice is much less adopted in Europe, Africa and Asia. In many countries this production system is virtually unknown (Derpsch, 2007).

Information on the area of arable land under CsT agriculture is very scarce. In Table 1.1 an estimation of the area under NT agriculture since the 1970’s is given (Derpsch, 2005 & 2007). According to Derpsch (2005) probably about 95% of the practical application of NT agriculture by farmers worldwide takes place in the Americas. Since NT agriculture accounts for less than 50% of CsT practices in the USA and Canada, but is almost the only CsT form practiced in

Latin America, it is not possible to extrapolate these assessments to estimations of the total area under CsT agriculture.

Table 1.1 Estimation of area (1000 ha) under no-tillage agriculture in the world (Derpsch, 2005 & 2007)

Country	1973/74	1983/84	1996/97	2000/01	2004/05
USA	2200	4800	19400	21120	25304
Brazil	1	400	6500	13470	23600
Argentina			4400	9250	18269
Canada			6700	4080	12522
Australia	100	400	1000	8640	9000
Mexico			490	650	1900
Paraguay			500	960	1700
Bolivia				350	550
Uruguay				50	263
Chile				100	120
Others	527	655	960	1220	2252
Total	2828	6255	39950	59890	95480

1.2.5. Conservation tillage agriculture in Europe

Currently, there is no survey at EU or country level of coverage of CsT agriculture in Europe. Available data are scarce and may not apply to the whole cropping system (Table 1.2). For instance, most of the areas listed as NT agriculture may correspond to fields managed under NT agriculture only for a part of a rotation, whereas the other crops of the rotation are managed using RT or CT agriculture. Indeed, cereals can be grown under RT or NT agriculture while root or tuber crops are difficult to manage under these systems (Lahmar, 2006).

Due to the lack of technology and technology transfer, the reluctance to take risk and the lack of institutional support the adoption of CsT agriculture in Europe was very slow. The last 5 to 10 years CsT agriculture is increasing gradually in Europe due to an increasing concern and awareness in soil and environmental protection. The European Conservation Agriculture Federation (ECAF) was constituted in Brussels on 14 January 1999. ECAF is a network of leading European academics, scientists and farmers. Its mission is to help develop and spread farming practices focused on maintaining the agricultural soil and its biodiversity in the context of sustainable agriculture. ECAF is in contact with farmer groups at European level, in order to coordinate actions. ECAF has member associations in Belgium, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Portugal, Russia, Slovakia, Spain, Switzerland and UK (ECAF, 2005).

Table 1.2 Estimation of area (1000 ha) and percentage of agricultural area under conservation tillage (CsT) and no-tillage (NT) agriculture in some countries in Europe in 2005 (ECAF, 2005; Lahmar, 2006)

Country	CsT		NT	
	(1000 ha)	(%)	(1000 ha)	(%)
Germany	3400	20	510	3
France	3000	17	150	0
Spain	2000	14	300	2
UK**	1440	30	24	1
Czech Republic	750	18	150	4
Italy	560	6	80	1
Hungary	500	10	8	0
Denmark	230	8	0	0
Norway*	158	15	6	1
Belgium	140	10		
Slovakia	140	10	10	1
Switzerland	120	40	9	3
Portugal	39	1	25	1
Ireland	10	4	0	0

*: In Norway, acreage under RT agriculture also comprises the area ploughed in spring.

**: The area under CsT agriculture given for the UK appears implausible as this farming technique is only now entering recognition amongst farmers in this country. It is thought that this figure includes the grazing areas that traditionally represent a very large segment of UK farming and which either are never tilled at all or only ploughed to renew the grazing or “ley”, i.e. once every 4-10 years.

Not only farmers and scientists have recognised the importance of soil conservation, but also the European Commission (Anonymous, 2007c). The priority areas of Agenda 2000 were a continuation of the agricultural reform along the lines of the changes made in 1988 and 1992, with a view to stimulating European competitiveness, taking great account of environmental considerations and ensuring fair income for farmers (Anonymous, 2007a). Following the Agenda 2000 reforms, the radical overhaul of the Common Agricultural Policy (CAP) in 2003 by the European ministers of agriculture was just the next logical step towards a policy that supports not just farming, but the long term livelihood of rural areas as a whole. The main goals of this reformation called Mid Term Review (MTR) are to provide farmers with a reasonable standard of living, consumers with quality food at fair prices and to preserve the rural heritage. Therefore the financial support for the farmers was shifted from production support to producer support. This "single farm payment" was made conditional upon "cross-compliance" with environment, food safety, animal and plant health and animal welfare, as well as the maintenance of the farmland in good agricultural and environmental condition. Erosion control measures, e.g. grass buffers and CsT agriculture, belong to the good agricultural and environmental conditions (Anonymous, 2003b, 2005c & 2006g). Significant benefits can be expected from linking the direct payments ("cross-compliance") to European farmers to the application of "soil-friendly" agricultural practices. However, these measures are not obligatory everywhere and they only apply to European farmers who are under the payment regimes. European farmers who do not receive payments are not bound to adopt these soil-friendly practices. Therefore, cross-compliance will only partially contribute to the preservation and sustainable use of soil (Anonymous, 2006f).

In 2002 the EU defined the priorities and objectives of the European environment policy and described the measures to be taken to help implement its sustainable development strategy in "Sixth Environment Action Programme. Environment 2010: Our future, our choice". The objectives were to protect natural resources and to promote a sustainable use of the soil by committing itself to the adoption of a "Thematic Strategy on soil protection" to halt and reverse soil degradation (No 1600/2002/EC) (Anonymous, 2002f). In its Communication "Towards a Thematic Strategy on Soil Protection", the European Commission identified erosion, SOM decline and soil compaction as main threats to which soils in the EU are confronted (COM(2002) 179) (Anonymous, 2002e). In the period 2003-2004, the Commission carried out an extensive stakeholder consultation and established technical working groups with the purpose to provide advice on the specific issues. In the working group "Soil Organic Matter" of the "Thematic Strategy on Soil Protection" it was concluded that CsT agriculture can increase soil fertility and SOM (Baritz *et al.*, 2004). In September 2006, the "Thematic Strategy for Soil Protection" was formulated as a proposal for a framework Directive setting out common principles for protecting soils across the EU (COM(2006) 231 & COM(2006) 232) (Anonymous, 2006a, b & e). Within this common framework, the EU Member States will be in a position to decide how best to protect soil and how to use it in a sustainable way on their territory (Anonymous, 2004b & 2006a).

1.2.6. Conservation tillage agriculture in Belgium

Although CsT agriculture was studied in Belgium since the 1970's, its adoption was limited till now. Until the mid 1990's, erosion and its related problems received little attention in the environmental debate. This has changed through the increasing reports on erosion and increased interest in environmental issues in general (Boardman *et al*., 2003; Vertraeten *et al*., 2003a). The promotion of CsT agriculture among scientists and farmers in Belgium is stimulated by the "Belgian Association in Research Application on Conservation Agriculture" or BARACA, founded in 2001 and integrated in ECAF (BARACA, 2007). The recent enthusiasm about CsT agriculture can also partly be explained by the progress in agricultural machinery, more specifically the sowing machines. Sowing in crop residues and green manure on the surface indeed demands adapted equipment. Moreover, the economical circumstances force the farmers to reduce the production costs, while the pressure on the environment urges farmers to manage his soil capital better and reduce runoff and erosion (Vandergeten & Roisin, 2004).

The area under CsT agriculture in Belgium is estimated to be about 140000 ha, which is around 10% of the agricultural area (Table 1.2). Although 70% of the farmers in the loess area in Wallonia reported problems with runoff and erosion in 2001, only 25% farmers adopted some CsT form (Bielders *et al*., 2003).

Mainly, two types of RT agriculture, namely reduced tillage with a cultivator or soil loosener (RT_C) and by direct drilling (RT_{DD}) agriculture, are practised in Belgium. Continuous NT agriculture is very rare in Belgium because of the high disturbance of the soil at the formation of the ridges and at harvest of root and tuber crops. Moreover, organic manure is often applied and needs to be incorporated in order to minimize ammonia losses.

A soil conservation policy recently emerged in Flanders and Wallonia subsidising farmers, who implement erosion control measures, e.g. grass buffers and CsT agriculture, on their fields partly paid with European funds (Anonymous, 1999, 2003a, 2004a, 2005a & b; Carels *et al*., 2006). In 2006, 671 ha and 78 ha was under a management contract for RT_C and RT_{DD} agriculture, respectively, for a total grant of 68 286 euro (Swerts & Vandekerckhove, 2007).

In Flanders there is also a decree concerning “the subsidy of small-scale erosion control measures to be taken by local authorities”, often called the ‘Soil erosion decree’, subsiding the municipalities for making an erosion control management plan and taken control measures indicated in the plan (Anonymous, 2002d).

Rainfall simulations in Belgium indicated that RT agriculture generally reduces erosion compared to CT agriculture. However, a large variation in erosion response was observed. The reduction of erosion by RT compared to CT agriculture measured in different experiments varied between 0 to 95% and was on average 35 to 55% (Gillijns *et al.*, 2002 & 2004; Goyens *et al.*, 2005; Leys *et al.*, 2007; Vermang *et al.*, 2007). However, little is known about the effect of RT agriculture on physical soil structure and C and N dynamics of soils under the specific Western European climatic and soil conditions, with crop rotations containing crops that seem less suitable for RT agriculture, including an important share of root and tuber crops. The study of the changes in physical soil structure and C and N dynamics after the shift of the management to RT gives an overall picture of the effect of RT agriculture on the soil properties.

1.3. OUTLINE OF THE THESIS

RT agriculture was introduced to reduce erosion and improve physical soil structure but the effect on the C and N cycle in typical Western European crop rotations and weather circumstances had not yet been examined. The objectives of this thesis were to investigate the less known effects of RT agriculture on soil properties and find out if there is potential for RT agriculture in Flanders.

Chapter 2 gives the general characteristics, crop rotation, tillage and manure application of the selected fields while chapter 3 focuses on the short and long term effects of RT agriculture on the physical soil properties. The objective was to evaluate the aggregate stability and infiltration rate to investigate the effect of RT agriculture on the potential of runoff and erosion, while the water retention curve (WRC) and penetration resistance (PR) were determined with the objective to find out if the soil structure and potential for water stockage are optimal for root and crop growth under RT agriculture.

The different components of the C and N cycle under CT and RT agriculture of Western European fields were studied in detail. In the past, researchers often concluded that the SOC and N stock under RT agriculture was higher than under

CT agriculture (Alvarez, 2005). However, this conclusion was mostly based on shallow measurements of % SOC and N in the upper layers of cereals and soybean fields. OC and N are present in soil fractions with different physical and biological relevance. RT agriculture can change the ratio of OC and N in these different fractions compared to CT agriculture and this can also affect the C and N mineralization.

The objectives of chapter 4 and 5 were to search for the answers to the following questions:

- Is there an increase in stratification and SOC and N stock under RT compared to CT agriculture for the Western European crop and weather conditions?
- Is there a difference in C and N mineralization rate between RT and CT fields and how would the C and N mineralization be affected by intensive tillage of RT fields?
- Does the shift of management to RT agriculture effect the distribution of the storage of C and N over the soil fractions with different physical and biological relevance?

With respect to N use efficiency but also because N_2O is a greenhouse gas and affects the stratospheric ozone layer, it is necessary to know the effect of RT agriculture on the N_2O emissions (Hofman & Van Cleemput, 2001). Some researches indicate higher N_2O losses (Fan *et al.*, 1997; Ball *et al.*, 1999; Choudhary *et al.*, 2002), while other researches showed lower annual N_2O emissions under RT compared to CT agriculture (Kessavalou *et al.*, 1998). These contradictory results indicate the necessity of research of the N_2O emissions under the specific Western European crop and weather conditions, which was in the objective of chapter 6.

Whether there is a potential for RT agriculture in Flanders also depends on other factors than the physical and chemical soil properties. Therefore, we combined data from literature and experiences from RT farmers concerning yields, overall C and N dynamics, control of weeds, diseases and pests and economics with the effects on the physical and chemical soil properties measured in this study in order to put our results in a wider perspective and to conclude whether there is potential for RT agriculture in Flanders (chapter 7).

UNDER RT AGRICULTURE SINCE 2003

Heestert: field 3
Photo of June 2005:
sugar beets with winter wheat/
mustard (*Sinapis alba* L.) residues

UNDER RT AGRICULTURE SINCE 2000

Kluisbergen: field 5
Photo of December 2005:
fodder maize residues

Baugnies: field 7
Photo of October 2004:
winter oat (*Avena sativa* L.) (green manure)
with winter wheat (*Triticum aestivum* L.) residues

UNDER RT AGRICULTURE SINCE 1995

Maulde: field 9
Photo of June 2005:
sugar beets

Villers-le-Bouillet: field 11
Photo of May 2006:
winter barley (*Hordeum vulgare* L.)
with winter wheat residues

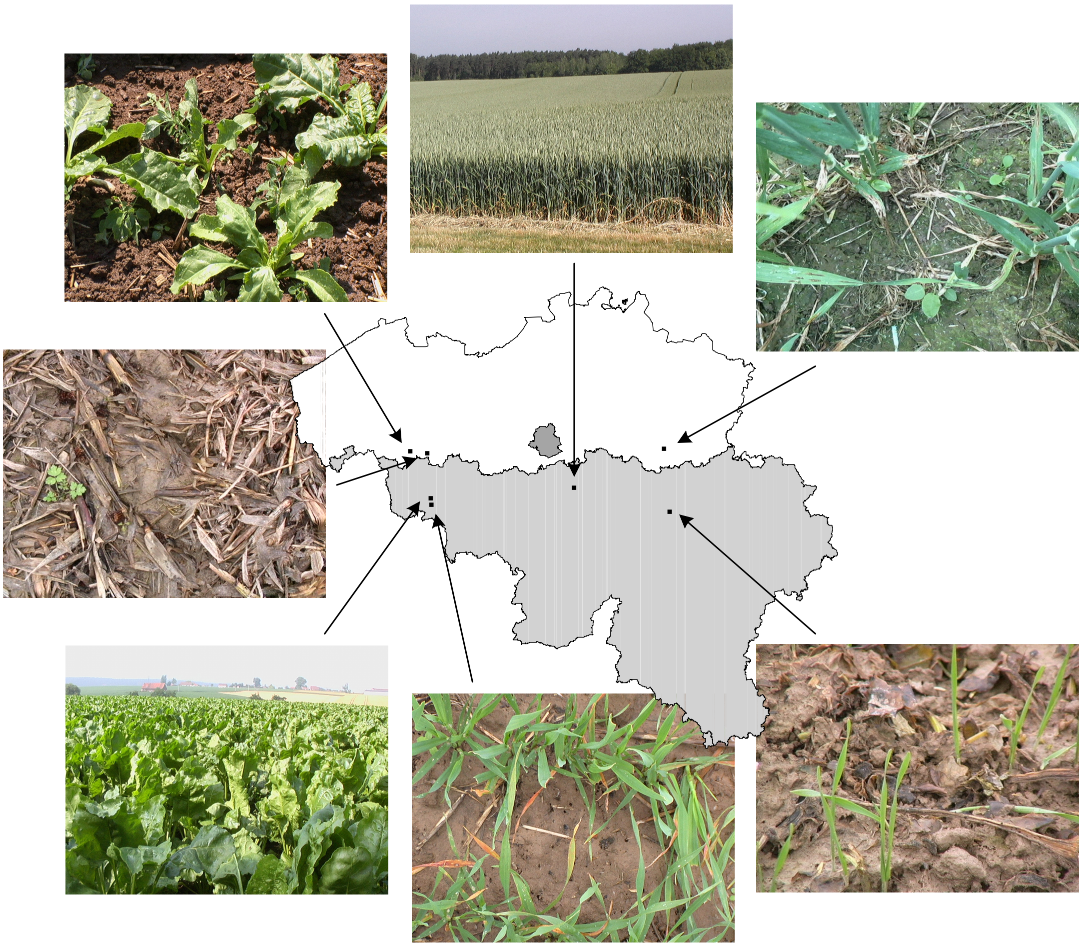
Kuttekoven: field 15
Photo of December 2005:
winter wheat with sugar beet residues

UNDER RT AGRICULTURE SINCE 1985

Court-Saint-Etienne: field 17
Photo of June 2005:
winter wheat

Chapter 2:

Selection of fields



2.1. INTRODUCTION

The soil of the upper 25 to 30 cm depth layer of fields under CT agriculture is in general inverted and mixed with the crop residues with a mouldboard plough. Depending on the crop residues and rotation and the application of organic manure ploughing of CT fields is combined with cultivating and/or harrowing. Two types of RT agriculture, namely RT_C and RT_{DD} agriculture, are practised in Belgium. However, many variants exist in these two main RT types. Different types of cultivators and soil looseners, not inverting the soil, are used in combination with harrows/cultivators. The solid tines of the soil loosener are spaced apart, more solid and longer than the cultivator making a deeper loosening of the soil possible.

Independent of the CsT type, two options are possible, namely with or without green manure. Growing green manure includes if desired removing the stubble and loosening the soil, sowing the green manure, destroying the green manure before possibly preparing the seedbed and sowing the crop. The combination of RT and green manure makes it possible to preserve the residues of the crops and green manure long on the soil surface (Vandergeten & Roisin, 2004).

At present, RT agriculture is being promoted strongly in Western Europe and Belgium, because of its proven effects on reduction of soil erosion by water (see 1.2.6). However, very little information is available on the evolution of important soil properties e.g. related to C and N dynamics in RT agriculture under the specific Western European climatic and soil conditions. In the study area, very little experimental sites exist where CT practices are compared to RT practices. Therefore, we had no choice but to include farmers' fields, where inevitably there is no perfect match between CT and RT fields. However, in the selection of the fields much care was taken to select paired fields which were similar from a soil type and management point of view. It was not possible to find short and long term RT fields which had exactly the same soil type, crop rotation and manure application as CT fields in the same area. Obviously some practices such as maintaining crop residues on the field are an inherent characteristic of RT agriculture which will result in more OC input, but it is not possible and not even desirable to separate these effects, as this would not be according to the common agricultural practices of RT and CT fields.

2.2. SELECTED FIELDS AND GENERAL SOIL AND CROP DATA

Eighteen fields with a silt loam texture were selected. They include the different RT types running for a different number of years, and were paired to fields under CT agriculture with comparable soil type and crop rotation. Our research sites are situated in the loess belt of central Belgium. Fields 1-6 and 15-16 are located in Flanders (northern part of Belgium) and fields 7-14 and 17-18 are located in Wallonia (southern part of Belgium) (Figure 2.1).

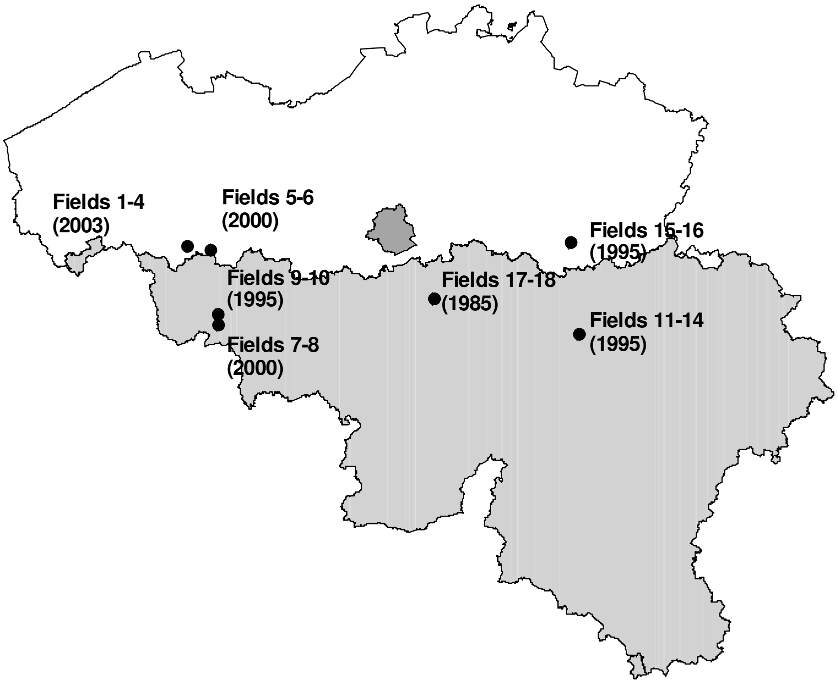


Figure 2.1 Location of the selected fields in Belgium (between brackets year of shift of management reduced tillage)

In central Belgium the 30 year average precipitation is 780 mm y^{-1} and average yearly temperature is 9.8 °C. However, significant deviations from the long term average rainfall (690 mm in 2003 and 914 mm in 2004) and temperature (11.1 °C in 2003, 10.7 °C in 2004 and 11.0 °C in 2005) have been observed in recent years (KMI, 2007). The temperate maritime climate has mild winters and cool summers.

In each field three plots of 150 m^2 (10 m x 15 m) with a distance of 10 meters between them were selected (Figure 2.2). To avoid effects from the edges, plots were located at least 20 meters from the edges of the fields. On the sloping fields the plots of the RT and CT field were located at the same slope position.

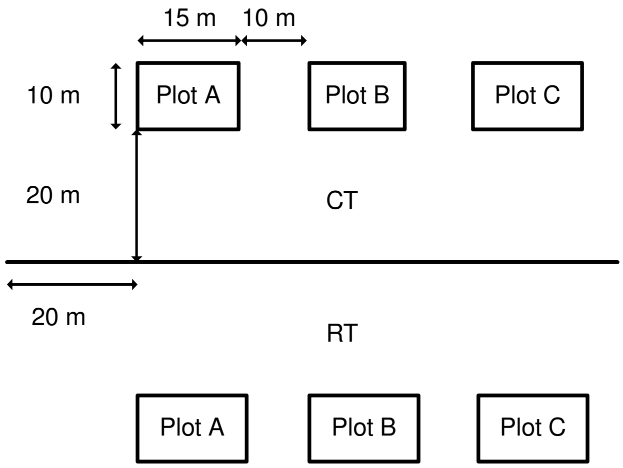


Figure 2.2 Lay-out of the plots in the fields

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 layer per plot 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 potassium chloride (KCl) (1:2.5 soil weight (g): extractant volume (ml)) suspension using a glass electrode.
Soil texture was determined per layer on a mixed soil sample of the three plots by the combined sieve and pipette method (De Leenheer, 1959).

The location, management (RT_C, RT_{DD} or CT agriculture), slope and granulometric composition, pH_{KCl} of the 0-10 cm depth layer of the 18 selected fields are given in Table 2.1. The period of RT agriculture (in years) is indicated in subscript. However, an extra year has to be added in chapter 6 and 7 because the soil samples were taken a year later. The granulometric composition and pH_{KCl} of the 0-20, 20-30 and 30-40 cm depth layer of the 18 selected fields are given in Appendix I - Table I.1.

The amount, effective organic carbon (EOC), i.e. the amount of organic carbon that remains in the soil one year after the application (Hénin & Dupuis, 1945; Vleeshouwers & Verhagen 2002; De Neve *et al.*, 2003; Mulier *et al.*, 2006; Tirez, 2007), of main crop residues, green manure and organic manure under the Belgian soil and weather conditions, and total nitrogen (TN) of these residues and manures during the period 2002-2005 of the selected fields were calculated (Hofman *et al.*, 1995; Anonymous, 2002a, b & c; Sleutel *et al.*, 2007a) (Table 2.3, Table 2.5, Table 2.7, Table 2.9, Table 2.12, Table 2.13 and Table 2.15).

Table 2.1 Location, management (reduced tillage with cultivator or soil loosener (RT_{C}), reduced tillage by direct drilling ($\mathrm{RT}_{\mathrm{DD}}$) or conventional tillage (CT) agriculture), period of RT agriculture, slope and granulometric composition and $\mathrm{pH}_{\mathrm{KCl}}$ (with standard deviation between brackets) of the 0-10 cm depth layer of the 18 selected fields

Location	Field	Management	RT since	Slope (%)	Clay (%)	Loam (%)	Sand (%)	$\mathrm{pH}_{\mathrm{KCl}}$
Heestert	1	RT_{C}	2003	3	13.5	52.6	33.9	7.0 (0.3)
	2	RT_{C}	2003	3	12.4	53.7	33.9	6.5 (0.2)
	3	RT_{C}	2003	3	12.1	59.9	28.0	6.6 (0.5)
	4	CT	/	3	12.7	54.4	32.9	6.5 (0.8)
Kluisbergen	5	RT_{C}	2000	10	18.1	51.6	30.3	6.5 (0.0)
	6	CT	/	10	16.4	56.0	27.6	5.6 (0.3)
Baugnies	7	RT_{C}	2000	0	10.6	59.0	30.4	7.3 (0.2)
	8	CT	/	0	11.1	59.6	29.3	6.7 (0.2)
Maulde	9	RT_{C}	1995	0	20.6	70.9	8.5	6.1 (0.1)
	10	CT	/	0	13.9	77.6	8.5	5.7 (0.1)
Villers-le-Bouillet	11	$\mathrm{RT}_{\mathrm{DD}}$	1995	0	19.8	72.2	7.9	6.5 (0.2)
	12	CT	/	0	18.9	75.4	5.7	6.6 (0.1)
	13	$\mathrm{RT}_{\mathrm{DD}}$	1995	0	16.7	77.2	6.1	6.5 (0.1)
	14	CT	/	0	16.2	74.6	9.4	5.8 (0.1)
Kuttekoven	15	$\mathrm{RT}_{\mathrm{DD}}$	1995	0	15.5	71.7	12.8	5.7 (0.1)
	16	CT	/	0	17.4	71.5	11.1	6.4 (0.2)
Court-Saint-Etienne	17	RT_{C}	1985	0	14.7	71.5	13.8	6.4 (0.2)
	18	CT	/	0	16.0	75.7	8.2	6.0 (0.3)

In Heestert (50°48’ N; 3°25’ E), an experiment was started in 2003 to study the effect of RT agriculture on soil losses by erosion, where different RT types were compared to CT agriculture (Table 2.2). Before sowing the main crop, the soil of fields 1-4 was 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 (Figure 2.3). The seedbed of RT_{C_2} field 1 was prepared by harrowing (Figure 2.4). RT_{C_2} fields 2 and 3 were worked to a depth of 15-20 cm with a soil loosener (working width of 3 m) with one row of four tines ending in a share sweep (width of 65 cm and set at 70 cm apart) and share sweep with a five-pronged horizontal fork (width of 60 cm and set at 80 cm apart) (D’Haene *et al.*, 2006), respectively, followed by a secondary tillage with a tine harrow (Figure 2.4).

Table 2.2 Type and depth of tillage operations (successive tillage operations are given per row) of 2002-2005 of fields 1-4 in Heestert

Field	Tillage (depth in cm)				Time*
1 RT_{C_2}	cultivator (10-15)	tine harrow (5)	tine harrow (5)		2002_{S}, $2003_{S,A}$, 2005_{A}
	rotary harrow (5)				$2004_{A}^{\dagger}$
	cultivator (10-15)	rotary harrow (5)			2005_{S}
2 & 3 RT_{C_2}	cultivator (10-15)	soil loosener (15-20)	tine harrow (5)	tine harrow (5)	2002_{S}, 2003_{S}
	soil loosener (15-20)	tine harrow (5)	tine harrow (5)		2003_{A}, 2005_{A}
	rotary harrow (5)				$2004_{A}^{\dagger}$
	soil loosener (15-20)	rotary harrow (5)			2005_{S}
4 CT	cultivator (10-15)	plough (25-30)	tine harrow (5)	tine harrow (5)	2002_{S}, 2003_{S}
	plough (25-30)	tine harrow (5)	tine harrow (5)		2003_{A}, 2005_{A}
	rotary harrow (5)				$2004_{A}^{\dagger}$
	plough (25-30)	cultivator (10-15)	rotary harrow (5)		2005_{S}

RT_{C_2}: under 2 years of reduced tillage with cultivator or soil loosener; CT: conventional tillage
*: $_{S}$: spring (March – May) tillage operation; $_{A}$: autumn (Aug. – Nov.) tillage operation, $_{W}$: winter (Dec. - Febr.) tillage operation, †: tillage operation before green manure

Field 4 was conventionally ploughed to a depth of 25-30 cm, followed by a secondary tillage with a tine harrow. The crop rotation and manure application were the same for the four fields (Table 2.3)

Figure 2.3 The cultivator used in field 1 in Heestert (photo Proclam)

Figure 2.4 The soil loosener used in field 2 (A) and 3 (B) in Heestert (photo Proclam)

Table 2.3 Amount of dry matter (DM), effective organic carbon (EOC) and total nitrogen (TN) content of crop residues and organic manure application of 2002-2005 on fields 1-4 in Heestert

Year	Crop (type of residue)/ Manure application	DM (Mg ha^{-1})	EOC* (kg ha^{-1})	TN (kg ha^{-1})
2002	maize (fodder) (stubble)	3.4	350	25
	cattle stable manure (40 Mg ha^{-1})	9.6	1540	195
2003	maize (fodder) (stubble)	3.4	350	25
	cattle stable manure (40 Mg ha^{-1})	9.6	1540	195
2004	winter wheat (stubble)	5.4	750	30
2005	mustard†	4.1	425	90
	sugar beet (heads + leaves)	7.0	575	160

maize: *Zea mays* ssp. *Mays* L.; winter wheat: *Triticum aestivum* L.; mustard: *Sinapis alba* L.; sugar beet: *Beta vulgaris* L.

†: green manure

*EOC: amount of organic carbon that is still in the soil one year after application

The main tillage operation of field 5 with monoculture maize under 5 years RT (RT$_{C\_5}$) agriculture in Kluisbergen (50°46’ N; 3°29’ E) was done to a depth of 30-35 cm in the spring with a soil loosener with one row of four tines ending in a chisel. The main tillage operation of the adjacent field 6 was ploughing to a depth of 25-30 cm (Table 2.4). Table 2.5 gives the amount, EOC and TN of the crop residues and manure application of these fields in 2002-2005.

Table 2.4 Type and depth of tillage operations (successive tillage operations are given per row) of 2002-2005 of fields 5 and 6 in Kluisbergen

Field	Tillage (depth in cm)				Time*
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}, 2004_{S}, 2005_{A}
	plough (25-30)	cultivator (10)	rotary harrow (5)		2005_{S}

RT$_{C\_5}$: under 5 years of reduced tillage with soil loosener; CT: conventional tillage

*: $_{S}$: spring (March - May) tillage operation; $_{A}$: autumn (Aug. - Nov.) tillage operation, $_{W}$: winter (Dec. - Febr.) tillage operation, †: tillage operation before green manure

Table 2.5 Amount of dry matter (DM), effective organic carbon (EOC) and total nitrogen (TN) content of crop residues and organic manure application of 2002-2005 on fields 5 and 6 in Kluisbergen

Field	Year	Crop (type of residue)/ Manure application	DM ($Mg\ ha^{-1}$)	EOC* ($kg\ ha^{-1}$)	TN ($kg\ ha^{-1}$)
5 RT_{C_5}	2002	maize (grain) (stubble)	8.0	1225	135
		pig slurry (20 $Mg\ ha^{-1}$)	1.8	270	155
	2003	maize (grain) (stubble)	8.0	1225	135
		pig slurry (20 $Mg\ ha^{-1}$)	1.8	270	155
	2004	maize (grain) (stubble)	8.0	1225	135
		pig slurry (20 $Mg\ ha^{-1}$)	1.8	270	155
	2005	maize (grain) (stubble)	8.0	1225	135
		pig slurry (20 $Mg\ ha^{-1}$)	1.8	270	155
6 CT	2002	maize (fodder) (stubble)	3.4	350	25
		pig slurry (25 $Mg\ ha^{-1}$)	2.3	340	195
	2003	maize (fodder) (stubble)	3.4	350	25
		pig slurry (25 $Mg\ ha^{-1}$)	2.3	340	195
	2004	potatoes (leaves)	2.1	425	20
		pig slurry (25 $Mg\ ha^{-1}$)	2.3	340	195
	2005	maize (fodder) (stubble)	3.4	350	25
		pig slurry (25 $Mg\ ha^{-1}$)	2.3	340	195

RT_{C_5}: under 5 years of reduced tillage with soil loosener; CT: conventional tillage
maize: *Zea mays* ssp. Mays L.; potatoes: *Solanum tuberosum* L.
*EOC: amount of organic carbon that is still in the soil one year after application

Fields 7 and 8 were located in Baugnies (50°33' N; 3°33' E). The tillage operations of RT_{C_5} field 7 were depended on the preceding and following crop. The deepest tillage operation during the period 2002-2005 was done to a depth of 35 cm with a cultivator (working width of 5 m) with three rows of five tines ending in a duckfoot sweep (width of 12 cm and set at 95 cm apart) (Figure 2.5). The most common tillage operation of field 8 was ploughing in autumn to a depth of 30 cm (Table 2.6). The amount, EOC and TN of the crop residues and manure application of these fields in 2002-2005 are given in Table 2.7.

Table 2.6 Type and depth of tillage operations (successive tillage operations are given per row) of 2002-2005 of fields 7 and 8 in Baugnies

Field	Tillage (depth in cm)				Time*
7 RT$_{C\_5}$	cultivator (25)	cultivator (25)	rotary harrow (5)		2002_S
	cultivator (10)	cultivator (35)	rotary harrow (5)		$2002_A^{\dagger}$
	cultivator (5)	cultivator (15)	rotary harrow (5)		2003_S, 2005_S
	cultivator (15)	cultivator (15)			2003_A, $2005_A^{\dagger}$
	cultivator (25)	rotary harrow (5)			$2004_A^{\dagger}$
8 CT	cultivator (10)	plough (30)	cultivator (10)	rotary harrow (5)	2002_A, 2003_A, 2004_A, 2005_A

RT$_{C\_5}$: under 5 years of reduced tillage with cultivator; CT: conventional tillage

*: $_S$: spring (March - May) tillage operation; $_A$: autumn (Aug. - Nov.) tillage operation, $_W$: winter (Dec. - Febr.) tillage operation, †: tillage operation before green manure

Figure 2.5 The cultivator used in field 7 in Baugnies

Table 2.7 Amount of dry matter (DM), effective organic carbon (EOC) and total nitrogen (TN) content of crop residues and organic manure application of 2002-2005 on fields 7 and 8 in Baugnies

Field	year	Crop (type of residue)/ Manure application	DM ($Mg\ ha^{-1}$)	EOC* ($kg\ ha^{-1}$)	TN ($kg\ ha^{-1}$)
7 RT_{C_5}	2002	maize (fodder) (stubble)	3.4	350	25
		cattle horse compost (20 $Mg\ ha^{-1}$)	10.2	1710	165
	2003	winter rye†	1.9	325	80
		sugar beet (heads + leaves)	7.0	575	160
		green compost (15 $Mg\ ha^{-1}$)	7.7	1280	70
	2004	winter wheat (stubble)	5.4	750	30
		cattle horse manure (25 $Mg\ ha^{-1}$)	6.0	960	210
	2005	winter oat †	1.9	325	80
		potatoes (leaves)	2.1	440	20
8 CT	2002	winter wheat (stubble)	5.4	750	30
		cattle stable manure (20 $Mg\ ha^{-1}$)	4.8	770	155
	2003	triticale (stubble)	5.4	750	30
		cattle stable manure (20 $Mg\ ha^{-1}$)	4.8	770	155
	2004	winter barley (stubble)	5.4	750	30
		cattle stable manure (15 $Mg\ ha^{-1}$)	3.6	580	115
	2005	maize (fodder) (stubble)	3.4	350	25

RT_{C_5}: under 5 years of reduced tillage with cultivator; CT: conventional tillage

maize: *Zea mays* ssp. *Mays* L.; winter rye: *Secale cereale* L.; sugar beet: *Beta vulgaris* L.; winter wheat: *Triticum aestivum* L.; winter oat: *Avena sativa* L.; potatoes: *Solanum tuberosum* L.; triticale: *X Triticosecale*; winter barley: *Hordeum vulgare* L.

†: green manure

*EOC: amount of organic carbon that is still in the soil one year after application

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 (Table 2.8). Field 9 was under RT_C agriculture since 1995 (Table 2.9).

Table 2.8 Type and depth of tillage operations (successive tillage operations are given per row) of 2002-2005 of fields 9 and 10 in Maulde

Field	Tillage (depth in cm)				Time*
9 RT$_{C\_10}$	cultivator (10)	rotary harrow (5)			2002 $_{S}$, 2004 $_{A}^{\dagger}$, 2005 $_{S}$
	cultivator (10)	soil loosener (20)	rotary harrow (5)		2002 $_{A}$, 2005 $_{A}^{\dagger}$
	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 $_{S}$, 2005 $_{S}$

RT$_{C\_10}$: under 10 years of reduced tillage with soil loosener; CT: conventional tillage
*: $_{S}$: spring (March - May) tillage operation; $_{A}$: autumn (Aug. - Nov.) tillage operation, $_{W}$: winter (Dec. - Febr.) tillage operation, †: tillage operation before green manure

Table 2.9 Amount of dry matter (DM), effective organic carbon (EOC) and total nitrogen (TN) content of crop residues and organic manure application of 2002-2005 on fields 9 and 10 in Maulde

Field	Year	Crop (type of residue)/ Manure application	DM (Mg ha^{-1})	EOC* (kg ha^{-1})	TN (kg ha^{-1})
9 RT$_{C\_10}$	2002	peas (stubble + straw)	6.0	500	180
	2003	winter wheat (stubble)	5.4	750	30
		winter wheat (straw)	4.7	650	40
	2004	winter wheat (stubble)	5.4	750	30
		winter wheat (straw)	4.7	650	40
	2005	mustard†	4.1	425	90
		sugar beet (heads + leaves)	7.0	575	160
10 CT	2002	sugar beet (heads + leaves)	7.0	575	160
	2003	maize (fodder) (stubble)	3.4	350	25
	2004	maize (fodder) (stubble)	3.4	350	25
		cattle stable manure (45 Mg ha^{-1})	10.8	1730	375
	2005	maize (fodder) (stubble)	3.4	350	25

RT$_{C\_10}$: under 10 years of reduced tillage with soil loosener; CT: conventional tillage
peas: *Pisum sativum* L.; winter wheat: *Triticum aestivum* L.; mustard: *Sinapis alba* L.; sugar beet: *Beta vulgaris* L.; maize: *Zea mays* ssp. *Mays* L.
†: green manure
*EOC: amount of organic carbon that is still in the soil one year after application

Fields 11-14 were 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 loosened with a cultivator (chisel) and from 2001 onwards they were under RT$_{DD}$ agriculture (RT$_{DD\_10}$). The main tillage operation of fields 12, 14 and 16 was ploughing (Table 2.10 and Table 2.11). On fields 11-16 two years of cereals are followed by sugar beets or potatoes (Table 2.12 and Table 2.13).

Table 2.10 Type and depth of tillage operations (successive tillage operations are given per row) of 2002-2005 of fields 11-14 in Villers-le-Bouillet

Field	Tillage (depth in cm)				Time*
11 RT$_{DD\_10}$	rotary harrow (5)				2002 $_{A}$, 2003 $_{A}^{\dagger}$, 2005 $_{A}$
12 CT	plough (25-30)	rotary harrow (5)			2002 $_{A}^{\dagger}$, 2003 $_{S, A}$
	soil loosener (25-30)	rotary harrow (5)			2004 $_{A}^{\dagger}$, 2005 $_{A}$
	rotary harrow (5)				2005 $_{S}$
13 RT$_{DD\_10}$	rotary harrow (5)				2002 $_{A}$, 2003 $_{A}^{\dagger}$, 2005 $_{A}$
14 CT	plough (25-30)	cultivator (10)	rotary harrow (5)		2002 $_{A}$, 2004 $_{A}$, 2005 $_{A}$
	cultivator (10)	plough (25-30)	cultivator (10)	rotary harrow (5)	2004 $_{S}$

RT$_{DD\_10}$: under 10 years of reduced tillage by direct drilling; CT: conventional tillage

*: $_{S}$: spring (March - May) tillage operation; $_{A}$: autumn (Aug. - Nov.) tillage operation, $_{W}$: winter (Dec. - Febr.) tillage operation, †: tillage operation before green manure

Table 2.11 Type and depth of tillage operations (successive tillage operations are given per row) of 2002-2005 of fields 15 and 16 in Kuttekoven

Field	Tillage (depth in cm)			Time*
15 RT_{DD_10}	rotary harrow (5)			2003 $_{A}$, 2004 $_{A}^{\dagger}$
16 CT	plough (20-25)	cultivator (10)	tine harrow (5)	2002 $_{W}$, 2005 $_{W}$
	plough (20-25)	tine harrow (5)		2002 $_{A}$, 2003 $_{A}$, 2005 $_{A}$
	cultivator (10)			2004 $_{A}^{\dagger}$

RT_{DD_10}: under 10 years of reduced tillage by direct drilling; CT: conventional tillage
*: $_{S}$: spring (March - May) tillage operation; $_{A}$: autumn (Aug. - Nov.) tillage operation, $_{W}$: winter (Dec. - Febr.) tillage operation, †: tillage operation before green manure

Table 2.12 Amount of dry matter (DM), effective organic carbon (EOC) and total nitrogen (TN) content of crop residues and organic manure application of 2002-2005 on fields 11-14 in Villers-le-Bouillet

Field	year	Crop (type of residue)/ Manure application	DM (Mg ha^{-1})	EOC* (kg ha^{-1})	TN (kg ha^{-1})
11	2002	winter wheat (stubble)	5.4	750	30
RT_{DD_10}		winter wheat (straw)	4.7	650	40
	2003	winter barley (stubble)	5.4	750	30
		winter barley (straw)	4.7	650	40
	2004	rapeseed†	4.1	425	90
		sugar beet (heads + leaves)	7.0	575	160
		cattle stable manure (25 Mg ha^{-1})	6.0	960	210
	2005	winter wheat (stubble)	5.4	750	30
		winter wheat (straw)	4.7	650	40
12	2002	winter wheat (stubble)	5.4	750	30
CT	2003	phacelia†	4.1	350	90
		sugar beet (heads + leaves)	7.0	575	160
	2004	winter wheat (stubble)	5.4	750	30
	2005	phacelia†	4.1	350	90
		maize (fodder) (stubble)	3.4	350	25

RT_{DD_10}: under 10 years of reduced tillage by direct drilling; CT: conventional tillage
winter wheat: *Triticum aestivum* L.; winter barley: *Hordeum vulgare* L.; rapeseed: *Brassica rapa* L.; sugar beet: *Beta vulgaris* L.; phacelia: *Phacalia tanacetifolia* L.; maize: *Zea mays* ssp. *Mays* L.;
†: green manure; *EOC: amount of organic carbon that is still in the soil one year after application

Table 2.12 Amount of dry matter (DM), effective organic carbon (EOC) and total nitrogen (TN) content of crop residues and organic manure application of 2002-2005 on fields 11-14 in Villers-le-Bouillet

Field	year	Crop (type of residue)/ Manure application	DM ($Mg\ ha^{-1}$)	EOC* ($kg\ ha^{-1}$)	TN ($kg\ ha^{-1}$)
13	2002	winter wheat (stubble)	5.4	750	30
RT_{DD_10}		winter wheat (straw)	4.7	650	40
	2003	winter barley (stubble)	5.4	750	30
		winter barley (straw)	4.7	650	40
	2004	rapeseed †	4.1	425	90
		potatoes (leaves)	2.1	440	20
		cattle stable manure (25 $Mg\ ha^{-1}$)	6.0	960	210
	2005	winter wheat (stubble)	5.4	750	30
		winter wheat (straw)	4.7	650	40
14 CT	2002	winter wheat (stubble)	5.4	750	30
	2003	winter barley (stubble)	5.4	750	30
	2004	potatoes (leaves)	2.1	440	20
		cattle stable manure (25 $Mg\ ha^{-1}$)	6.0	960	210
	2005	winter wheat (stubble)	5.4	750	30

RT_{DD_10}: under 10 years of reduced tillage by direct drilling; CT: conventional tillage

winter wheat: *Triticum aestivum* L.; winter barley: *Hordeum vulgare* L.; rapeseed: *Brassica rapa* L.; potatoes: *Solanum tuberosum* L.

†: green manure

*EOC: amount of organic carbon that is still in the soil one year after the application

Table 2.13 Amount of dry matter (DM), effective organic carbon (EOC) and total nitrogen (TN) content of crop residues and organic manure application of 2002-2005 on fields 15 and 16 in Kuttekoven

Field	year	Crop (type of residue)/ Manure application	DM ($Mg\ ha^{-1}$)	EOC* ($kg\ ha^{-1}$)	TN ($kg\ ha^{-1}$)
15	2002	rapeseed[†]	4.1	425	90
RT_{DD_10}		sugar beet (heads + leaves)	7.0	575	160
		cattle stable manure (25 $Mg\ ha^{-1}$)	6.0	960	210
	2003	winter wheat (stubble)	5.4	750	30
		winter wheat (straw)	4.7	650	40
	2004	winter barley (stubble)	5.4	750	30
		winter barley (straw)	4.7	650	40
	2005	rapeseed[†]	4.1	425	90
		sugar beet (heads + leaves)	7.0	575	160
		cattle stable manure (25 $Mg\ ha^{-1}$)	6.0	960	210
16	2002	mustard[†]	4.1	425	90
CT		sugar beet (heads + leaves)	7.0	575	160
		cattle stable manure (25 $Mg\ ha^{-1}$)	6.0	960	210
	2003	winter wheat (stubble)	5.4	750	30
	2004	winter barley (stubble)	5.4	750	30
	2005	mustard[†]	4.1	425	90
		sugar beet (heads + leaves)	7.0	575	160
		cattle stable manure (25 $Mg\ ha^{-1}$)	6.0	960	210

RT_{DD_10}: under 10 years of reduced tillage by direct drilling; CT: conventional tillage
rapeseed: *Brassica rapa* L.; sugar beet: *Beta vulgaris* L.; winter wheat: *Triticum aestivum* L.; winter barley: *Hordeum vulgare* L.; mustard: *Sinapis alba* L.
[†]: green manure
*EOC: amount of organic carbon that is still in the soil one year after application

Fields 17 and 18 were located in Court-Saint-Etienne (50°38’ N; 4°34’ E). RT_{C_20} field 17 was under RT agriculture for 20 years. The deepest tillage operation to a depth of 25 cm was done in the autumn with a soil loosener (working width of 3 m) with one row of four tines ending in a share-and-point sweep (width 60 cm and set at 70 cm apart) (Figure 2.6). Field 18 was conventionally ploughed to a depth of 25 cm every 2 years in the winter before the sugar beets (Table 2.14). These fields have a 2 year sugar beet - winter wheat / mustard crop rotation (Table 2.15)

Figure 2.6 The soil loosener used in field 17 in Court-Saint-Etienne.

Table 2.14 Type and depth of tillage operations (successive tillage operations are given per row) of 2002-2005 of fields 17 and 18 in Court-Saint-Etienne

Field	Tillage (depth in cm)				Time*
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 (5)	2003$_{A}^{\dagger}$, 2005$_{A}^{\dagger}$
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$_{A}^{\dagger}$, 2005$_{A}^{\dagger}$

RT$_{C\_20}$: under 20 years of reduced tillage with soil loosener; CT: conventional tillage
*: $_{S}$: spring (March – May) tillage operation; $_{A}$: autumn (Aug. – Nov.) tillage operation, $_{W}$: winter (Dec. - Febr.) tillage operation, †: tillage operation before green manure

Table 2.15 Amount of dry matter (DM), effective organic carbon (EOC) and total nitrogen (TN) content of crop residues and organic manure application of 2002-2005 on fields 17 and 18 in Court-Saint-Etienne

Field	year	Crop (type of residue)/ Manure application	DM ($Mg\ ha^{-1}$)	EOC* ($kg\ ha^{-1}$)	TN ($kg\ ha^{-1}$)
17	2002	mustard†	4.1	425	90
RT_{C_20}		sugar beet (heads + leaves)	7.0	575	160
	2003	winter wheat (stubble)	5.4	750	30
		winter wheat (straw)	4.7	650	40
		cattle stable manure (30 $Mg\ ha^{-1}$)	7.2	1160	250
	2004	mustard†	4.1	425	90
		sugar beet (heads + leaves)	7.0	575	160
	2005	winter wheat (stubble)	5.4	750	30
		winter wheat (straw)	4.7	650	40
		chicken manure (7 $Mg\ ha^{-1}$)	3.5	800	235
18	2002	mustard†	4.1	425	90
CT		sugar beet (heads + leaves)	7.0	575	160
	2003	winter wheat (stubble)	5.4	750	30
		cattle stable manure (40 $Mg\ ha^{-1}$)	9.6	1540	330
	2004	mustard†	4.1	425	90
		sugar beet (heads + leaves)	7.0	575	160
	2005	winter wheat (stubble)	5.4	750	30
		cattle stable manure (30 $Mg\ ha^{-1}$)	7.2	1160	250

RT_{C_20}: under 20 years of reduced tillage with cultivator or soil loosener; CT: conventional tillage

mustard: *Sinapis alba* L.; sugar beet: *Beta vulgaris* L.; winter wheat: *Triticum aestivum* L.

†: green manure

*: amount of organic carbon that is still in the soil one year after application

Chapter 3:

The effect of reduced tillage agriculture on physical soil properties of silt loam soils

HEESTERT:
FIELD 2 WITH WINTER WHEAT STUBBLE IN SEPTEMBER 2006

LEFT: HAND PENETROLOGGER
RIGHT: AUTOMATED PENETROLOGGER

Modified from:

D'Haene, K., Vermang, J., Cornelis, W.M., Leroy, B.L.M., Schiettecatte, W., De Neve, S., Gabriels, D., Hofman, G. Reduced tillage effects on the physical properties of silt loam soils growing root crops. Soil Till. Res., submitted.

3.1. ABSTRACT

Crop rotations in Western Europe often include beets and potatoes, which are generally assumed to be less suitable under RT agriculture because they result in a high disturbance of the soil at the formation of the ridges and at harvest. Nevertheless, in the scope of the increasing concern for soil conservation, RT agriculture is growing more important in today's agriculture. Therefore, the short and long term effect of RT agriculture on BD, WRC, aggregate stability, field-saturated hydraulic conductivity (K_{fs}) and PR of silt loam soils with crop rotations including root and tuber crops was evaluated. Ten fields at seven locations representing the important RT types, applied for a different number of years, and eight fields under CT agriculture with comparable soil type and crop rotation were selected.

At each location, BD of the 5-10 cm depth layer was mostly lower in the RT fields (1.42±0.05 Mg m^{-3} [average with standard deviation]) compared to the CT fields (1.44±0.09 Mg m^{-3}) and the water content at saturation was mostly higher (0.394±0.027 m^3 m^{-3} and 0.382±0.021 m^3 m^{-3} for RT and CT fields, respectively). No differences in BD (1.53±0.03 Mg m^{-3}) or WRC could be found in the 25-30 cm depth layer when comparing the RT with the CT fields. The PR of the RT_{DD} fields was higher in the upper 10-30 cm depth layer compared to CT fields but was only higher in the 20-30 cm depth layer of RT_C fields compared to the CT fields if the working depth was lower under RT_C than CT agriculture. However, no change in PR in the 30-60 cm depth layer could be determined for the RT_C or RT_{DD} compared to CT fields. The stability index of the 0-10 cm layer measured by the 'dry and wet sieving' method of De Leenheer and De Boodt (1959) was 40% higher under RT than CT agriculture. The mean weight diameter (MWD) measured with the three methods of Le Bissonnais (1996) was significantly higher even after short term RT compared to CT agriculture i.e. the MWD after a heavy shower, a slow wetting of the soil and stirring the soil after prewetting was 19%, 38% and 34% higher for RT than CT fields, respectively. The K_{fs} tended to be higher under RT compared to the CT fields. Despite the high disturbance of the soil every 2 or 3 years of crop rotations including sugar beets or potatoes, RT agriculture had a positive effect on the investigated physical soil properties.

3.2. INTRODUCTION

One of the most important negative consequences of modern agricultural production is probably the soil physical degradation resulting in erosion and soil compaction, which is attributed to deep and intensive tillage practices (Esteve *et al.*, 2004). Erosion causes financial damage on the farm through the formation of rills and gullies and the washing away of seeds, manure, fertilizers and fertile soil. The yearly erosion from silt loam soils in the hilly areas in Belgium varies between a few to 100 Mg soil ha^{-1} y^{-1} (Verstraeten *et al.*, 2003b). Soil compaction is another process that threatens the agricultural production in some areas. Soil compaction at the soil surface can be remediated by the usual soil tillage, root growth and biological activity. However, deep soil compaction under the plough layer decreases the growth of plants by reducing rooting depth and PASW, often results in a decrease of crop yield (Ide *et al.*, 1984 & 1987; Ide & Hofman, 1990) and is extremely difficult to remediate.

Under RT agriculture, the soil is not inverted and mixed with the crop residues and this seems to profoundly impact many soil properties particularly in the upper depth soil layer. Under a temperate climate most researchers report comparable or higher BD in the 0-5 cm layer of short term (≤11 years) RT fields with cereals and soybean (Angers *et al.*, 1997; Yang & Wander, 1999; Kay & Vanden Bygaart, 2002; Al-Kaisi *et al.*, 2005b; Puget & Lal, 2005), while under long term RT agriculture the BD is comparable or lower than on CT agriculture (Tebrügge & Düring, 1999; Deen & Kataki, 2003; Dolan *et al.*, 2006). In the 5-20 cm depth layer, mostly no differences in BD were measured under short term RT compared to CT fields, while for long term RT fields BD decreased in following order: $RT_{DD} \geq RT_C \geq$ CT agriculture. Deeper in the soil profile, BD was comparable for RT and CT fields (Angers *et al.*, 1997; Tebrügge & Düring, 1999; Yang & Wander, 1999; Kay & Vanden Bygaart, 2002; Deen & Kataki, 2003; Al-Kaisi *et al.*, 2005b; Puget & Lal, 2005; Dolan *et al.*, 2006). Studies by Friedel *et al.* (1996), Hussain *et al.* (1999) and Liebig *et al.* (2004) showed that the aggregate stability of the upper layer of fields with a cereal, maize and soybean crop rotation, increased in RT_C or RT_{DD} compared to CT fields.

In the scope of the increasing concern for soil conservation, RT agriculture is growing more important in today's agriculture in Western Europe although the crop rotations 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 agriculture on BD and aggregate stability of soils with crop rotations including beet and with heavy soil disturbance at harvest, that seem less suitable for RT agriculture.

In their literature review of runoff and erosion during rainfall simulations and natural rainfall under field conditions in temperate climate, Strauss *et al.* (2003) concluded that RT_{DD} agriculture mostly decreased runoff and erosion compared to CT agriculture. Rainfall simulation studies in Flanders showed that runoff and erosion were often lower in RT_C than CT fields (Goyens *et al.*, 2005; Leys *et al.*, 2007 – see 1.2.6). However, RT fields often have a lower field-saturated hydraulic conductivity K_{fs} compared to CT fields. It has been reported that 3 to 18 years after converting from CT to RT_C or RT_{DD} agriculture on loam soils, the K_{fs} was lower or at best comparable under RT_{DD} than RT_C and CT agriculture (Wienhold & Tanaka, 2000; Lipiec *et al.*, 2006; Singh & Malhi, 2006). On the other hand, Liebig *et al.* (2004) reported that after 15 years of RT_{DD} agriculture on a silt loam soil in the Great Plains, K_{fs} was higher than under CT agriculture. Seeing these contrasting results further research on the effect of a conversion from CT to RT agriculture on K_{fs} seems therefore needed.

The objective of this study was to investigate the short and long term effects of RT agriculture on BD, WRC, PR, aggregate stability and field-saturated hydraulic conductivity K_{fs} under the specific Western European climatic and soil conditions and typical rotations including crops which are often assumed to be less suitable for RT agriculture such as beets and potatoes.

3.3. MATERIALS AND METHODS

3.3.1. Soil sampling

BD and WRC were determined in two replicates on undisturbed soil samples taken from the 5-10 and 25-30 cm depth layers of each plot using the core method as described by Cornelis *et al.* (2005). Soil samples for the measurement of the % SOC and TN were taken at the same time. Fields 1-4 were sampled on 3 December 2004, with the mustard crop (green manure) on the fields. Field 5 had maize crop residues whereas field 6 was bare at the time of sampling (10 December 2004). At the time of the sampling, 20 December 2004, field 7 had winter oat (green manure) on the field and field 8 was bare. Field 9 had mustard as green manure whereas field 10 had maize crop residues at sampling (17 March 2005). Fields 11-12 were sampled 9 March 2005 with winter wheat and Phacelia (*Phacelia* L.) (green manure), respectively. Fields 13-14 with winter wheat as crop were sampled 10 March 2005. Fields 15 and 16 were sampled on 11 March 2005. Rapeseed (*Brassica rapa* L.) was grown as green manure on field 15 while field 16 was bare. Fields 17 and 18 were sampled 15 December 2004 with winter wheat as crop.

The PR was measured with a hand digital penetrologger (Eijkelkamp Agrisearch Equipment, the Netherlands) in June - July 2005, one month after the sowing period of beets and maize, in November - December 2005, one month after the harvest of beets and maize, and March - April 2006 after the winter. A fully automated digital penetrologger was used in fields 1-4 in Heestert in September 2006 to have an idea of the 2 dimensional variability of the PR of the soil under RT and CT fields.

Ten samples for aggregate stability were taken per plot from the 0-10 cm depth layer. Fields 1-4 were sampled on 21 June 2005 with sugar beets on the fields. Field 5 and 6 had maize as crop at the time of sampling (21 June 2005). At the time of the sampling, 13 July 2005, field 7 and 8 had potatoes and maize on the field, respectively. Field 9 had sugar beets whereas field 10 had maize as crop at sampling (13 July 2005). Fields 11, 13 and 14 were sampled 18 July 2005 with winter wheat, while field 12 had maize as crop. Fields 15 and 16 were sampled with sugar beets on 15 July 2005 and fields 17 and 18 on 18 July 2005 with winter wheat as crop. These samples were then mixed to obtain a representative composite sample.

Field-saturated hydraulic conductivity K_{fs} was measured in three replicates per plot between 13 and 18 July 2005, but only on fields under more than 10 years of RT.

The measurement of SOC and TN was done as described in chapter 4 and 5, respectively.

3.3.2. Soil bulk density and water retention curve

BD was determined from the oven dry mass (105 °C) of the undisturbed samples and volume of the soil core. No shrinkage was observed in any of the cores.

To construct the WRC, the sand box method (Eijkelkamp Agrisearch Equipment, the Netherlands) was used for water tensions between 0 and –0.01 MPa, whereas for the lower water tensions (down to –1.5 MPa) the pressure membrane method (Soilmoisture Equipment, USA) was used following the procedure of Cornelis *et al.* (2005). The water retention function of van Genuchten (1980) was fitted to the desorption data:

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{\left[1 + (\alpha \cdot h)^n\right]^m} \tag{1}$$

where θ_r and θ_s are the residual and the saturated soil water content, respectively (m^3 m^{-3}), h is the soil water tension, and α, n and $m = 1 - 1 / n$ are parameters obtained by fitting Eq. 1 to the measured water retention data (van Genuchten *et al.*, 1991).

The total and readily plant available soil water (respectively TPASW and RPASW) were calculated as the moisture content at field capacity (-0.03 MPa) minus the moisture content at respectively wilting point (-1.5 MPa) and a critical water tension set here at -0.05 MPa. Selecting a critical water tension at -0.05 MPa, was based on data by Taylor & Ashcroft (1972) and Wesseling (1991) for the crops under consideration.

We further applied the WRC to derive the index of soil physical quality S defined by Dexter (2004) as the slope of the inflection point of the WRC. It is assumed to be a measure of the soil microstructure, which controls many of the soil physical properties. The index S can be written as:

$$S = n(\theta_s - \theta_r)\left(\frac{2n-1}{n-1}\right)^{\left(\frac{1}{n}-2\right)} \tag{2}$$

Since the index greatly depends on θ_r which is a rather ill-defined parameter and often set equal to zero in the curve-fitting procedure to avoid negative values (Khlosi *et al.*, 2006), it was set here to zero for all soil samples. This should allow better comparison between the various fields. Based on pot and field experiments in several countries, Dexter (2004) suggested a value of $S = 0.035$ as the boundary between good and poor structural soil quality. Values of $S < 0.02$ indicate a very poor soil physical quality.

3.3.3. Penetration resistance

The PR is the resistance of the soil against penetration of a cone and is a measure for the compaction of the soil. The maximum resistance a root can penetrate is 3 MPa (Ide *et al.*, 1987; Ide & Hofman, 1990) and this is half of the maximum PR of the used penetrologgers.

To have an idea of the PR during the year, the PR was measured three times with a hand digital penetrologger (Eijkelkamp Agrisearch Equipment, the Netherlands). The hand penetrologger (60° angle cone with a base of 1 cm^2) was pushed perfectly straight to 60 cm depth into the soil by applying equal pressure on both grips. The hand penetrologger was used 12 times at random per plot.
A fully automated digital penetrologger (30° angle cone with a base of 1 cm^2) (CRA Gembloux, Belgium) was used to have an idea of the 2 dimensional variability of the PR of the soil under RT and CT agriculture. Seventeen measurements were taken over 80 cm to a depth of 60 cm in three replicates. The speed used to push the cone of the automated penetrologger into the soil was constant at 2 cm s^{-1} (Roisin, 2003 & 2007).

3.3.4. Aggregate stability

The stability of the aggregates was measured on air-dried soil samples using the "dry and wet sieving" method of De Leenheer & De Boodt (1959), adjusted by Hofman (1973) as described by Leroy *et al.* (2007). The instability index was calculated as the difference of the MWD of the wet sieving minus the MWD of the dry sieving. The inverse of the instability index, i.e. the stability index (SI), was taken as a measure of the stability of the aggregates (De Leenheer & De Boodt, 1959; De Boodt & De Leenheer, 1967).

Additionally, the aggregate stability was measured with the three methods of Le Bissonnais (1996), being fast wetting of the soil simulating a heavy shower (most aggressive), slow wetting of the soil (least aggressive) and stirring the soil after prewetting to test the wet mechanical cohesion of the soil aggregates. The MWD for method 1, 2 and 3 are referred to as MWD_{fast}, MWD_{slow} and MWD_{stir}, respectively.

3.3.5. Field-saturated hydraulic conductivity

The field-saturated hydraulic conductivity K_{fs} was measured with a Guelph pressure infiltrometer with 0.097 m inner diameter (Soilmoisture Equipment, USA) using the single head method (Reynolds & Elrick, 2002). Using the single head method with the soil-structure parameter α^* (see e.g. Reynolds & Elrick, 2002) taken from Elrick *et al.* (1989) to calculate K_{fs} is often sufficient for practical applications. The method involves measuring the steady-state rate of water infiltration in which a constant depth (head) of water is maintained. A "bulb" of saturated soil with specific dimensions under the ring is rather quickly established by the infiltrometer. This bulb is very stable and its shape depends on the type of soil, the radius of the ring and the head of water in the ring (Reynolds & Elrick, 2002).

Using the equation of Reynolds & Elrick (1990) which is based on a solution for three-dimensional flow, K_{fs} can then be calculated from the steady-state infiltration rate.

3.3.6. Statistical analysis

The homogeneity of variances was tested with the Levene's test ($P = 0.05$). A *t*-Test was used to find significant differences for locations with only 2 fields. One way analysis of variances (ANOVA) with field as factor/post hoc Duncan test and Welch/post hoc Games-Howell test were used to determine significant differences for the locations with more than 2 fields for homogeneous and heterogeneous variances, respectively. A correlation analysis was performed using a Pearson's correlation matrix in SPSS (version 12.0, SPSS Inc., USA).

3.4. RESULTS

3.4.1. Soil bulk density and water retention curve

In the 5-10 cm depth layer the BD tended to be lower in the RT compared to the CT fields at the same location, except for RT_{C_5} field 7 compared to CT field 8 (Table 3.1). The water content at saturation θ_s of the upper depth layer was generally higher for the RT compared to the CT fields at the same location, except for RT_{C_2} 1-3 compared to CT field 4 and RT_{C_20} field 17 compared to CT field 18, though in case of the latter, differences were not significant at $P = 0.05$. No clear trends were observed when comparing TPASW, RPASP and S of the RT and CT fields (Table 3.1 and Appendix II - Table II.1).

Table 3.1 Bulk density (BD), moisture content at saturation (θ_s) and S of 5-10 cm depth layer of the 18 selected fields (with standard deviation between brackets)

Field		BD (Mg m^{-3})	θ_s (m^3 m^{-3})	S
1	RT$_{C\_2}$	1.38 (0.10) a	0.374 (0.015) a	0.041 (0.001) a
2	RT$_{C\_2}$	1.49 (0.08) a	0.391 (0.012) a	0.044 (0.004) a
3	RT$_{C\_2}$	1.46 (0.02) a	0.397 (0.014) a	0.045 (0.003) a
4	CT	1.48 (0.08) a	0.404 (0.019) a	0.036 (0.004) a
5	RT$_{C\_5}$	1.37 (0.04) a	0.374 (0.001) a	0.038 (0.014) a
6	CT	1.43 (0.04) a	0.352 (0.006) b	0.032 (0.005) a
7	RT$_{C\_5}$	1.46 (0.10) a	0.400 (0.035) a	0.055 (0.005) a
8	CT	1.24 (0.07) b	0.359 (0.024) a	0.046 (0.001) b
9	RT$_{C\_10}$	1.43 (0.04) a	0.420 (0.024) a	0.033 (0.006) b
10	CT	1.49 (0.04) a	0.411 (0.018) a	0.053 (0.003) a
11	RT$_{DD\_10}$	1.37 (0.04) b	0.399 (0.019) ab	0.042 (0.013) a
12	CT	1.40 (0.03) b	0.382 (0.008) b	0.049 (0.010) a
13	RT$_{DD\_10}$	1.47 (0.03) a	0.415 (0.007) a	0.045 (0.004) a
14	CT	1.49 (0.04) a	0.378 (0.006) b	0.050 (0.004) a
15	RT$_{DD\_10}$	1.47 (0.01) b	0.406 (0.022) a	0.048 (0.007) a
16	CT	1.51 (0.02) a	0.397 (0.004) a	0.042 (0.002) a
17	RT$_{C\_20}$	1.35 (0.08) a	0.349 (0.022) a	0.033 (0.005) a
18	CT	1.47 (0.08) a	0.369 (0.016) a	0.039 (0.001) 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 between tillage treatments per location ($P = 0.05$)

(one way ANOVA/Duncan post hoc test, Welch/Games-Howell post hoc test or *t*-Test)

In the 25-30 cm depth layer, similar observations were made, though less pronounced (Table 3.2 and Appendix II - Table II.2).

Table 3.2 Bulk density (BD), moisture content at saturation (θ_s) and S of 25-30 cm depth layer of the 18 selected fields (with standard deviation between brackets)

Field		BD (Mg cm^{-3})	θ_s (m^3 m^{-3})	S
1	$\mathrm{RT}_{\mathrm{C\_2}}$	1.51 (0.03) a	0.380 (0.002) b	0.038 (0.002) b
2	$\mathrm{RT}_{\mathrm{C\_2}}$	1.47 (0.14) a	0.410 (0.027) ab	0.043 (0.001) ab
3	$\mathrm{RT}_{\mathrm{C\_2}}$	1.50 (0.04) a	0.403 (0.006) a	0.047 (0.002) a
4	CT	1.48 (0.03) a	0.411 (0.009) ab	0.040 (0.005) b
5	$\mathrm{RT}_{\mathrm{C\_5}}$	1.52 (0.05) a	0.396 (0.015) a	0.039 (0.013) a
6	CT	1.53 (0.02) a	0.405 (0.001) a	0.040 (0.005) a
7	$\mathrm{RT}_{\mathrm{C\_5}}$	1.54 (0.02) a	0.393 (0.020) a	0.056 (0.002) a
8	CT	1.51 (0.03) a	0.402 (0.013) a	0.054 (0.002) a
9	$\mathrm{RT}_{\mathrm{C\_10}}$	1.55 (0.05) a	0.431 (0.018) a	0.036 (0.009) b
10	CT	1.51 (0.01) a	0.410 (0.023) a	0.052 (0.001) a
11	$\mathrm{RT}_{\mathrm{DD\_10}}$	1.50 (0.05) a	0.408 (0.004) a	0.037 (0.003) a
12	CT	1.54 (0.03) a	0.387 (0.004) a	0.042 (0.011) a
13	$\mathrm{RT}_{\mathrm{DD\_10}}$	1.53 (0.04) a	0.389 (0.012) ab	0.039 (0.004) a
14	CT	1.50 (0.06) a	0.374 (0.015) b	0.050 (0.009) a
15	$\mathrm{RT}_{\mathrm{DD\_10}}$	1.50 (0.02) b	0.401 (0.004) a	0.045 (0.003) a
16	CT	1.56 (0.01) a	0.401 (0.003) a	0.042 (0.002) a
17	$\mathrm{RT}_{\mathrm{C\_20}}$	1.58 (0.03) a	0.386 (0.017) a	0.034 (0.005) a
18	CT	1.59 (0.06) a	0.385 (0.003) a	0.037 (0.004) a

RT_{C}: reduced tillage with cultivator or soil loosener, $\mathrm{RT}_{\mathrm{DD}}$: by direct drilling with in subscript the period in years; CT: conventional tillage

same 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)

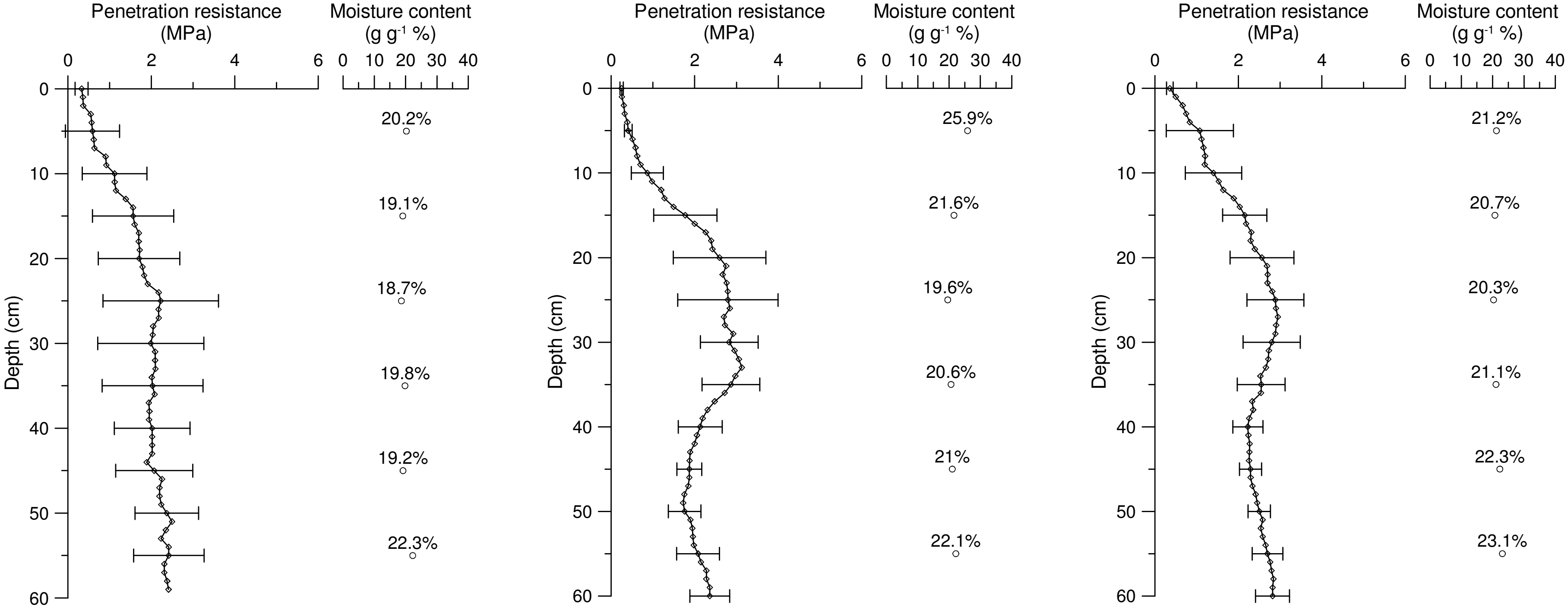
3.4.2. Penetration resistance

Shortly after the field work a low PR was measured in the RT$_C$ and CT fields. During the growing season or winter period the PR of the RT$_C$ but especially of the CT fields was increased (e.g. RT$_{C\_5}$ 7 and CT 8 fields in Figure 3.1 and Figure 3.2, respectively).

The PR of the 10-20 cm depth layer was higher in the soil profile under RT$_{DD}$ compared to RT$_C$ and CT fields (e.g. RT$_{DD\_10}$ field 11 in Figure 3.3 compared to RT$_{C\_5}$ 7 and CT 8 fields in Figure 3.1 and Figure 3.2, respectively).

In CT fields 8, 10, 14 and 18 an obvious plough pan was measured, except when the moisture conditions were too high (e.g. the plough pan was not measured on 13/12/2005 in CT field 8 (Figure 3.2)).

Next to the hand penetrologger, an automated penetrologger was used in fields 1 to 4 in Heestert to have an idea of the 2 dimensional variability of the PR of the soil under RT and CT fields. The locations of the tines of cultivator or soil loosener in the RT fields were visible (↓ in Figure 3.5 and Figure 3.6 and  in Figure 3.7). The PR in the 5-15 and 15-20 cm depth layer in RT$_{C\_2}$ field 1 was lower and higher compared to fields 2-4, respectively (Figure 3.4).

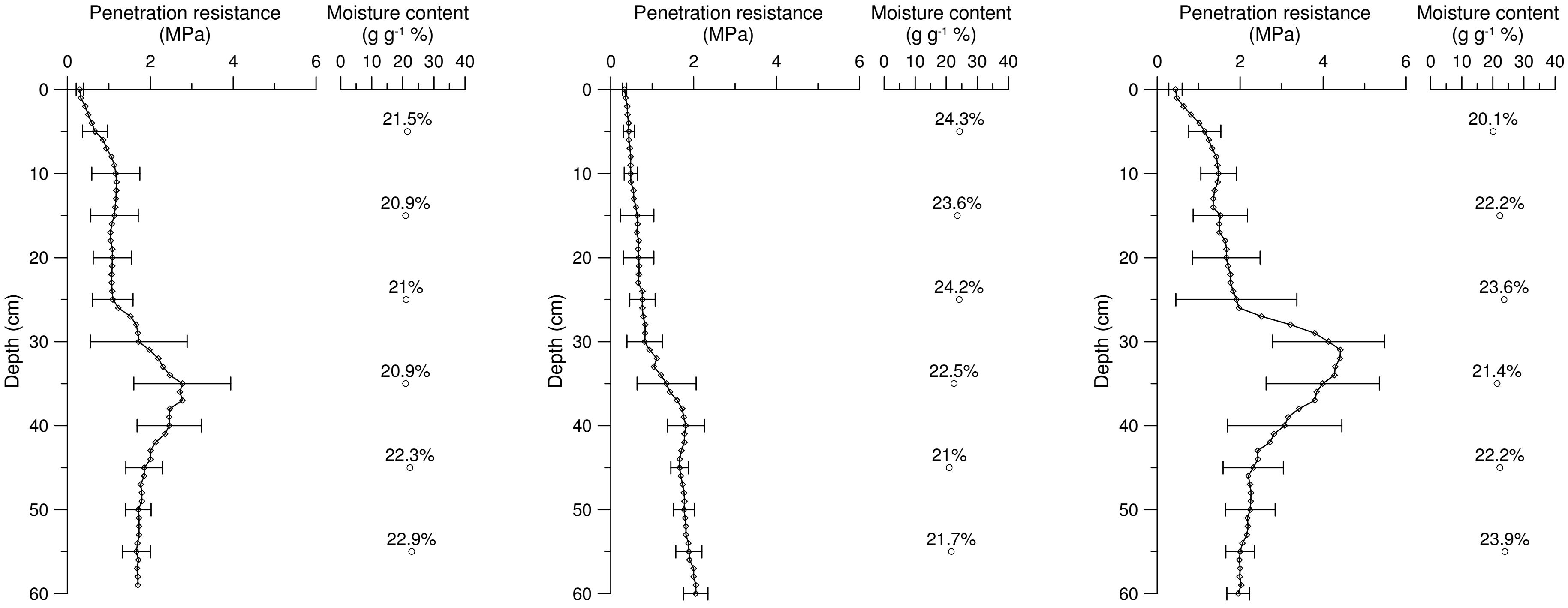


Measurement: 13/07/2005
After planting potatoes

Measurement: 13/12/2005
After harvesting potatoes and sowing barley

Measurement: 24/03/2006
With barley

Figure 3.1 Penetration resistance (MPa) and moisture content (g g^{-1}) of field 7 (reduced tillage by cultivator since 2000) in Baugnies



Measurement: 13/07/2005
After sowing maize

Measurement: 13/12/2005
After harvesting maize and
before ploughing

Measurement:24/03/2006
Fallow after ploughing

Figure 3.2: Penetration resistance (MPa) and moisture content (g g^{-1}) of ploughed field 8 in Baugnies

Measurement: 06/16/2005
With winter wheat

No measurement possible because the penetration resistance was too high

Measurement: 11/24/2005
With winter barley

Measurement: 05/19/2006
With winter barley

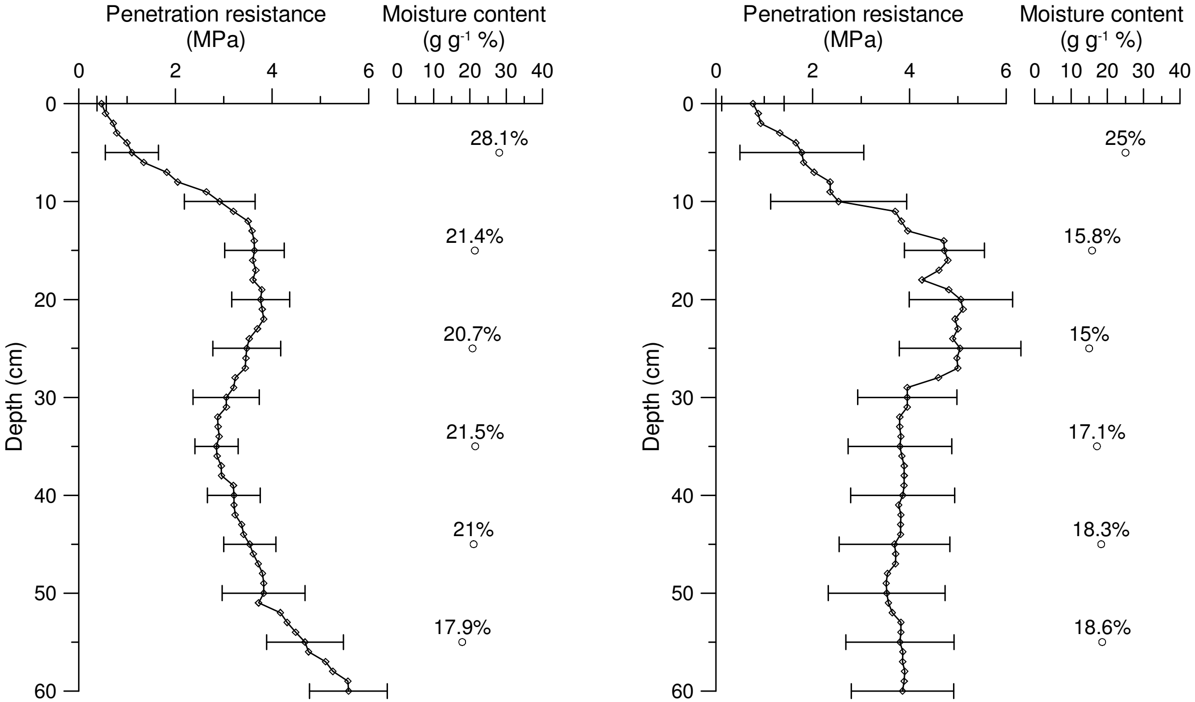
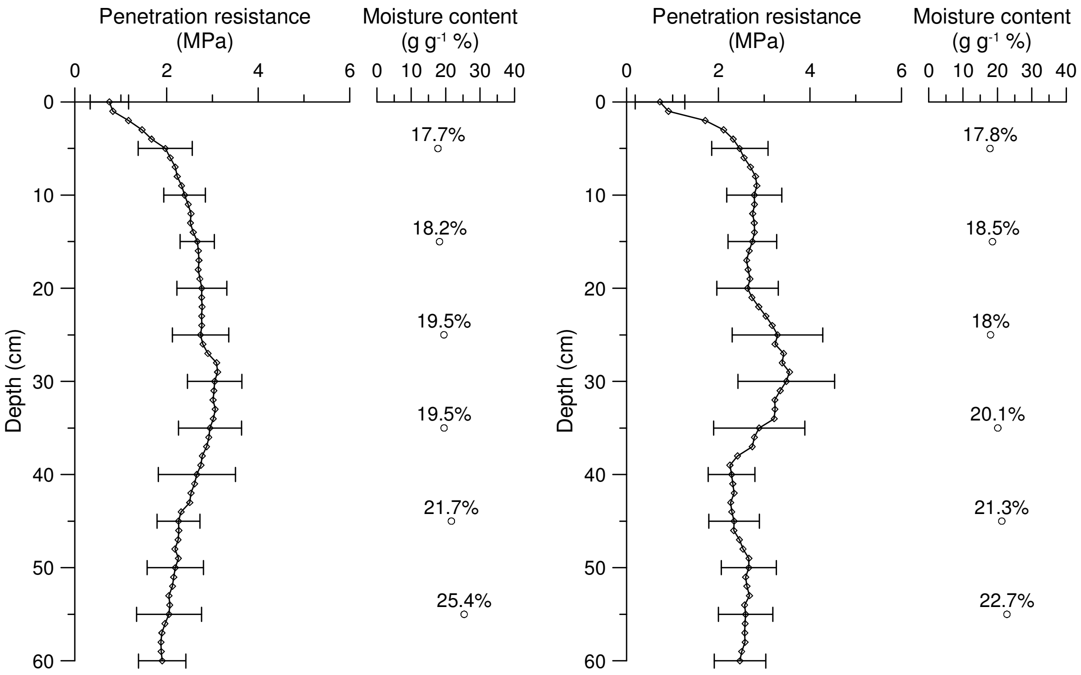


Figure 3.3: Penetration resistance (MPa) and moisture content (g g^{-1}) of field 11 (reduced tillage by direct drilling since 1995) in Villers-le-Bouillet

Field 1 Field 2



Field 3 Field 4

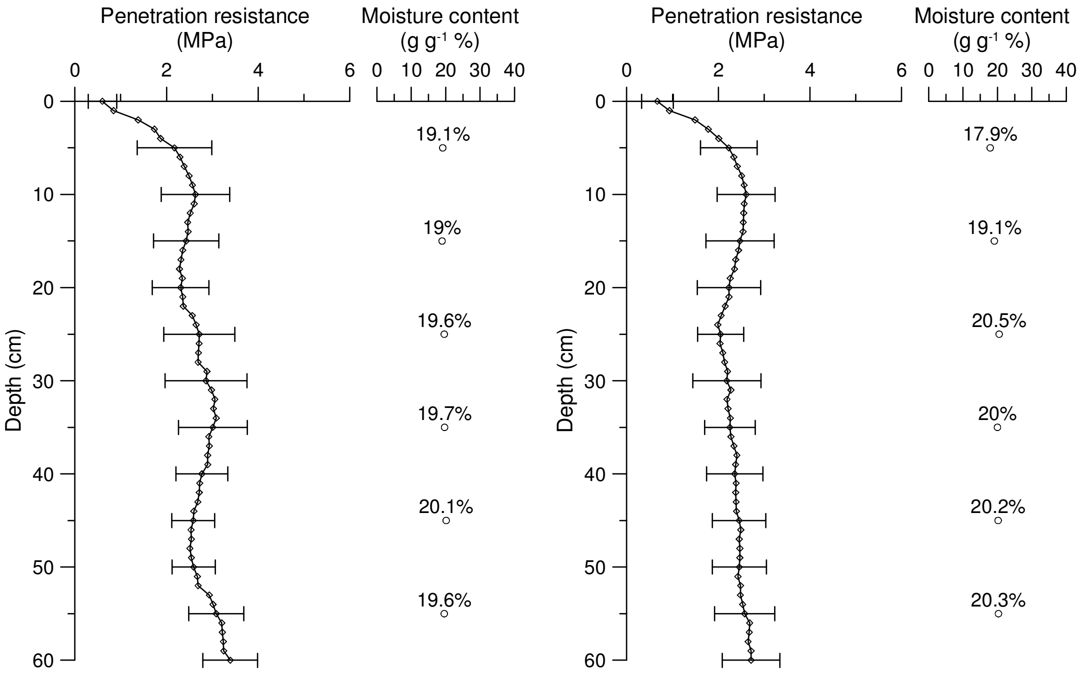


Figure 3.4 Penetration resistance (MPa) and moisture content (g g^{-1}) of fields 1-3 (reduced tillage with cultivator or soil loosener since 2003) and ploughed field 4 measured with a hand penetrologger on 08/09/2006

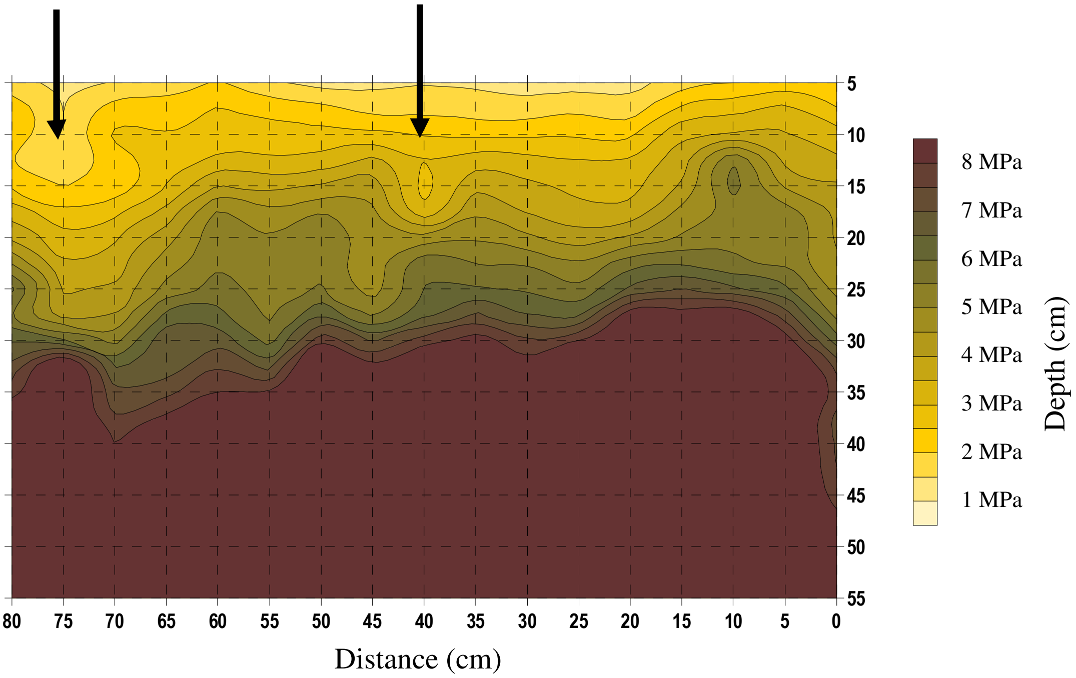


Figure 3.5 Penetration resistance (MPa) of field 1 (reduced tillage with cultivator since 2003) on 08/09/2006 (CRA Gembloux) (↓ indicates where the cultivator loosened the soil)

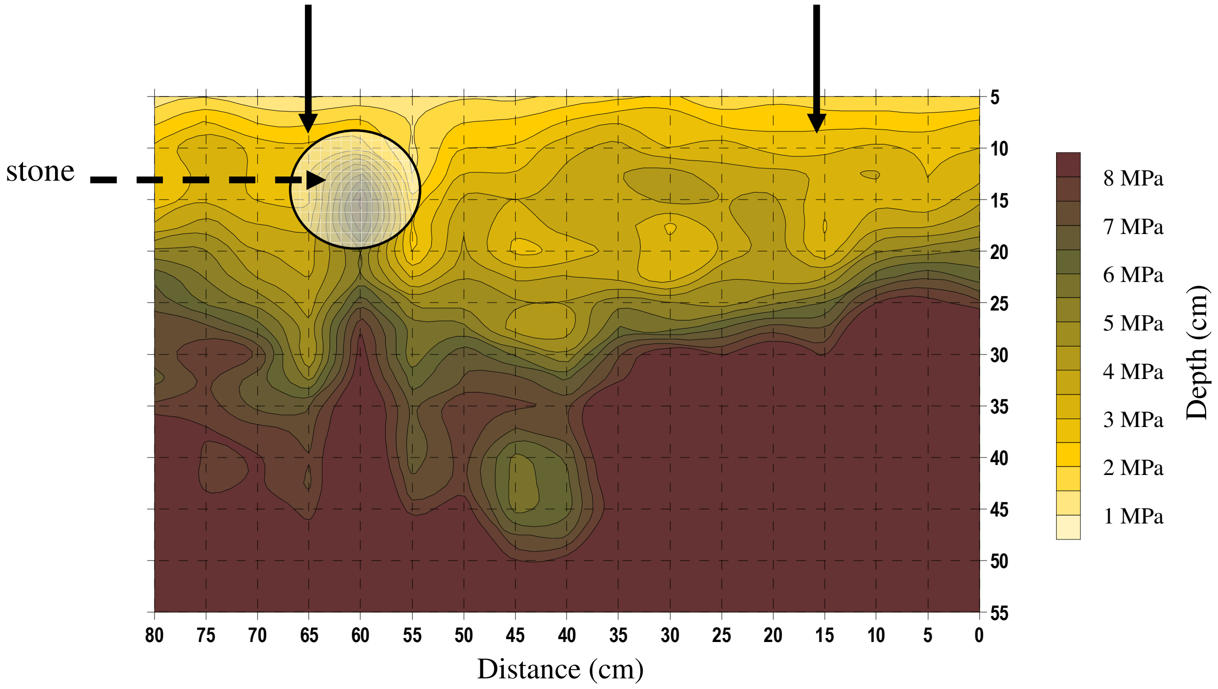


Figure 3.6 Penetration resistance (MPa) of field 2 (reduced tillage with soil loosener since 2003) on 08/09/2006 (CRA Gembloux) (↓ indicates where the soil loosener loosened the soil)

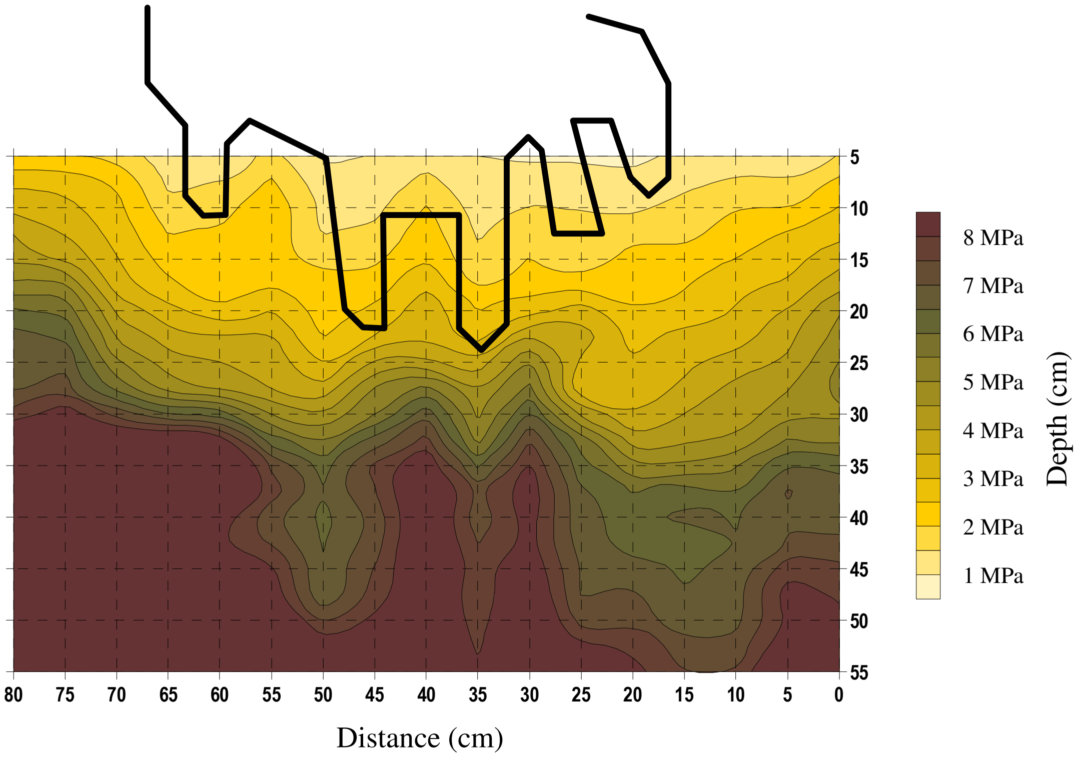


Figure 3.7 Penetration resistance (MPa) of field 3 (reduced tillage with soil loosener since 2003) on 08/09/2006 (CRA Gembloux) ( indicates where the soil loosener loosened the soil)

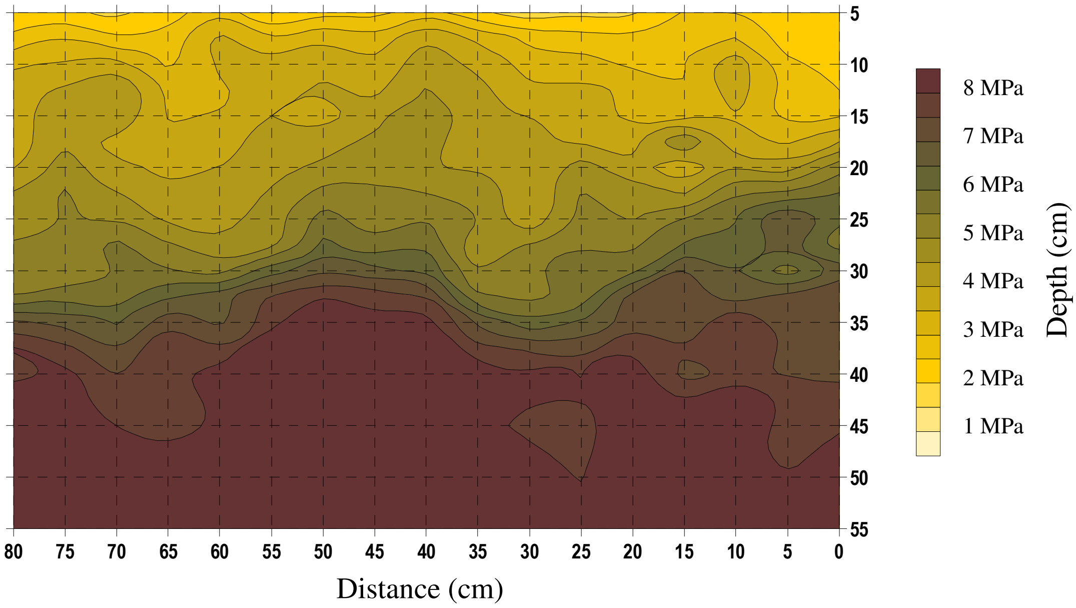
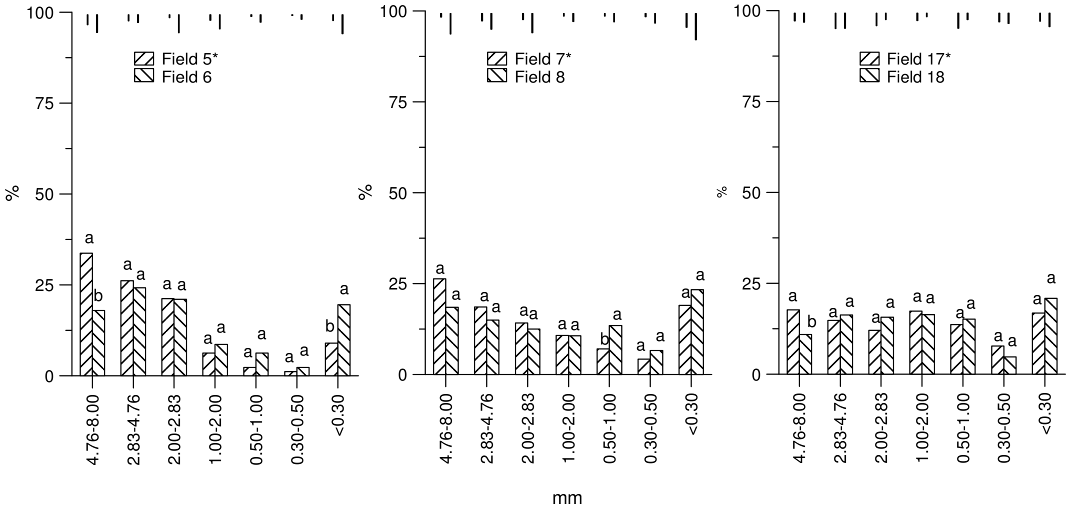


Figure 3.8 Penetration resistance (MPa) of ploughed field 4 on 08/09/2006 (CRA Gembloux)

3.4.3. Aggregate stability

The distribution of the aggregate sizes fractions of the 0-10 cm depth layer for fields 5-8 (RT_{C_5}) and fields 17-18 (RT_{C_20}) obtained with the "dry and wet sieving" method of De Leenheer & De Boodt (1959) is given as an example in Figure 3.9. The aggregate size fractions 8-4.76 mm and 2.83-4.76 mm were (significantly) higher in RT_{C_5} field 5 compared with CT field 6. A similar distribution was found in field 7 and 8. Also in RT_{C_20} field 17, the aggregate size fraction >4.76 mm was significantly higher in comparison with CT field 18. Similar trends, i.e. higher percentages of large aggregates, under RT agriculture were observed in the other fields (data not shown).



*: reduced tillage field

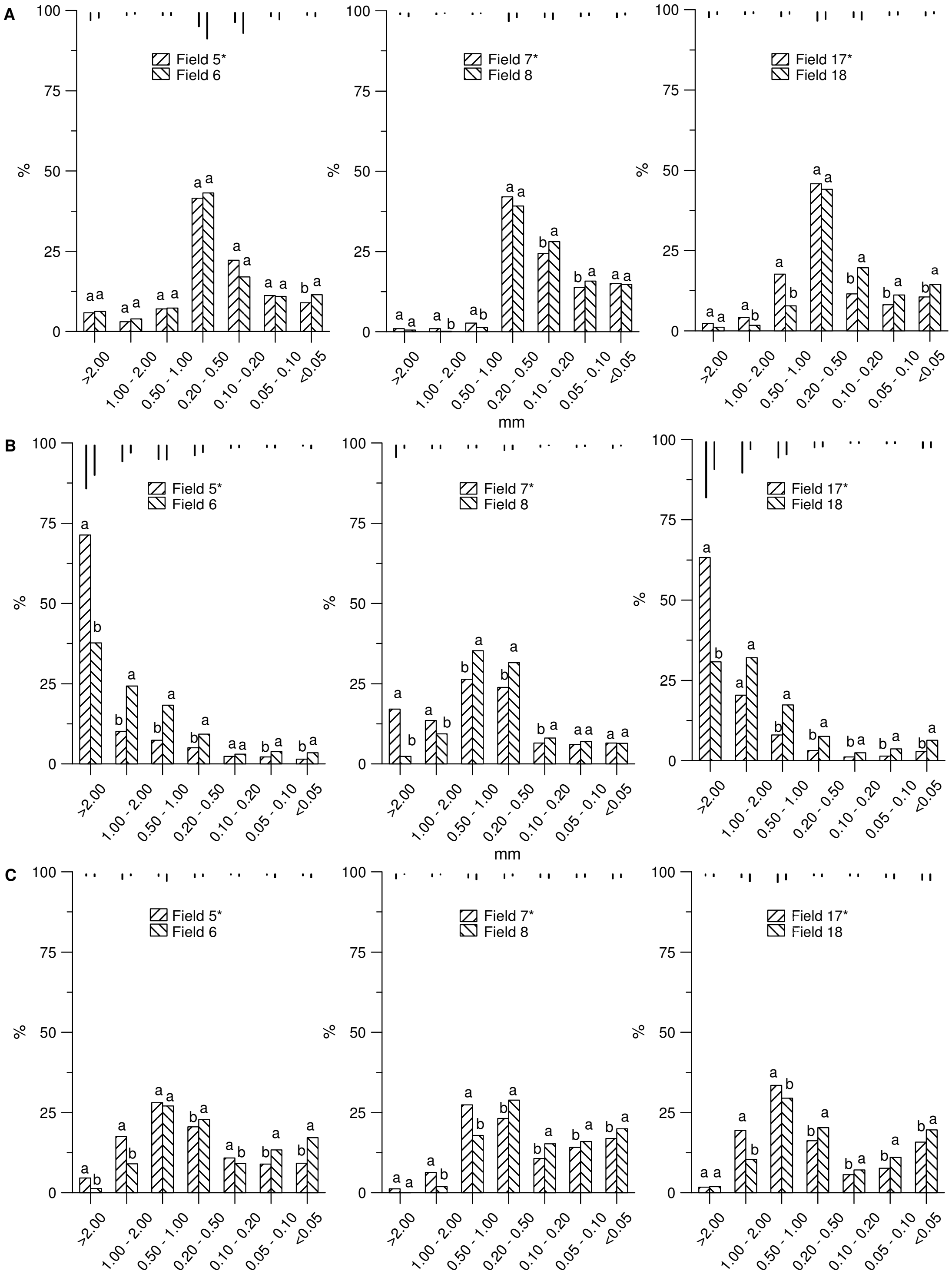
same letter per aggregate size per location indicates no significant differences between tillage treatments (P = 0.05) (*t*-Test)

Figure 3.9 Distribution of aggregate size fractions (%) (vertical lines = standard deviation) of the 0-10 cm depth layer of fields 5-8 (5 years reduced tillage with cultivator RT_C) and of fields 17-18 (20 years RT_C) measured with the "dry and wet sieving" method of the Leenheer and De Boodt (1959)

When applying the methods of Le Bissonnais (1996), aggregate sizes fractions were strongly affected by the method used (Figure 3.10). There were few aggregate sizes larger than 0.5 mm in fields 5-8 and 18 and larger than 1 mm for field 17 (Figure 3.10A) after the aggressive method 1, while after the slow wetting of method 2, there were little aggregate sizes smaller than 0.2 mm (Figure 3.10B). After 5 years RT_C agriculture, method 2 resulted in a significant increase ($P = 0.05$) in % aggregate size >2 mm both in field 5 compared to field 6, and field 7 compared to field 8. The same significant increase was observed after 20 years of RT_C agriculture (RT_{C_20} field 17 compared to CT field 18). The aggregate sizes obtained with the third method were in between the most and least aggressive method (Figure 3.10C). The % aggregate size >2 mm, 1-2 mm and 0.5-1 mm obtained with the third method was (significantly) higher in the RT_C compared to the CT fields. The same trend in distribution of particle sizes was found for the other fields (data not shown).

There were no significant differences between tillage treatments in SI between fields 1 to 4 (Figure 3.11). After 5 years RT_C agriculture, the SI was significantly higher ($P = 0.05$) in field 5 in comparison with CT field 6 but not significantly higher in field 7 compared to CT field 8. After 10 years RT_C agriculture, there was a significant increase in SI in field 9 compared to CT field 10. When comparing fields 11 to 14 (RT_{DD_10} vs. CT), CT field 14 had the lowest SI. There was no difference in SI between RT_{DD_10} field 15 and CT field 16. After 20 years RT_C agriculture, there was an insignificant increase in SI in RT_{C_20} field 17 compared to CT field 18.

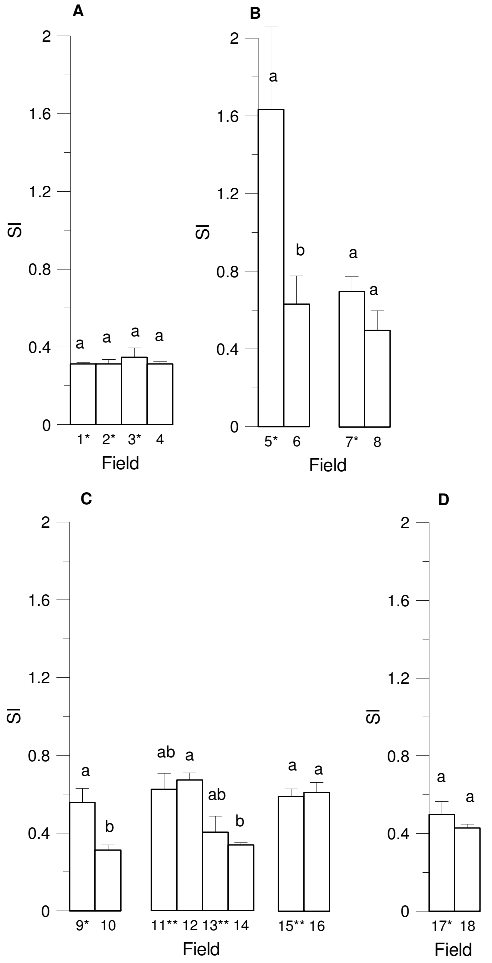
The results of field 1-4 showed that the MWD according to the three methods of Le Bissonnais (1996) increased shortly after changing from CT to RT_C agriculture (Figure 3.12). The MWD_{slow} and MWD_{stir} of RT_{C_2} fields 1-3 (RT_{C_2}) were significantly higher compared to field 4 (CT). MWD_{fast} showed the same trend. After 5 years RT_C agriculture the MWD_{slow} and MWD_{stir} was significantly higher (RT_{C_5} on field 5 compared to CT agriculture on field 6, RT_{C_5} on field 7 compared to CT agriculture on field 8). There was no obvious trend in MWD_{fast} after 5 years RT_C agriculture. After 10 years RT_C agriculture, the MWD in the three methods was significantly higher on RT_{C_10} field 9 compared to CT field 10. RT_{DD_10} fields 11 and 13 had significantly higher MWD_{slow} and MWD_{stir} values than CT fields 12 and 14, respectively. On the other hand, MWD_{stir} was significantly lower when comparing RT_{DD_10} field 15 with CT field 16. After 20 years RT_C agriculture (field 17), the MWD_{fast}, MWD_{slow} and MWD_{stir} were significantly higher than CT field 18. The MWD obtained after the different methods of Le Bissonnais (1996) resulted in the order $MWD_{slow} > MWD_{stir} > MWD_{fast}$ (Figure 3.10).



*: reduced tillage with cultivator or soil loosener

same letter per aggregate size per location indicates no significant differences between tillage treatments (P = 0.05) (*t*-Test)

Figure 3.10 Distribution of aggregate size fractions (%) (vertical lines = standard deviation) obtained with method 1 (A), 2 (B) and 3 (C) of Le Bissonnais (1996) of the 0-10 cm depth layer of fields 5-8 (5 years reduced tillage with cultivator (RT_C) and fields 17-18 (20 years RT_C)



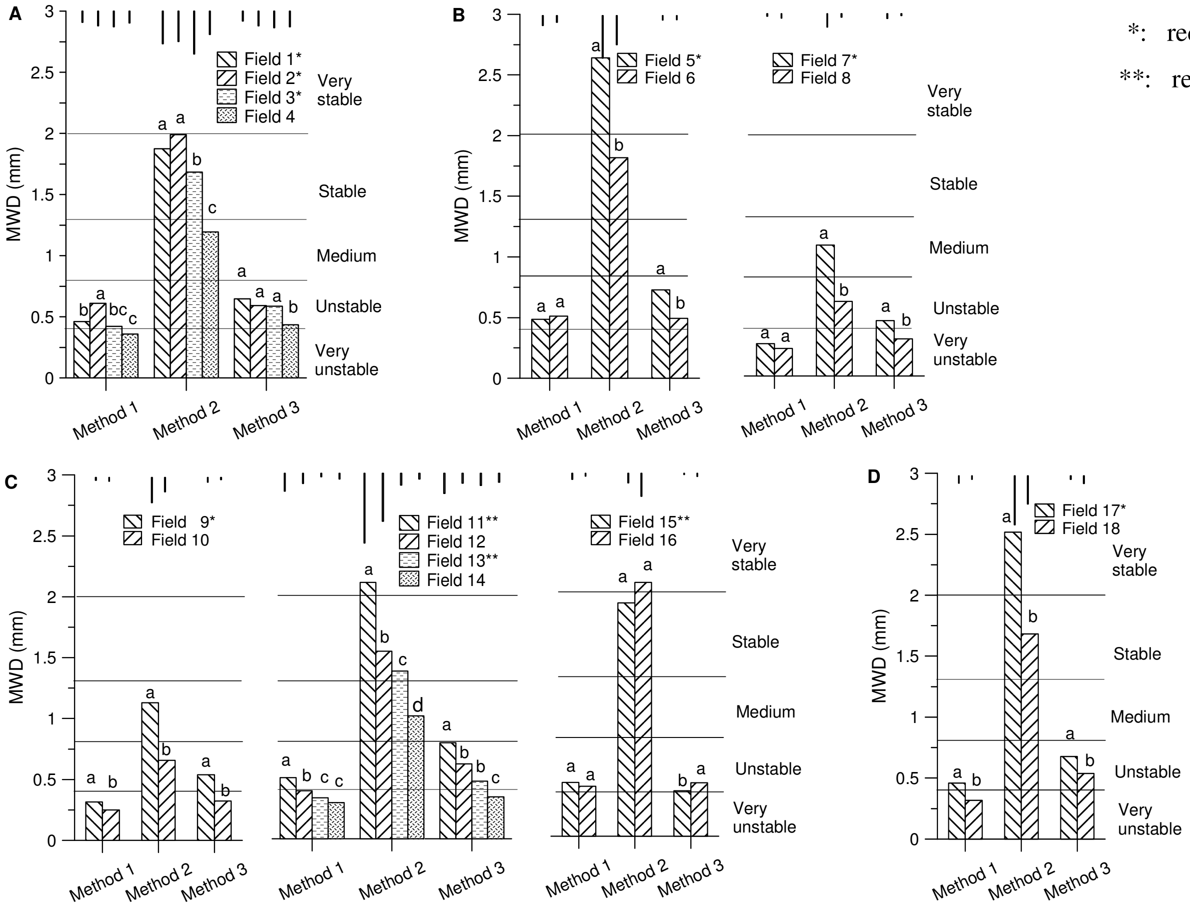
*: reduced tillage with
cultivator or soil loosener (RT_C)

**: reduced tillage by
direct drilling (RT_{DD})

A: 2 years RT_C
B: 5 years RT_C
C: 10 years RT_C or RT_{DD}
D: 20 years RT_C

same letter indicates no significant differences between tillage treatments at P = 0.05 per location (one way ANOVA/Duncan post hoc test, Welch/Games-Howell post hoc test or *t*-Test)

Figure 3.11 Stability index (SI) (line = standard deviation) determined by the 'dry and wet sieving' method of De Leenheer & De Boodt (1959) of the 0-10 cm depth layer of the 18 selected fields



*: reduced tillage with cultivator or soil loosener (RT_C)

**: reduced tillage by direct drilling (RT_{DD})

A: 2 years RT_C

B: 5 years RT_C

C: 10 years RT_C or RT_{DD}

D: 20 years RT_C

same letter per location indicates no significant differences between tillage treatments at P = 0.05

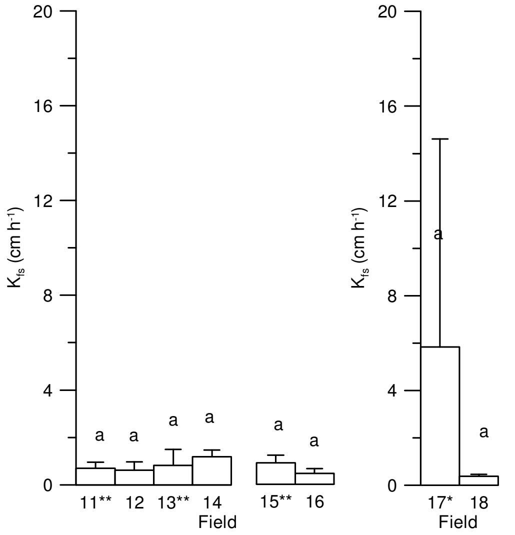
(one way ANOVA/Duncan post hoc test, Welch/Games-Howell post hoc test or *t*-Test)

(vertical lines = standard deviation)

Figure 3.12 Mean weight diameter (MWD) (mm) measured by the 3 methods of Le Bissonnais (1996) of the 0-10 cm depth layer of the 18 selected fields

3.4.4. Field-saturated hydraulic conductivity

Per location there were no significant differences in K_{fs} between the fields 11-18 (Figure 3.13), but the high variability in K_{fs} between the plots of some fields complicated the comparison. The K_{fs} was higher under RT than CT agriculture at two of the three locations.



*: reduced tillage with cultivator or soil loosener (RT_C)
**: reduced tillage by direct drilling (RT_{DD})

same letter indicates no significant differences between tillage treatments per location (P = 0.05) (one way ANOVA/Duncan post hoc test or *t*-Test)

Figure 3.13 Field-saturated conductivity K_{fs} (cm h^{-1}) (vertical lines = standard deviation) measured with a Guelph infiltrometer of fields 11-18

3.5. DISCUSSION

3.5.1. Soil bulk density and water retention curve

The BD of the 5-10 cm depth layer during winter was lower in the RT than CT fields at the same location, except for RT_{C_5} field 7 compared to CT field 8 (Table 3.1). However, field 8 was ploughed only a few weeks before sampling which is probably the reason for this low BD at the soil surface. The higher SOC content of the RT compared to CT fields (Figure 4.3) is probably an important reason for the lower BD of the RT fields (Saini, 1966; Adams, 1973; Friedel *et al.*, 1996). Under a temperate climate most researchers found a comparable or higher BD in the 0-5 cm depth layer under short term (≤11 years) RT fields with maize, wheat and soybean (Angers *et al.*, 1997; Yang & Wander, 1999; Kay & Vanden Bygaart, 2002; Puget & Lal, 2005; Al-Kaisi *et al.*, 2005b) while under long term RT agriculture the BD was comparable or lower than CT agriculture (Tebrügge & Düring, 1999; Deen & Kataki, 2003; Dolan *et al.*, 2006).

The saturated θs of the 5-10 cm depth layer was mostly higher for the RT_{DD} and RT_C compared to the CT fields at the same location. Riley (1998) measured a higher θs after 15 years RT_C compared to CT agriculture, while McVay *et al.* (2006) found a comparable θs for 4 locations and a significant decrease in θs in 1 location under RT compared to CT agriculture 12 to 37 years after conversion to RT agriculture. These contrary results show that it is very difficult to find a trend in the change of pore sizes after conversion to RT agriculture. Ploughing results in more unstable large pores, which disappear quickly during the growing season or winter. More large pores (>50 µm) and fewer pores of 10-50 µm were found in the soil profile of CT fields compared to 9 year RT fields in Germany (Ahl *et al.*, 1998). However, Wahl *et al.* (2004) found more large pores (minimum diameter 1 mm) after 10 years RT compared to CT agriculture up to 120 cm depth, which they contributed to channels of roots and earthworms. Several researchers (e.g. Logan *et al.*, 1991; Warkinton, 2001) have measured more biopores under RT than CT fields.

In Norway the available water capacity (at -0.01 minus -1.5 MPa) of the 3-7 cm depth layer was higher after 15 years RT_C compared to CT agriculture (Riley, 1998). However we measured comparable TPASW and RPASW in the 5-10 cm depth layer for the RT and CT fields except for the significantly lower TPASW and RPASW of RT_{C_10} field 9 compared to CT field 10 ($P = 0.05$) (Appendix II - Table II.1 and Table II.2). The lower TPASW and RPASW of RT_{C_10} field 9 compared to CT field 10 can be explained by the wet soil conditions at sowing of the green manure of RT_{C_10} field 9 resulting in soil compaction while the maize residues were not removed from CT field 10.
The physical soil quality index S was for all fields close to or higher than 0.035, which, according to Dexter (2004), indicates a good physical quality of the soil.

In the 25-30 cm soil layer, no differences in BD and WRC were measured under RT compared to CT fields which is similar as the results of other researches (Angers *et al.*, 1997; Tebrügge & Düring, 1999; Yang & Wander, 1999; Kay & Vanden Bygaart, 2002; Deen & Kataki, 2003; Al-Kaisi *et al.*, 2005b; Puget & Lal, 2005; Dolan *et al.*, 2006).

The lower crop yield in wet years and the higher yield in dry years that are generally observed on RT compared to CT fields, is often attributed to higher TPASW and RPASW under RT_C and RT_{DD} compared to CT fields. However, our results, i.e. comparable TPASW and RPASW between RT and CT fields, indicate that other factors are responsible for the differences in crop yields of RT and CT fields. The soil temperature and evaporation of RT fields can be lower due to a higher amount of residues of crops or green manure which results in larger soil - water contents in RT compared to CT fields.

3.5.2. Penetration resistance

The PR is influenced by the soil moisture content. The penetrologger can be pushed through wet soil as if it were butter. As a consequence a plough pan can not be detected in wet soils. The same soil could be very difficult to penetrate when dry. Since different tillage practices and crop rotations result in different soil moisture contents, measurements of the PR of RT and CT fields in the same period don't detect the compacted layers of all measured fields. No PR measurements could be done in RT_{DD_10} field 11 at the first sampling due to the dry soil circumstances (Figure 3.3), while the soil moisture was too high to measure the PR at the second sampling in CT field 8 (Figure 3.2).

A general conclusion for the differences in PR under RT_C compared to CT agriculture is difficult because the quality of loosening the soil depends on three major factors: the moisture content of the soil, the initial soil structure and the used cultivator or soil loosener (Vandergeten & Roisin, 2004). If the working depth under RT_C agriculture was lower compared to CT agriculture, the PR was higher in the 20-30 cm depth layer of RT_C fields e.g. the higher PR in the 15-20 cm depth layer of RT_{C_2} field 1 compared to fields 2-4 (Figure 3.4). Other researchers also found that the changed depth and intensity of the field work in RT_C compared to CT agriculture influenced the PR. After 8 years RT_C agriculture a higher PR was measured in the 10-25 cm in a silt clay loam under RT_C compared to CT agriculture in Sweden. In the 0-10 and 25-50 cm depth layers, there were no differences in PR. The depth of disturbance under RT_C agriculture was 12 cm instead of 25 cm under CT agriculture (Stenberg *et al.*, 2000). After 12 years of RT_C agriculture on a sandy loam soil in Norway and 15 years RT_C agriculture on a silt loam soil in Sweden a higher PR was measured compared to CT agriculture due to the lower depth of disturbance. This was correlated with a higher density and lower % SOC (Etana *et al.*, 1999; Riley *et al.*, 2005).

The smaller tines of the cultivator used in RT_{C_2} field 1 caused a larger mixture of the soil. This resulted in a lower PR in the 5-15 cm depth layer in RT_{C_2} field 1 compared to fields 2-4 (Figure 3.4). The lower heterogeneity under CT than RT agriculture (Perfect & Caron, 2002; Roisin, 2003) was observed under CT field 4 compared to RT_{C_2} fields 1-3 (Figure 3.4). The location where the tines had worked the field remained visible for several years (e.g. ↓ in Figure 3.5), as was also found by e.g. Franzluebbers, 2002; Baritz *et al.*, 2004 and Vandergeten & Roisin, 2004. At the top of the soil profile of RT_{C_2} field 2 a local higher PR was visible which was probably caused by a stone in the field (Figure 3.6). With the hand penetrologger these measurements are done again.

3.5.3. Aggregate stability

There is an enormous variety in the methods for measuring the aggregate stability, which complicates a comparison of the results. The retention of crop residues at the soil surface exerts a positive influence on the formation of aggregates even in the short term (Hermawam & Bomke, 1997; Martens, 2000; Denef *et al.*, 2001a; Coppens *et al.*, 2006). Bossuyt *et al.* (2001) measured a higher aggregate stability after addition of crop residues, which was higher for the crop residues with a higher C:N ratio. Changing from CT agriculture to RT agriculture under temperate climate conditions mostly resulted in a (significant) higher aggregate stability in the upper layers of RT fields (Hussain *et al.*, 1999; Diaz-Zorita *et al.*, 2002; Liebig *et al.*, 2004). The results of our study confirm that the reduction of tillage intensity and the retention of crop residues at the soil surface of RT fields result in a higher aggregate stability of the RT compared to CT fields despite the frequent disturbance on the occasion of harvest of root and tuber crops might every two to three years.

Since the wet sieving according to the method of De Leenheer & De Boodt (1959) was started with an equal amount of three aggregate fractions, the differences in distribution of aggregate size fractions were smaller than with the three methods of Le Bissonnais (1996). The SI was significantly correlated with MWD_{slow}. There was a good correlation between the MWD obtained with the three methods of Le Bissonnais (1996) (Table 3.3). The MWD_{slow} and MWD_{stir} of silt loam soils in Brittany showed a clear linear correlation with SOC (up to maximum 1.5%) and clay content (up to a maximum of 30%). The high differences in clay content of the monoculture maize fields of Le Bissonnais *et al.* (2002) resulted in a high difference in SOC content in the upper layers and a significant correlation between MWD and the soil parameters. Our fields with a high soil disturbance at the harvest of beet or potatoes resulted in a low increase in SOC content, MWD and SI. The lack of correlation between the MWD or SI with texture and SOC content in this research is obviously related to the small range in soil texture and SOC content.

Table 3.3 Pearson correlation between mean weight diameter after fast wetting (MWD_{fast}), MWD after slow wetting (MWD_{slow}), MWD after stirring (MWD_{stir}), stability index (SI) and clay, soil organic carbon (SOC) and field-saturated hydraulic conductivity (K_{fs})

	MWD_{slow} (mm)	MWD_{stir} (mm)	SI	Clay (%)	SOC (%)	K_{fs} (cm h^{-1})
MWD_{fast} (mm)	0.827 **	0.666 **	0.217	0.196	0.175	0.044
MWD_{slow} (mm)		0.750 **	0.472	0.326	0.214	0.289
MWD_{stir} (mm)			0.391	0.381	0.427	0.157
SI				0.382	0.227	-0.303

Significant differences *: P = 0.05; **: P = 0.01

The disadvantage of the three methods of Le Bissonnais (1996) is the time intensity of the measurements while the advantage is that MWD is studied after fast wetting of the soil simulating a heavy shower, slow wetting of the soil and stirring the soil after prewetting to test the wet mechanical cohesion of the soil aggregates. If the MWD under the three circumstances is needed, the three methods must be used. However, the aggregate stability is mostly studied to have an idea about the sensitivity of soils for runoff and erosion and then one method is enough. The MWD_{fast} and MWD_{stir} show a good relation with runoff and erosion (Amezketa *et al.*, 1996; Barthès & Roose, 2002). However, the aggressive character of method 1 results in a low MWD_{fast} which makes comparison of soils difficult. The method of De Leenheer & De Boodt (1959) is a good alternative to measure the stability of aggregates to have an idea of the susceptibility of soils to runoff and erosion. Leroy *et al.* (2007) also concluded that the most sensitive procedure to assess organic treatments in terms of aggregate stability was the one described by De Leenheer & De Boodt (1959).

3.5.4. Field-saturated hydraulic conductivity

Our results confirm the high variability of K_{fs} (Reynolds *et al.*, 2000). We observed a higher K_{fs} under RT compared to CT agriculture in June-July 2005 after autumn tillage operations in RT fields 15 and 17 in 2004 and no tillage operations in the previous 12 months in RT fields 11 and 13. The higher K_{fs} under RT compared to CT agriculture can possibly be explained by the higher aggregate stability, the fact that the channels made by earthworms and roots were less (RT_C) or not (RT_{DD}) destroyed compared to CT fields and vertical cracks from loosening the soil. The very high variability of K_{fs} of RT_{C_20} field 17 was possibly caused by the presence of these natural or manmade channels. Liebig *et al.* (2004) also measured a higher K_{fs} with an infiltrometer in RT compared to CT fields in the spring after autumn tillage. However, often a lower K_{fs} is measured in RT compared to CT fields 2-3 months after the tillage operations (Wienhold & Tanaka, 2000; Lipiec *et al.*, 2006; Singh & Malhi, 2006). This suggests that 2-3 months after tillage operations, the K_{fs} of RT fields is lower than CT fields, while after a longer period (>6 months) of stabilization the opposite can be found. However, under long term RT_{DD} agriculture a compacted crust can be formed at the surface which can decrease K_{fs} and increase soil erosion.

3.6. CONCLUSION

In the scope of the increasing concern for soil conservation, RT agriculture is growing more important in Western European agriculture although the crop rotations contain a large share of erosion sensitive root and tuber crops. At each location, BD of the 5-10 cm depth layer was mostly lower under RT than CT fields, while the θ_s was mostly higher. No differences in BD or WRC could be found in the 25-30 cm depth layer between RT and CT fields. The PR was only higher in the 20-30 cm depth layer under RT_C compared to the CT agriculture if the working depth was lower while the PR in the upper 10-30 cm depth layer of the RT_{DD} fields was higher than CT fields. The aggregate stability of the 0-10 cm depth layer measured by the method of De Leenheer & De Boodt (1959) was higher under RT than CT agriculture. The MWD_{fast}, MWD_{slow} and MWD_{stir} (Le Bissonnais, 1996), was significantly higher even after short term RT compared to CT agriculture. This explains the low erosion and runoff of RT fields. The K_{fs} tended to be higher under RT than CT agriculture.

Chapter 4:

The effect of reduced tillage agriculture on carbon dynamics in silt loam soils

LEFT: CARBON MINERALIZATION INCUBATION
RIGHT: MEASUREMENT OF THE CARBON MINERALIZATION RATE

Modified from:

D'Haene, K., Sleutel, S., De Neve, S., Gabriels, D., Vandenbruwane, J., Hofman, G. The influence of reduced tillage on carbon dynamics in silt loam soils. Soil Till. Res., submitted.

D'Haene, K., De Neve, S., Sleutel, S., Van den Bossche, A., Gabriels, D., Hofman, G., 2007. Soil organic carbon of silt loam soils under ten years of reduced tillage. In: Chabbi, A. (Ed.), Proceedings of the international symposium "Organic matter dynamics in agro-ecosystems". Institut Scientifique de Recherche Agronomique (INRA), 16-19/07/2007, Poitiers, p. 366-367.

4.1. ABSTRACT

RT agriculture is an effective measure to reduce soil loss from soils susceptible to erosion in the short term and is claimed to increase the SOC stock. The change in distribution and total stock of SOC in the 0-60 cm depth layer, the stratification of microbial biomass carbon (MB-C) content in the 0-40 cm depth layer, the distribution of OC over the different physical fractions in the 0-10 cm depth layer and the C mineralization in the upper 0-5 cm depth layer (disturbed and undisturbed) in silt loam soils in Western Europe with different periods of RT agriculture was evaluated. Ten silt loam fields at seven locations, representing the important RT types and maintained for a different number of years, and eight fields under CT agriculture with comparable soil type and crop rotation were selected.

RT agriculture resulted in a higher stratification of SOC in the soil profile. However, the total SOC stock in the 0-60 cm depth layer was not changed, even after a period of 20 years of RT agriculture. The amounts of OC in three different POM fractions of the 0-10 cm depth layer were found to be (significantly) higher both on an absolute as well as a relative basis in the RT compared to the CT fields. In general the difference was the highest for the coarse free POM fraction, which is the most labile fraction. The MB-C content was significantly higher in the 0-10 cm depth layer under RT agriculture, even after only 5 years, compared to CT agriculture. The higher percentage of (labile) OC and MB-C content in the upper 0-5 cm depth layer of RT fields resulted in a higher C mineralization rate in undisturbed soil under controlled conditions in the laboratory. Simulating ploughing by disturbing the soil resulted both in lower and higher C mineralization rates of the silt loam soils, but due to the large variability of the estimated C mineralization parameters, these differences were not significant. It seems that under the specific management and climatic conditions of Western Europe, RT practices increase the SOC content and microbial activity in the top layers, but do not result in enhanced SOC sequestration when the entire soil profile is considered. A crop rotation with sugar beets or potatoes, with heavy soil disturbance every 2 or 3 years at the harvest of beets or potatoes, possibly limited the anticipated positive effect of RT agriculture in our research.

4.2. INTRODUCTION

In the framework of "global change" ample attention is given to the possible role of agricultural soils as a C sink. Increasing the SOC stock removes CO_2 from the atmosphere and this can help in the reduction of the greenhouse effect. Art. 3.4 of the Kyoto Protocol allows C sequestration due to human-induced agricultural activities, which have started after 1990, to be accounted for during the 2008-2012 commitment period (IPCC, 2000). Recent studies of the changes in SOC in agricultural fields (0-24 cm depth layer) in Flanders however, showed a decrease of 354×10^3 Mg SOC y^{-1} during the 1990's (Sleutel *et al.*, 2003a & b). SOC plays an important role in the formation of aggregates. A better aggregation stability of the soil improves the soil structure and reduces the risk of erosion (Holland, 2004). As a consequence of the decrease of SOC stock in the upper soil layer, it is likely that erosion will become more problematic in Flanders in the near future.

RT agriculture is often an effective measure to reduce erosion in the short term, which is one of the main reasons for farmers to switch to RT agriculture (see 1.2). RT agriculture can theoretically increase the SOC stock in the soil profile. Leaving crop residues at the soil surface under RT agriculture results in a lower rate and extent of decomposition because the residues physically separated from the soil nutrients and decomposers and in an environment with less favourable temperature and moisture conditions than under CT agriculture. The crop residues at the soil surface can reduce soil temperature and increase soil moisture content. The aggregates and soil structure are less disrupted under RT than CT agriculture where ploughing results in decomposition of physically protected SOM (Drury *et al.*, 1999; Stockfisch *et al.*, 1999; Balesdent *et al.*, 2000; Larney *et al.*, 2003; Baritz *et al.*, 2004; Six *et al.*, 2004a).

In a literature study about the effect of RT agriculture on various experimental fields Alvarez (2005) concluded that under a temperate climate RT agriculture increases the SOC stock compared to CT agriculture. However, this conclusion was based on measurements of % SOC in the upper 15 to 30 cm depth layer, as in most other studies. To have a complete view on the change in SOC stock, the % SOC has to be measured to a depth extending below the plough layer. After 11 years RT_C or RT_{DD} agriculture of a silt loam soil in Illinois, the SOC stock was significantly increased in the 0-20 cm depth layer compared to CT agriculture but the increase of the SOC stock in the 0-30 cm depth layer or deeper was not significant (Yang & Wander, 1999). The SOC stock in the 0-40 cm depth layer of a silt loam soil was similar after 20 years RT_C compared to CT agriculture in eastern Canada (Yang & Kay, 2001) and after 22 years RT_C or RT_{DD} compared to CT agriculture in Minnesota (Dolan *et al.*, 2006) but was increased in the 0-60 cm depth layer after 25 years RT_{DD} compared to RT_C and CT agriculture in eastern Canada (Deen & Kataki, 2003). Ahl *et al.* (1998) even found a decreased SOC stock in the 0-30 cm depth layer of a sandy loam soil and in the 0-50 cm depth layer of a silt loam soil after 9 years of RT_C compared to CT agriculture in Germany.

The lower macro-aggregate turnover under RT_{DD} compared to CT agriculture is believed to lead to a stabilization of POM in stable micro-aggregates since intensive tillage disrupts aggregates and formerly physically protected SOM becomes subjected to mineralization (Beare *et al.*, 1994). The current hypothesis is indeed that macro-aggregates (>250 µm) are formed around fresh residue which then becomes coarse intra-macro-aggregate POM (Figure 4.1) (Six *et al.*, 2000a). Fresh residue induces the formation of macro-aggregates because it is a C source for microbial activity and for the production of microbial-derived binding agents (Six *et al.*, 2000a & b; Jarecki & Lal, 2003). Fine intra-macro-aggregate POM within a macro-aggregate is derived from the decomposition and subsequent fragmentation of coarse intra-macro-aggregate POM. As fine intra-macro-aggregate POM is formed it gradually becomes encrusted with clay particles and microbial products to form micro-aggregates (>53 and <250 µm) within macro-aggregates. Eventually, the binding agents in macro-aggregates degrade, resulting in loss of macro-aggregate stability and the release of stable micro-aggregates, which become the building blocks for the next cycle of macro-aggregate formation. Micro-aggregate stability is higher and less dependent on agricultural management than macro-aggregate stability (Six *et al.*, 2000a & b). Moreover, the formation of macro-aggregates depends on fungal and bacterial activity, active root growth and fauna, e.g. earthworms, which is higher under RT than CT agriculture (Six *et al.*, 2002b).

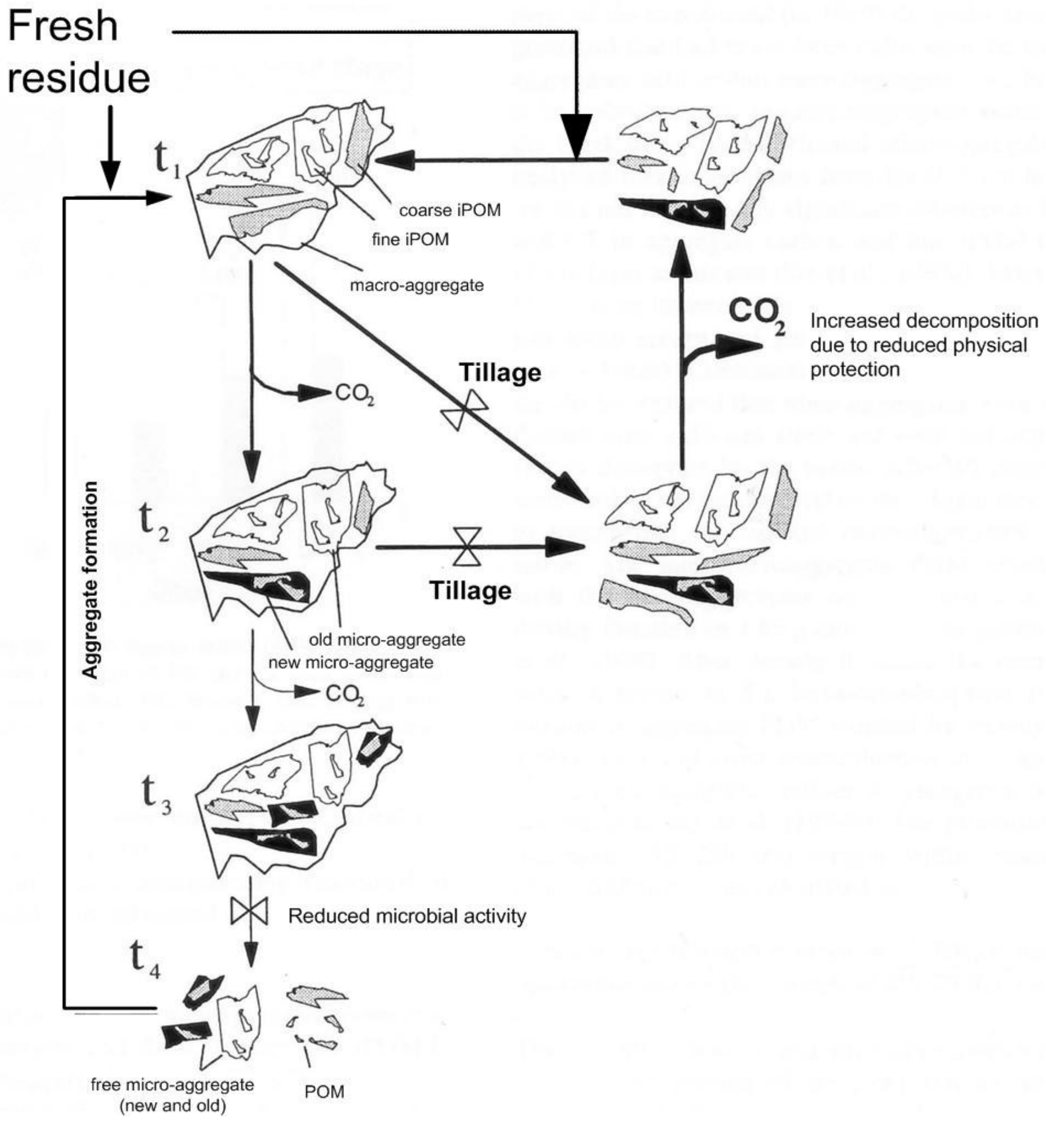


Figure 4.1 Formation of macro- and micro-aggregates (Six *et al.*, 2000a)

The physical fractionation procedure and the associated conceptual SOM model, which Six *et al.* (2002a) proposed, specifically takes physical protection of organic matter (OM) into account since it differentiates POM inside aggregates from POM outside of these aggregates. Five soil fractions are isolated: coarse free POM (coarse fPOM) (>250 μm), fine free POM (fine fPOM), intra-micro-aggregate POM (iPOM), intra-micro-aggregate silt + clay sized fraction and the remaining silt + clay sized soil fraction (<53 μm) (Figure 4.2). The coarse and fine fPOM and iPOM represent the unprotected and physically protected OM fraction, respectively. The intra-micro-aggregate and free <53 μm POM fractions are bound to silt and clay particles and have been associated with chemically and biochemically protected SOM pools.

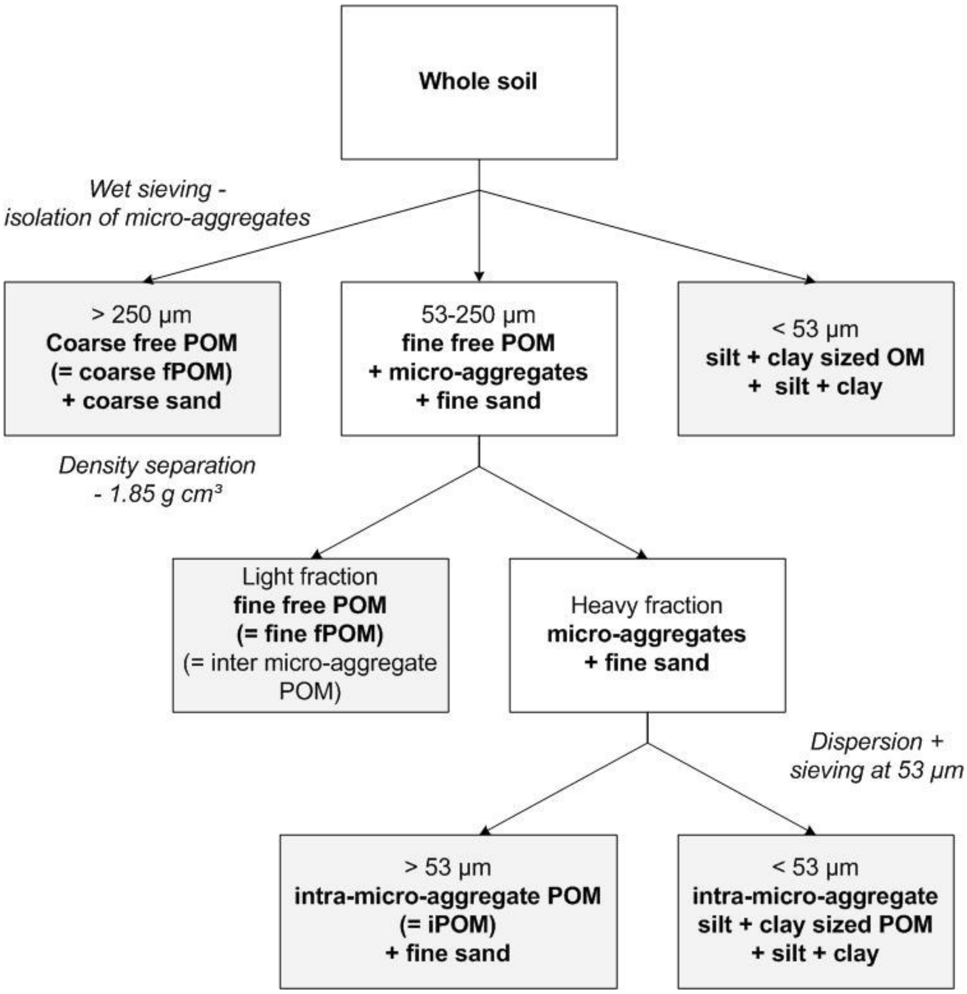


Figure 4.2 Physical fractionation as described by Six *et al.* (2002a)

Sleutel *et al.* (2005) physically fractionated the 0-10 cm depth layer of a clay loam field from Hungary after 3 years RT_C or RT_{DD} agriculture according to Six *et al.* (2002a). A higher percentage of dry matter (DM) of the coarse sand + coarse fPOM and silt + clay fraction was measured while the DM of the intra-micro-aggregate silt + clay sized fraction was decreased under RT_C and RT_{DD} compared to CT agriculture. The 3 years RT agriculture resulted in an absolute increase of SOC present in the five size and density fractions compared to CT agriculture. There was a relative increase of the two fPOM fractions in the RT compared to CT fields and therefore a shift towards more labile OM. Up to 60% of the accumulation of SOC could be attributed to an increase of SOC in fPOM and up to 30% iPOM. Wander & Bollero (1999) found no significant higher POM in the upper 0-15 cm depth layer from RT_{DD} (>5 years) compared to CT fields from farmers in Illinois. After 10 years RT_{DD} agriculture, Wander & Bidart, (2000) measured significantly higher POM in the upper 0-5 cm depth layer under RT compared to CT agriculture in Illinois while Mikha & Rice (2004) detected that the number of large (>2000 µm) and small macro-aggregates (>250 and <2000 µm) in the 0-5 cm depth layer of a silt loam soil in Kansas were significantly increased compared to CT agriculture. The aggregate associated SOC of the large and small macro-aggregates and micro-aggregates in the 0-5 cm depth layer of the RT_{DD} field was significantly higher than the CT field. Crushing the macro- and micro-aggregates resulted in a significantly increased C mineralization of the OC of the large and small macro-aggregates and micro-aggregates. The highest increase was measured for the large macro-aggregates. Oorts *et al.* (2007) measured an increase of large and small macro-aggregates and intra-aggregate silt + clay associated OM and intra-aggregate POM in a 32 year old RT_{DD} silt loam field compared to CT field in Northern France. Sieving the moist soil to 2 mm didn't change the C mineralization of the RT_{DD} and CT field. However, sieving to 250 or 50 µm resulted in a small decrease of C mineralization in the 0-5 cm depth layer, an increase in the 5-20 cm depth layer and an overall small increase in the 0-20 cm depth layer of the RT_{DD} field while the C mineralization of the 0-20 cm depth layer of the CT field was unaffected. Increased loss of SOM following sieving or crushing macro- and micro-aggregates of RT fields corroborates the theory that more relatively labile SOM is stored as occluded POM in less disturbed soils (Balesdent *et al.*, 2000; Mikha & Rice, 2004; Oorts, 2006; Oorts *et al.*, 2007).

It is important to know to what extent the SOC is stable, i.e. how much of the stored SOC will be released in case RT fields are ploughed (Dick *et al.*, 1998; Stockfisch *et al.*, 1999; Kettler *et al.*, 2000; Conant *et al.*, 2007). Stockfisch *et al.* (1999) found a more pronounced stratification of SOC in the 0-50 cm depth layer of a silt loam field for 21 years under shallow RT compared to CT agriculture in Germany but the SOC stock was not significantly higher. Ploughing the RT field resulted in a reduction of the stratification and a significant decrease of the SOC stock of the RT compared to CT field. Measurements of Dick *et al.* (1998) indicated that ploughing a RT_{DD} plot of a loam soil in Michigan after 7 years RT_{DD} agriculture resulted in a redistribution of the % SOC and stimulated C mineralization. Five years after ploughing, the % SOC was higher in the 0-20 cm depth layer than the plot that had been ploughed for 12 years but lower than the plot that had remained RT_{DD} agriculture during the whole experiment. The same trend was found when RT_{DD} or RT_C fields were ploughed as a weed control measure of a silt loam soil in Nebraska (Kettler *et al.*, 2000). These research results indicate that RT agriculture under cereal crop rotations can stabilize some SOC and sequester a small amount of C into the soil.

These studies suggest that changes in SOC stratification and stock, and C mineralization dynamics, when converting to RT agriculture, are strongly dependent on soil conditions and type of RT practices adapted. However, little is known about the influence of RT agriculture on % SOC, the SOC stock, MB-C and potential C mineralization under the specific Western European climatic and soil conditions and with rotations containing crops that seem less suitable under RT agriculture including an important share of root and tuber crops. Therefore, this research focussed on the short and long term effects of RT agriculture on % SOC and SOC stocks, MB-C, distribution of SOC in the 0-10 cm depth layer over the different fractions and C mineralization under the specific Western European conditions.

4.3. MATERIALS AND METHODS

4.3.1. Soil sampling

Soil samples were taken in December 2004 for fields 1-8 and 17-18 and in March 2005 for fields 9-16 for the determination of % SOC and MB-C and for measuring the C mineralization rate in lab incubations (see 3.3.1).

Additional soil samples were taken for the physical fractionation in June – July 2005 (see 3.3.1).

4.3.2. Soil organic carbon

Five subsamples per plot were taken from the 0-5, 5-10, 10-15, 15-20, 20-30, 30-40 and 40-60 cm depth layers to measure the % SOC in the soil profile. The subsamples were bulked per layer and per plot into one composite sample, thoroughly mixed and let to dry to the air in the laboratory. The % SOC was measured with the method of Walkley & Black (1934).

4.3.3. Microbial biomass carbon

Five subsamples per plot were taken of the 0-10, 10-20, 20-30 and 30-40 cm depth layers, were bulked into one composite sample and homogenized. 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 before and after fumigation was analyzed with a TOC analyzer (TOC-V CPN, Shimadzu, Japan).

To correct for the incomplete release and extraction of MB-C an extraction efficiency of carbon (K_{EC}) factor is needed (Voroney *et al.*, 1993; Joergensen & Mueller, 1996). K_{EC} depends on the soil depth (Dictor *et al.*, 1998; Tessier *et al.*, 1998). However, the variation in the value of K_{EC} is relatively small in the upper 50 cm and a correct K_{EC} is not essential when aiming to compare different soils (Dictor *et al.*, 1998). As suggested by Voroney *et al.* (1993) and Jenkinson *et al.* (2004) an extraction efficiency K_{EC} value of 0.25 was used.

4.3.4. Carbon mineralization

In order to measure the C mineralization, soil cores inside PVC tubes with a 6.8 cm inner diameter and 7 cm height were used. On each field, visible crop residues were removed before sampling. The tubes were pushed into the soil until they were filled with 5 cm soil. The tube was carefully dug out, excess soil from the bottom of the tube was removed, and the bottom was covered with a PVC cap. Two tubes were taken per plot. One of the duplicate tubes per plot was incubated “undisturbed” (U). In order to simulate the effect of an intensive tillage operation, the soil of the other tube was removed and the tube was then refilled with the “disturbed soil” (D), adjusted to the same bulk density. Since 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 fall within the optimum range of soil moisture content for C mineralization (De Neve & Hofman, 2002), it was 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.

The % WFPS was calculated as (Linn & Doran, 1984):

$$\% \text{ WFPS} = \frac{\text{gravimetric water content x BD x 100}}{\text{total soil porosity}} \qquad (3)$$

with total soil porosity = 1 – (BD / 2.65)

The tubes with field moist soil were placed inside 2 l glass jars. Small vials containing 15 ml of 1 M natrium hydroxide (NaOH) solution were placed in the jars to trap evolved CO_2. The jars were closed airtight and incubated at 14 °C for 12 weeks. Samples were taken after 1, 2 and 4 days, twice weekly in weeks 2 to 5 and weekly during the rest of the experiment by removing the NaOH vials. Amounts of evolved CO_2 were measured by titration of the NaOH with 1 M HCl to pH 8.3 in the presence of barium dichloride ($BaCl_2$) (Anderson, 1982). After removal of the vials, the glass jars were left open for 1 h to allow replenishment of dioxygen (O_2). Next, the soil moisture content was adjusted if needed, fresh vials containing NaOH were added, and the jars were closed again to continue the C mineralization measurements.
The incubation experiments started on 7 December 2004 for fields 1-4; 13 December for fields 5 and 6 and 20 December for fields 7-10.

C mineralization rates became linear after the first week of incubation, showing that the disturbance of microbial activity was kept to a minimum.

The C mineralization rates were estimated by fitting a zero-order kinetic model $C = k_C \cdot t$ to the cumulative CO_2-C production, where t is the period (in days) and k_C is the carbon mineralization rate (mg C kg^{-1} dry soil day^{-1}) using data from day 7 until day 91 in the linear part of the C mineralization.

4.3.5. Physical fractionation

Ten subsamples per plot were taken from the 0-10 cm depth layer and were bulked into one composite sample, thoroughly mixed and were left to dry in the laboratory. The physical fractionation procedure was carried out in triplicate. To avoid possible slaking of micro-aggregates during wet sieving, all soil samples were pre-wetted according the method used by Gale *et al.* (2000): a 10 g sub sample was weighed on a 20 µm nylon filter on top of a glass-fibre filter (Whatman GF/A) in a Petri-shell. The soil samples were wetted by slowly adding water to the edges of the glass-fibre filter and by allowing it to be absorbed by the soil. The samples were left to equilibrate overnight in a refrigerator. The complete physical fractionation procedure described by Sleutel *et al.* (2006a), was based on the procedure of Six *et al.* (1998; 2000a). Five soil fractions were isolated: coarse fPOM (>250 µm), fine fPOM, iPOM, intra-micro-aggregate silt + clay size fraction and the remaining <53 µm fraction (Figure 4.2). The <53µm fractions of the soils containing calcium carbonate ($CaCO_3$) were analyzed for total carbon (TC) and inorganic carbon (IC) with a total organic carbon (TOC) analyzer (TOC-V CPN, Shimadzu, Japan). The TOC was calculated as TC – IC. Sub samples of the separated soil fractions not containing $CaCO_3$ were analyzed for TOC with a CNS-analyzer (Variomax, Elementar Analysesysteme, Germany).

4.3.6. Statistical analysis

The homogeneity of variances was tested with the Levene's test (P = 0.05). A *t*-Test was used to assess whether % SOC per depth layer, results of the physical fractionation and SOC stock were significant different between fields for locations with only 2 fields. One way ANOVA with field as factor combined with post hoc Duncan test and Welch combined with post hoc Games-Howell test were used to determine significant differences in % SOC per depth layer, results of the physical fractionation and SOC stock for the locations with more than 2 fields for homogeneous and heterogeneous variances, respectively.

The C mineralization rate was calculated by linear regression of the cumulative C mineralization data to time. Significant differences in the fitted C mineralization rate were searched per location with one way ANOVA/post hoc Duncan test and Welch/post hoc Games-Howell test for homogeneous and heterogeneous variances, respectively. A correlation analysis between the fitted C mineralization rate, MB-C content, % clay and % SOC was performed using a Pearson's correlation matrix. An univariate general linear model was used to correlate the fitted C mineralization rate with the results of the physical fractionation (SPSS version 12.0, SPSS Inc., Chicago).

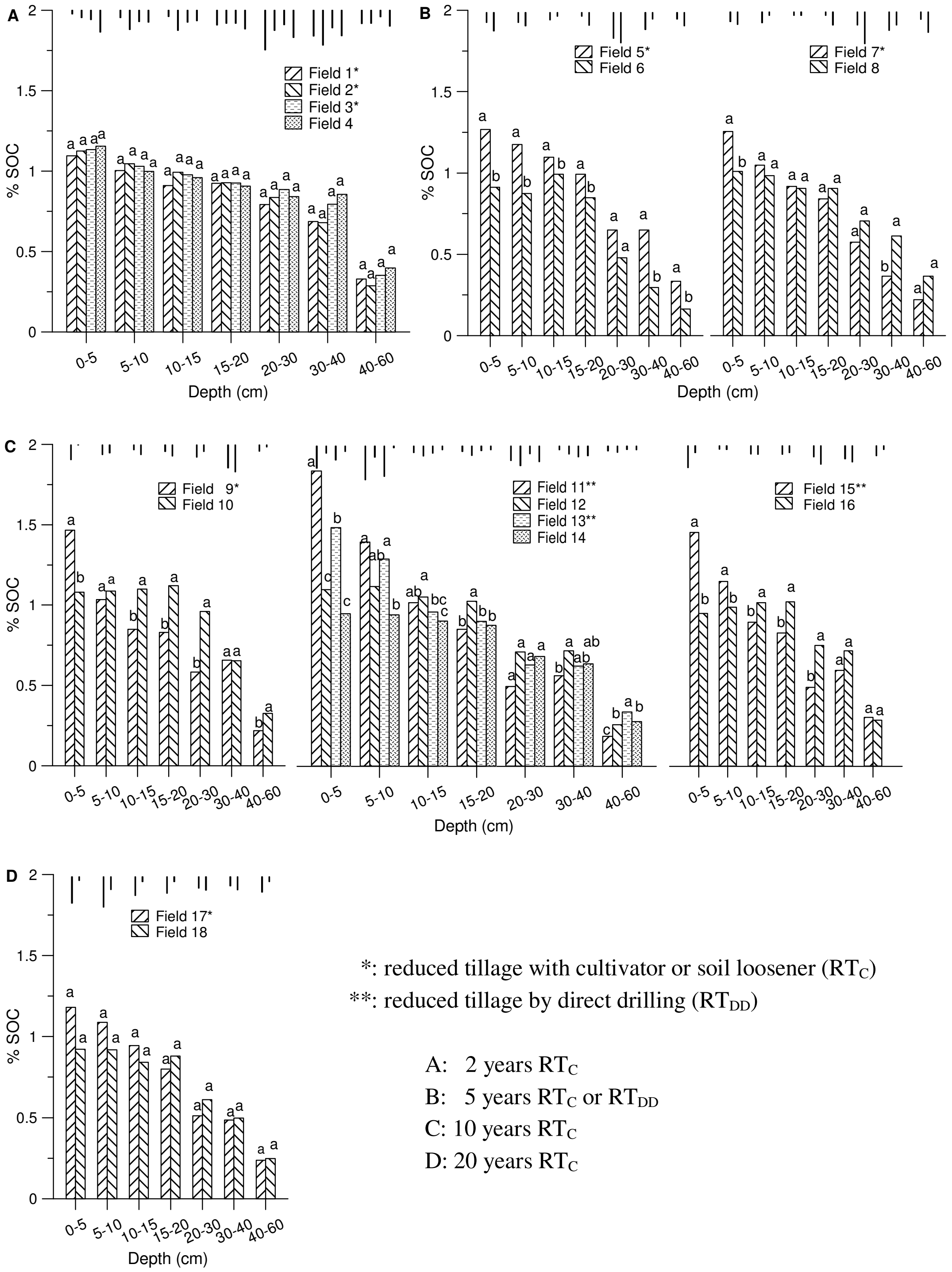
4.4. RESULTS

4.4.1. Soil organic carbon percentage and stock

The depth stratification of % SOC in the soil profile of the RT fields was more pronounced compared to CT fields (Figure 4.3). The ratio of % SOC in the layer 0-5 cm to the layer 40-60 cm was on average 5.0 and 3.2 for the RT and CT fields, respectively. However, the differences in degree of stratification between RT and CT agriculture varied between the investigated locations.

There was no significant difference (P = 0.05) in % SOC between RT_{C_2} fields 1-3 managed under RT agriculture for a short term (2 years) and CT field 4 (Figure 4.3A). A significantly higher % SOC was measured in the 0-5 cm depth layer for the fields under 5 years RT compared to CT agriculture (Figure 4.3B). The % SOC in RT_{C_5} field 5 was (significantly) higher in the whole profile (0-60 cm) compared to field 6. The % SOC of field 7 under 5 years RT agriculture tended to be higher than in CT field 8 in the 5-10 cm depth layer and lower in the 15-20, 20-30 and 40-60 cm depth layers and was significantly lower (P = 0.05) in the 30-40 cm depth layer. After 10 years under RT agriculture, the % SOC was significantly higher (P = 0.05) in the 0-5 cm depth layer compared to CT agriculture (Figure 4.3C). In the 5-10 cm depth layer there was a significant higher % SOC in the RT_{DD_10} fields compared to CT fields. The % SOC was (significantly) lower in the 10-15, 15-20 and 20-30 cm depth layers in RT_{C_10} field 9 in comparison with CT field 10. There was a lower % SOC in the 10-15, 15-20 and 20-30 cm depth layers of the RT_{DD_10} fields. Deeper in the soil profile the % SOC was comparable between the CT and RT fields. After 20 years of RT agriculture, the % SOC was higher in the upper 0-5, 5-10 and 10-15 cm depth layers in RT_{C_20} field 17, but lower deeper in the profile as compared to CT field 18 (Figure 4.3D). However, these differences in % SOC between fields 17 and 18 were not significant (P = 0.05).

The SOC stock of the 0-60 cm depth layer (Mg SOC ha^{-1}) was calculated using the measured bulk densities (Figure 4.4). The SOC stock of fields 1 to 4 was similar for all four fields. The lower % SOC and comparable soil bulk densities of CT field 6 resulted in a significant lower (P = 0.05) SOC stock in the 0-60 cm depth layer compared to RT field 5. The SOC stock in field 7 and 8 was comparable. The total SOC stock of the 0-60 cm depth layer was not significantly (P = 0.05) different between the CT and RT fields after 10 years of RT agriculture, except the SOC stock of RT_{C_10} field 9 was significantly lower than CT field 10. The SOC stock of RT_{C_20} field 17 under 20 years RT agriculture was comparable to that of the CT field 18.



*: reduced tillage with cultivator or soil loosener (RT_C)

**: reduced tillage by direct drilling (RT_{DD})

A: 2 years RT_C

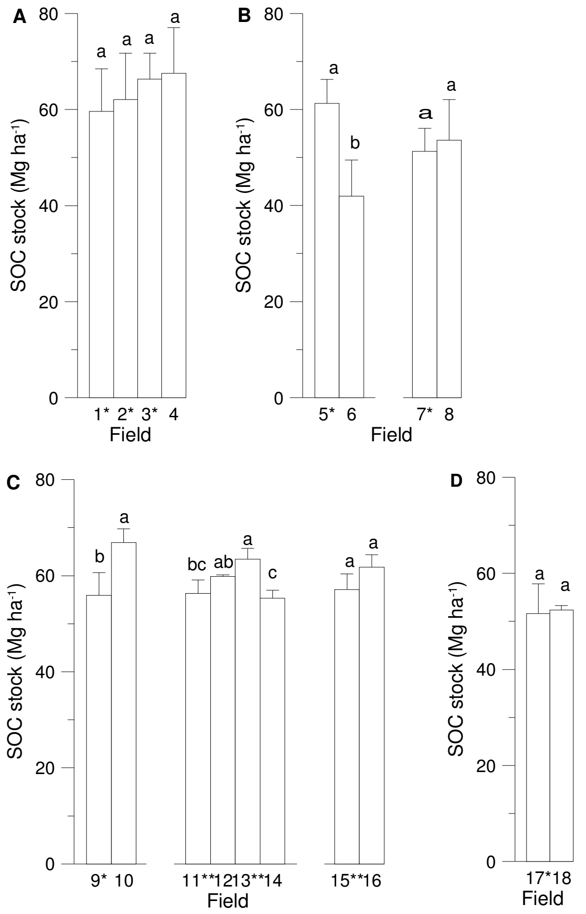
B: 5 years RT_C or RT_{DD}

C: 10 years RT_C

D: 20 years RT_C

same letters indicate no significant differences between tillage treatments per location per depth layer (P = 0.05) (one way ANOVA/Duncan post hoc test or *t*-Test)

Figure 4.3 Soil organic carbon (SOC) (%) (vertical lines = standard deviation) of the 0-5, 5-10, 10-15, 15-20, 20-30, 30-40 and 40-60 cm depth layers of the 18 selected fields



*: reduced tillage with cultivator or soil loosener (RT_C)

**: reduced tillage by direct drilling (RT_{DD})

A: 2 years RT_C
B: 5 years RT_C or RT_{DD}
C: 10 years RT_C
D: 20 years RT_C

same letters indicate no significant differences between tillage treatments between tillage treatments per location (P = 0.05) (one way ANOVA/Duncan post hoc test or *t*-Test)

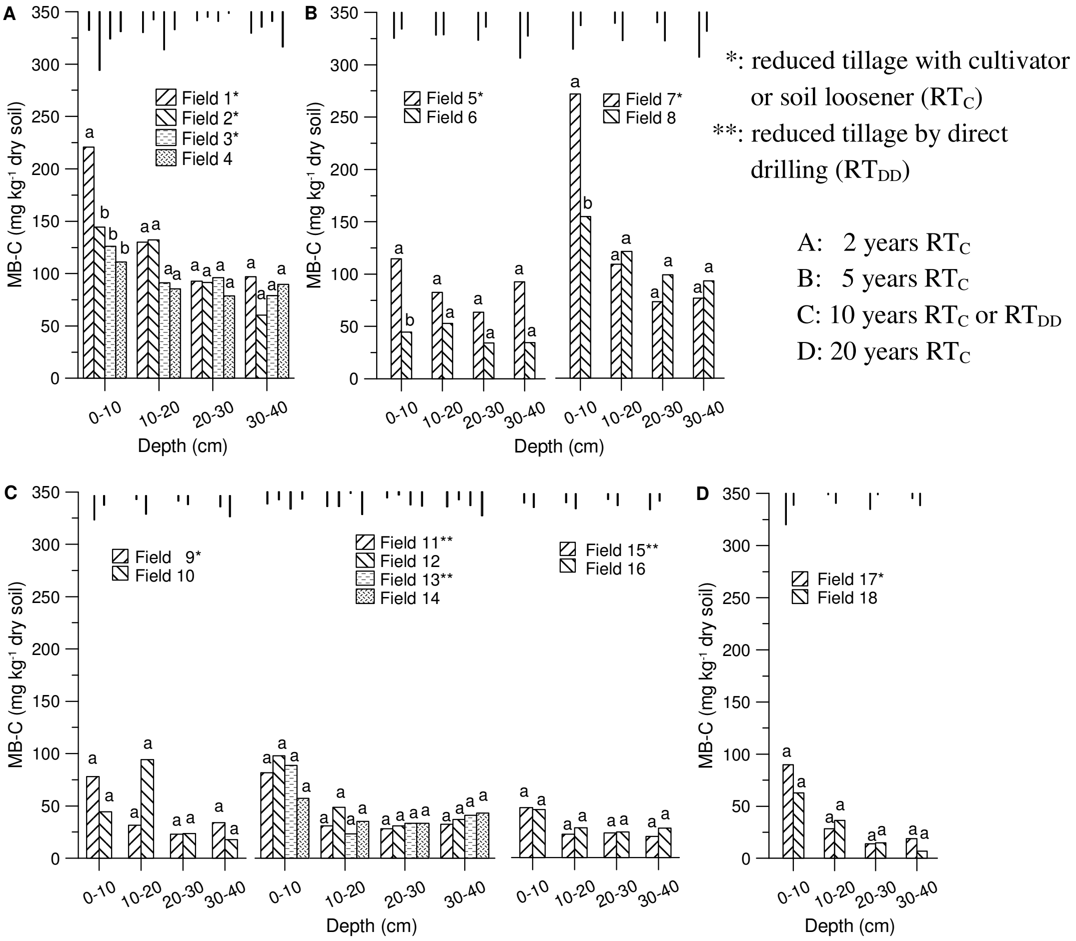
Figure 4.4 Soil organic carbon (SOC) stock (Mg ha^{-1}) (vertical lines = standard deviation) in the 0-60 cm depth layer of the 18 selected fields

4.4.2. Microbial biomass carbon

The MB-C content in the upper 10 cm depth layer was 1.5 to 3 times higher in the RT compared to CT fields (Figure 4.5). We found a more pronounced stratification for the MB-C content than the % SOC under RT compared to CT agriculture at the same location. The ratio's of the MB-C content of the 0-10 cm to 30-40 cm depth layer were on average 2.5 and 2.2 and of % SOC 2.1 and 1.6 under RT and CT agriculture, respectively.

The MB-C in the 0-10 cm depth layer of CT field 4 was significantly lower (P = 0.05) than in RT_{C_2} field 1 but comparable with RT_{C_2} fields 2 and 3 (Figure 4.5A). Deeper in the soil profile, the MB-C content was comparable for fields 1-4. The MB-C content was significantly higher in the 0-10 cm depth layer under

5 year RT than CT agriculture (Figure 4.5B). Deeper in the soil profile the MB-C content was comparable between the CT and 5 years RT fields. After 10 years RT agriculture a significant higher (P = 0.05) MB-C content was measured in the 0-10 cm depth layer of RT_{C_10} field 9 compared to CT field 10 in Maulde and RT_{DD_10} fields 13 compared to CT field 14 in Villers-le-Bouillet. The MB-C content tended to be lower in the 10-20 cm depth layer under RT compared to CT agriculture. The MB-C content of RT_{C_20} field 17 (20 years RT agriculture) was higher in the 0-10 cm depth layer and lower in the 10-20 cm depth layer than in CT field 18 (Figure 4.5C).



*: reduced tillage with cultivator or soil loosener (RT_C)
**: reduced tillage by direct drilling (RT_{DD})

A: 2 years RT_C
B: 5 years RT_C
C: 10 years RT_C or RT_{DD}
D: 20 years RT_C

same letters indicate no significant differences between tillage treatments between tillage treatments per location and per depth layer (P = 0.05) (one way ANOVA/Duncan post hoc test, Welch/Games-Howell post hoc test or *t*-Test)

Figure 4.5 Microbial biomass carbon (MB-C) (mg kg^{-1} dry soil) (vertical lines = standard deviation) of the 0-1, 10-20, 20-30 and 30-40 cm depth layers of the 18 selected fields

4.4.3. Physical fractionation

The dry matter (DM) distributions of the size and density fractions isolated according to physical fractionation method of Six *et al.* (2000a) are presented in Table 4.1. The sum of the DM amounts of coarse fPOM, fine fPOM and iPOM fractions ranged between 7 and 33% and was higher in the RT than CT fields at the same locations, except for RT_{C_2} field 3 compared to CT field 4 in Heestert. This sum was roughly equal to the sand fraction DM obtained from the soil texture analysis, except for fields 2, 3, 4 and 6.

In all fields, the DM amounts of the intra-micro-aggregate silt and clay fraction and the free silt and clay fraction ranged between 22-38% and 38-63%, respectively. These DM contents were smaller in the RT than CT fields, except for RT_{C_2} field 3 compared to CT field 4.

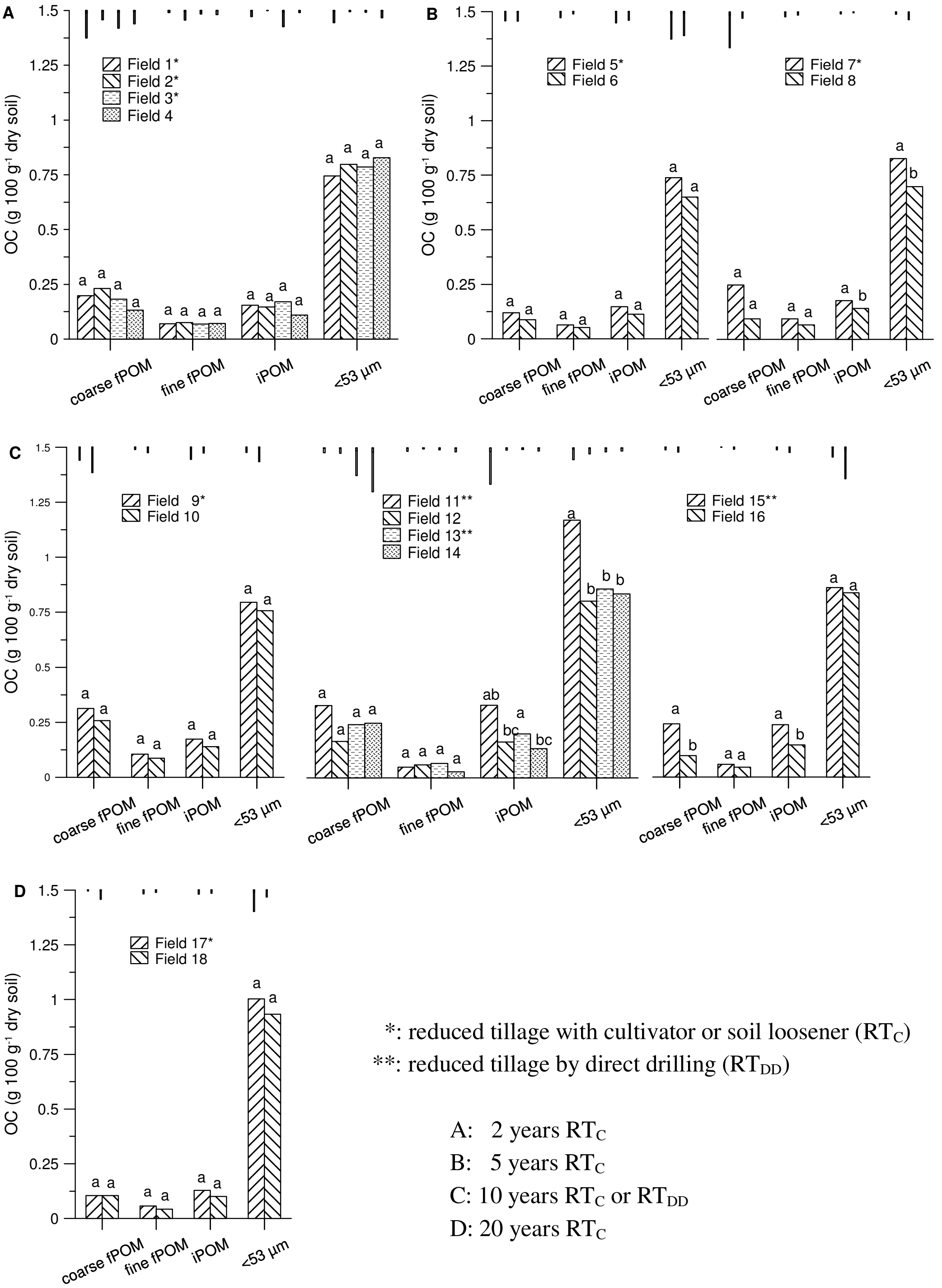
The amounts of OC in all three isolated POM fractions was found to be (significantly) higher both on an absolute (g OC 100 g^{-1} dry soil) as well as relative basis (g OC g^{-1} SOC) in the RT compared to the CT fields (Figure 4.6 and Figure 4.7), except in Heestert (RT_{C_2} fields 1-3 compared to CT field 4). In general the difference was the highest for the coarse fPOM fraction. For some fields, the amount was twice as high under RT compared to CT agriculture (e.g. RT_{DD_10} field 15 compared to CT field 16).

In contrast, the absolute amount of OC in the intra-aggregate and free silt and clay fractions was only slightly higher in the RT than CT fields. As a consequence of the relative higher amount of OC in the POM fractions, the relative amount of OC in the intra-aggregate and free silt and clay fractions was lower under RT than CT agriculture.

Table 4.1 Distribution of the dry matter content of the coarse sand + coarse free particulate organic matter (fPOM) (>250 µm), fine fPOM (53-250 µm), intra-aggregate organic matter (iPOM) (53-250 µm) and <53 µm fraction isolated according to physical fractionation method of Six *et al.* (2000a) in % (averages with standard deviation between brackets) of the 0-10 cm depth layer of the 18 selected fields

Field		Coarse sand + coarse fPOM (>250 µm)	Micro-aggregates + fine free POM +fine sand (53-250 µm)			Silt + clay (<53 µm)
			fine fPOM	>53 µm (iPOM)	<53 µm (silt + clay)	
1	RT_{C_2}	1.49 (0.33) a	0.19 (0.05) a	30.5 (4.3) a	28.6 (6.4) a	37.9 (5.1) a
2	RT_{C_2}	1.82 (0.41) a	0.21 (0.13) a	24.8 (2.6) b	30.1 (1.2) a	43.2 (1.3) a
3	RT_{C_2}	1.47 (0.47) a	0.18 (0.04) a	20.3 (1.0) b	21.2 (7.9) a	55.5 (6.0) a
4	CT	1.40 (0.21) a	0.18 (0.07) a	23.7 (0.7) b	32.0 (2.0) a	42.8 (2.8) a
5	RT_{C_5}	2.20 (0.44) a	0.32 (0.07) a	27.0 (5.6) a	29.8 (1.2) a	42.9 (2.5) a
6	CT	0.84 (0.20) a	0.16 (0.04) a	12.8 (0.8) a	36.6 (2.9) a	46.7 (3.1) a
7	RT_{C_5}	3.10 (0.30) a	0.32 (0.09) a	29.9 (3.1) a	23.3 (2.1) a	44.7 (1.3) a
8	CT	1.86 (0.20) b	0.21 (0.06) a	26.5 (1.5) a	26.2 (2.9) a	43.5 (1.1) a
9	RT_{C_10}	2.21 (0.86) a	0.28 (0.03) a	9.1 (1.8) a	36.1 (2.1) a	47.8 (2.6) a
10	CT	1.81 (0.74) a	0.24 (0.09) a	8.7 (1.6) a	38.2 (6.2) a	55.7 (4.8) a
11	RT_{DD_10}	2.38 (0.59) a	0.16 (0.06) a	6.1 (0.8) a	32.5 (9.2) a	58.9 (10.2) a
12	CT	1.61 (0.26) a	0.17 (0.02) a	6.2 (1.3) a	36.0 (2.3) a	54.7 (1.8) a
13	RT_{DD_10}	2.31 (0.75) a	0.18 (0.03) a	5.8 (0.3) a	35.5 (3.2) a	54.6 (3.7) a
14	CT	1.32 (0.07) a	0.05 (0.04) b	5.7 (0.1) a	29.7 (4.1) a	63.2 (4.1) a
15	RT_{DD_10}	1.64 (0.45) a	0.14 (0.00) a	14.5 (0.9) a	34.5 (2.7) a	48.5 (1.6) a
16	CT	1.01 (0.45) a	0.10 (0.04) a	12.3 (0.6) b	35.6 (6.4) a	49.1 (7.2) a
17	RT_{C_20}	2.33 (0.37) a	0.16 (0.06) a	6.9 (0.3) a	35.7 (9.3) a	53.9 (8.9) a
18	CT	2.24 (0.55) a	0.11 (0.04) a	6.1 (0.7) a	37.9 (2.6) a	53.7 (2.4) a

RT_C: reduced 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 between tillage treatments per location and per depth layer (P = 0.05) (one way ANOVA/Duncan post hoc test, Welch/Games-Howell post hoc test or *t*-Test)

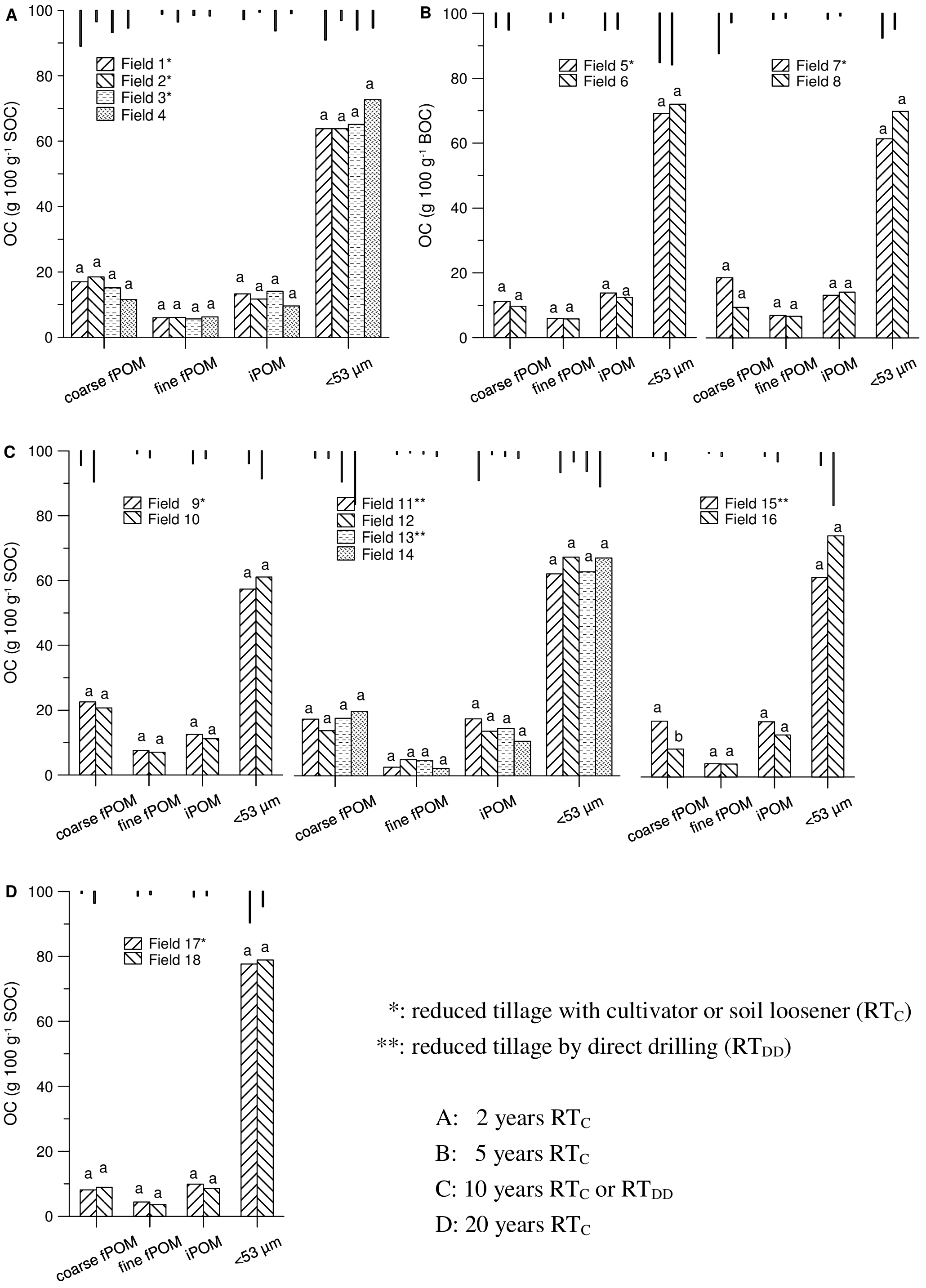


*: reduced tillage with cultivator or soil loosener (RT$_C$)
**: reduced tillage by direct drilling (RT$_{DD}$)

A: 2 years RT$_C$
B: 5 years RT$_C$
C: 10 years RT$_C$ or RT$_{DD}$
D: 20 years RT$_C$

same 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)

Figure 4.6 Absolute amount of organic carbon (OC) (g 100 g^{-1} dry soil) in the coarse free particulate organic matter (fPOM) (>250 µm), fine fPOM (53-250µm), intra-aggregate organic matter (iPOM) (53-250 µm) and <53 µm soil fractions isolated according to physical fractionation method of Six *et al.* (2000a) (vertical lines = standard deviation) of the 0-10 cm depth layer of the 18 selected fields



*: reduced tillage with cultivator or soil loosener (RT$_C$)

**: reduced tillage by direct drilling (RT$_{DD}$)

A: 2 years RT$_C$

B: 5 years RT$_C$

C: 10 years RT$_C$ or RT$_{DD}$

D: 20 years RT$_C$

Same 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)

Figure 4.7 Relative distribution of organic carbon (OC) (g 100 g^{-1} SOC) in the coarse free particulate organic matter (fPOM) (>250 µm), fine fPOM (53-250µm), intra-aggregate organic matter (iPOM) (53-250 µm) and <53 µm soil fractions isolated according to physical fractionation method of Six *et al.* (2000a) (vertical lines = standard deviation) of the 0-10 cm depth layer of the 18 selected fields

4.4.4. Carbon mineralization

In Figure 4.8 the measured cumulative CO_2 respiration of the disturbed and undisturbed soil cores of 0-5 cm depth layer of fields 9, 10 and 11 are given as an example.

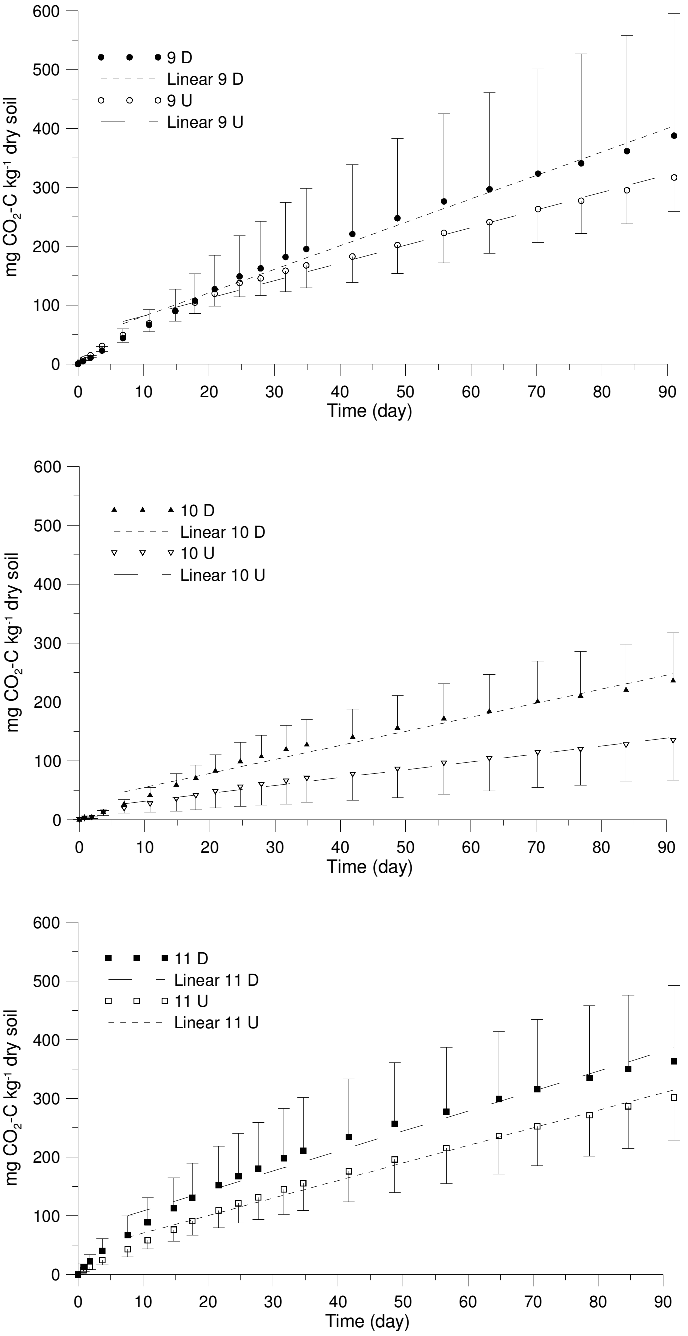
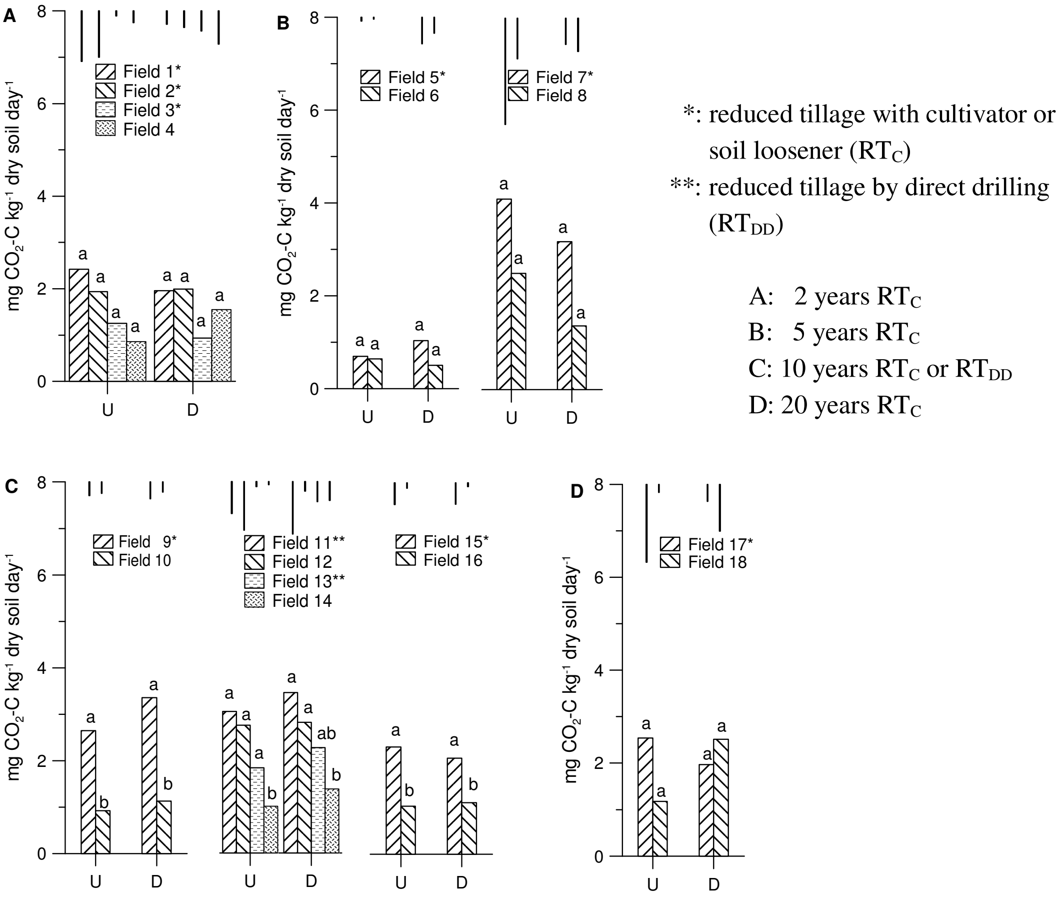


Figure 4.8 Cumulative respiration (mg CO_2-C kg^{-1} dry soil) of the undisturbed (U) and disturbed (D) soil samples (vertical lines = standard deviation) of the 0-5 cm depth layer of fields 9 (reduced tillage by soil loosener), 10 (conventional tillage) and 11 (reduced tillage by direct drilling)

The estimated C mineralization rate in the undisturbed soil cores varied between 0.6 and 4.1 mg C kg^{-1} dry soil day^{-1}. The C mineralization rate in the undisturbed soil cores of the RT fields was 1.5 to 3 times higher than the C mineralization rate under CT agriculture, except for fields 5 and 6 (Figure 4.9). However, these differences were not significant due to the high variability of the measurements. Disruption of the soil to simulate an intensive tillage operation resulted in a reduction or increase of C mineralization rate, but the differences between the disturbed and undisturbed soil cores were not significant.



*: reduced tillage with cultivator or soil loosener (RT$_C$)

**: reduced tillage by direct drilling (RT$_{DD}$)

A: 2 years RT$_C$
B: 5 years RT$_C$
C: 10 years RT$_C$ or RT$_{DD}$
D: 20 years RT$_C$

The C mineralization rate was estimated by fitting a zero-order kinetic model $C = k_C \cdot t$ to the cumulative CO$_2$-C production, where t is the period (days) and k_C is the mineralization rate (mg CO$_2$-C kg^{-1} dry soil day^{-1}) using data from day 7 until day 91 in the linear part of the C mineralization

same 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)

Figure 4.9 Carbon mineralization rate (mg CO$_2$-C kg^{-1} dry soil day^{-1}) of the undisturbed (U) and disturbed (D) soil samples (vertical lines = standard deviation) of the 0-10 cm depth layer of the 18 selected fields

The C mineralization rate was also expressed as a percentage of the SOC content. After incubation of 90 days, on average 1.6±0.7% and 1.5±0.5% of the SOC content was mineralized in the undisturbed and disturbed soil cores of the RT fields, respectively. For the CT fields only 1.2±0.7% and 1.4±0.7% of the SOC content was mineralized in the undisturbed and disturbed soil cores, respectively.

4.5. DISCUSSION

4.5.1. Soil organic carbon percentage and stock

In the selection of the fields much care was taken to select paired fields which were similar from a soil type and management point of view. Obviously some practices such as maintaining crop residues on the field (e.g. RT_{C_5} field 5) are an inherent characteristic of RT agriculture which will result in more OC input, but it is not possible and not even desirable to separate these effects, as this would not be according to the common agricultural practices in RT and CT agriculture (see 2.1). Therefore, searching for the effect of the change of management to RT agriculture not only the change in tillage intensity but also applied EOC has to be considered as for example including a green manure in the crop rotation can result in an extra 0.25 to 0.42 Mg EOC (Sleutel *et al.*, 2007a).
Since the period between soil tillage and sampling influences the measured BD, the calculated SOC stock depends on the sampling date (Tebrügge & Düring, 1999). The paired fields, i.e. the fields at the same location in this study, were tilled at the same time and hence the SOC stock can be directly compared.

Researchers often concluded that the higher stratification of % SOC in loamy RT experimental fields under a temperate climate resulted in a higher SOC stock of RT compared to CT fields (Alvarez, 2005). However, this conclusion was mostly based on shallow measurements of % SOC in the top layers of the experimental fields. In this study no higher SOC stock was found in the 0-60 cm depth layer under RT, even after 20 years, than CT agriculture in spite of the fact that the amount of EOC of the manure and crop residues beet - winter wheat / mustard rotation of fields 17 and 18 was comparable, namely 1780 kg EOC y^{-1} in RT_{C_20} field 17 compared to 1645 kg EOC y^{-1} in CT field 18. The lower amount of EOC applied with the manure in RT_{C_20} field 17 (only 30 Mg cattle manure ha^{-1}) compared to CT field 18 (40 Mg cattle manure ha^{-1}) in 2003 was compensated with the EOC of the straw that was left on the soil surface of

RT_{C_20} field 17 (Table 2.15). The cultivation of grain maize on RT_{C_5} field 5 resulted in a higher amount of crop residues and as a consequence a larger input of EOC compared to fodder maize and potatoes of CT field 6 (Table 2.5). The higher amount of EOC in combination with reduced tillage intensity might explain the higher SOC stock of RT_{C_5} field 5 compared to CT field 6. Since farmer 7 had composted his manure in 2003 and 2004, a large fraction of the OC applied through manure may have remained in the soil (Table 2.7). Application of composted manure and sowing green manure has not resulted in a higher SOC stock after 5 years RT agriculture in RT_{C_5} field 7 compared to CT field 8. Sowing the green manure in RT_{C_5} field 7, however, resulted in extra tillage times compared to CT field 8.

The studies of e.g. Yang & Kay (2001); Halvorson *et al.* (2002) and Dolan *et al.* (2006) confirm our finding that long term RT agriculture does not necessarily result in a higher SOC stock under RT than CT agriculture. Ahl *et al.* (1998) even found a decreased SOC stock after 9 years of RT compared to CT agriculture in Germany. A 2 or 3 year crop rotation with sugar beets or potatoes, with heavy soil disturbance every 2 or 3 years at the harvest of beets or potatoes, possibly limited the anticipated positive effect of RT agriculture in the research of Ahl *et al.* (1998) and perhaps also in the present research. In crop rotations with cereals, maize and soybean SOC stocks are more likely to be increased by RT agriculture, because of the absence of soil disturbance at harvest. Moreover, although tillage intensity in this study was lower in the RT compared to CT fields, the soil disturbance caused by tillage remained relatively intense in the RT fields.

Another important consideration is that the net rate of accumulation strongly depends on the degree of saturation of the soil with SOC. In fields 1-4 the SOC content was relatively high at the onset of the experiment, which may have limited the potential for SOC sequestration in these soils. Furthermore, according to Alvarez (2005) the SOC (g cm^{-3}) will reach a new equilibrium 25 to 30 years after changing to RT agriculture. The accumulation rate of SOC starts slowly and a maximum accumulation rate can be found 5 to 10 years after changing the management (Alvarez, 2005; West & Six, 2007). This could possibly explain why there was no change in % SOC in the fields 1-4.

4.5.2. Microbial biomass carbon

Comparing the MB-C of the fields in Kluisbergen (fields 5 and 6) and Baugnies (fields 7 and 8), it is clear that the MB-C was lower in Kluisbergen (115±25 and 45±16 mg MB-C kg^{-1} dry soil in RT_{C_5} field 5 and CT 6, respectively) compared to Baugnies (272±36 and 155±13 mg MB-C kg^{-1} dry soil in RT_{C_5} field 7 and 8 under CT, respectively). Tillage and application of manure was done in August in fields 7 and in October in field 8, only a few months before sampling in December, while fields 5-6 were tilled in April. Tillage and/or incorporation of crop residues or manure might have stimulated the growth of MB-C in fields 7 and 8 (He *et al.*, 1997). The MB-C in the 0-10 cm depth layer of RT_{C_5} field 7 was higher than in any other field. The farmer had put his stable manure at the soil surface which resulted in a high MB-C content in RT_{C_5} field 7.

Under a temperate climate increased stratification of MB-C following the adoption of RT agriculture is generally observed. After only 4 years of RT_C agriculture of a sandy loam soil in Austria a significantly higher MB-C content was found in the 0-10 cm depth layer but not in the 10-20 cm depth layer (Kandeler *et al.*, 1999a & b). Spedding *et al.* (2004) measured a significantly higher MB-C content in the 0-10 cm depth layer of sandy loam soils in Canada after 10 years RT_C or RT_{DD} compared to CT agriculture, but not in the 10-20 cm depth layer. Höflich *et al.* (1999) looked at the results of several long term experiments (between 2 and 19 years RT_C agriculture) on sandy loam soils in Germany. They found a significant increase of the MB-C content in the 0-15 cm depth layer after 5 years RT_C agriculture, whereas an increase in the 15-30 cm depth layer was only observed after 18 years RT_C agriculture (Höflich *et al.*, 1999). Stockfisch *et al.* (1999) also measured a 1.5 times higher amount of MB-C content in the 0-10 cm depth layer under 21 years of RT_C compared to CT agriculture. These and our results confirm that RT agriculture under Western European crop and weather conditions results in a higher MB-C content shortly after the implementation of RT agriculture while changes in % SOC are observed only after an extended period of RT agriculture in the upper soil layers. MB-C seems to be a very sensitive indicator for the effects of changes in tillage management. The higher MB-C content results in a higher aggregate formation and protection of SOM (Carter, 1991; Balesdent *et al.*, 2000) and according to Carter (1991) the MB-C content to % SOC ratio can be used as an indication of the anticipated accumulation of % SOC. In our study next to tillage also the accompanying shift of amount of EOC may have stimulated the higher MB-C content of the RT_{C_5} field 5 compared to CT field 6 and RT_{C_5} field 7 compared to CT field 8.

4.5.3. Physical fractionation

The sum of the DM amounts of coarse fPOM and fine fPOM fractions, 1.0-3.4%, was higher in the RT compared to the CT fields at the same locations. The summed DM weight of the iPOM and intra-micro-aggregate silt + clay sized fractions, 35-59%, was not consistently higher in the RT than CT fields (Table 4.1). These results suggest no substantial differences in the amount of micro-aggregates in the RT fields in contrast to previous findings by Denef *et al.* (2001b). However, this lack of increase of micro-aggregates was in agreement with Pulleman (2005), who measured no significant differences in the amount of micro-aggregates between pasture, organically and CT fields in spite of obvious large differences in soil disturbance.

The much higher amount of OC present in coarse and fine fPOM (on average 67 and 37% higher in the RT than CT fields) (Figure 4.6) is likely to have resulted from lower disturbance of the crop residues (Kader *et al.*, 2006 & 2007) because the unprotected coarse and fine labile fPOM are very sensitive to management practices (Bremer *et al.*, 1994). The crop rotation also contributes to the POM production (West & Post, 2002; Kader *et al.*, 2006 & 2007; Soon *et al.*, 2007). The little accumulation of fPOM in Court-Saint-Etienne may be due to 2 year crop rotation sugar beet - winter wheat which causes a high disturbance at the harvest of the root crop. Carter *et al.* (2007) also found no significant increase of OC present in POM as well as total OC in the RT compared to CT field in one of three sites in Atlantic Canada for a 3 year rotation with red clover, potatoes and barley.

On average 46% more OC was present in the iPOM of RT than CT fields. Although the DM weight of the iPOM and intra-micro-aggregate silt + clay sized fractions was not constantly higher in the RT fields, RT agriculture seems to lead to more physically protected iPOM in the top depth layer, which confirms the conceptual model of Six *et al.* (2002a).

Only 14% more OC was measured in the intra-micro-aggregate and free <53 µm OM fractions of RT compared to CT fields. This was expected since this OC pool is more stable and is only affected by management in the long term. E.g. Tiessen & Stewart (1983) found that coarse silt and fine clay fractions decreased up to 50% after a longer period of tillage (60 years of cultivation of former grassland soils under fallow-grain rotation).

The largest differences in the OC distribution over soil fractions between the tillage treatments were found for the RT_{DD} fields, particularly for the iPOM and coarse fPOM fraction. These results confirm research of other regions, namely a reduction in tillage intensity results firstly in a higher amount of the more labile

OC fractions (Denef *et al.*, 2004; Mikha & Rice, 2004; Sleutel *et al.*, 2005; Dou & Hons, 2006).

Sleutel *et al.* (2006c & 2007b) further analysed RT_{DD_10} field 11 and CT field 14 by using pyrolysis-field ionization mass spectroscopy (Py-FYMS). They found significant differences in the SOM composition of the sand and clay fractions under RT and CT agriculture while no differences were observed in the silt fractions. This result also accords with observations made by Tiessen & Stewart (1983) and Tiessen *et al.* (1983). They found that the cultivation of native silt loam soil with small cereal - fallow cropping sequence decreased the SOM concentration of all size separates while the relative proportion of fine silt remained unchanged even after 90 years of cultivation as this fraction contains highly aromatic, stable material of intermediate C:N ratios. The higher amount of clay sized OC under RT compared to CT agriculture may also partly have resulted from the larger amount of accumulation of rather labile SOM compounds, such as soil MB and its metabolites as well as root exudates and lysates (Leinweber & Schulten, 1995). This is also reflected in the higher amounts of MB-C in the RT compared to CT fields (Figure 4.5).

4.5.4. Carbon mineralization

The C mineralization rates in the undisturbed soil cores of the RT fields were 1.5 to 3 times higher than the C mineralization rates of the C fields, except for fields 5 and 6. Although we removed crop residues left at the soil surface before taking samples, the higher C mineralization rate in the RT fields in the incubation experiments may also be due to the presence of fresh crop residues on the RT fields while almost no crop residues were left on the CT fields.

The difference in C mineralization rate of RT compared to CT fields was higher than the difference in % SOC resulting in a higher % SOC mineralized under RT than CT fields under laboratory conditions. Alvarez *et al.* (1995) found that after an incubation of 160 days a higher % of SOC was mineralized in the upper 5 cm of a silt loam soil in Argentina under RT compared to CT agriculture. However, this higher potential for C mineralization of RT fields does not necessarily translate in higher C losses in the field, because temperature and moisture content tend to be less favourable for aerobic decomposition in RT fields. During a 3 year measuring period, the annual CO_2 losses of a loam soil in Nebraska were measured weekly, and the CO_2 losses were lower under RT (23 to 25 years) than CT agriculture (Kessavalou *et al.*, 1998).

The higher amount of more labile OC in fPOM and iPOM under RT compared to CT agriculture suggests that the risk of loosing OC at soil disturbance is high under RT agriculture. Surprisingly, disturbance of the soil resulted only in a small difference (higher or lower) in C mineralization rate, except for 2 of the 3 the RT_{DD_10} fields. In contrast, most studies found that the disturbance of the soil resulted in a higher C mineralization rate (Franzluebbers, 1999; Balesdent *et al.*, 2000; Stenger *et al.*, 2002). However, in these experiments the soil was disturbed by sieving, which is far more extreme than the disturbance in this experiment and than an intensive tillage operation in the field. Sieving likely results in a destruction of both macro- and micro-aggregates and releases large amounts of physically protected SOC. The release of physically protected SOC caused by disturbance in this experiment was probably minimal, which may well explain the limited effect of soil disturbance on the C mineralization rate. As mentioned before, the frequent disturbance on the occasion of harvest of these silt loam fields with crop rotations including root and tuber crops under RT agriculture might be another important reason why little effect of additional disturbance on C mineralization rate was observed.

The C mineralization rate of the undisturbed soil cores of the RT fields under laboratory conditions showed no correlations with the parameters MB-C content, % clay and % SOC (Table 4.2). The C mineralization rate in the undisturbed soil cores of the CT fields was positively correlated with the MB-C content (Pearson correlation $P = 0.05$). In the disturbed soil cores, the C mineralization rates of the RT and CT fields were positively correlated with % SOC (Pearson correlation $P = 0.05$), which suggests a better contact between the MB and SOC as a result of soil disturbance.

We tried to derive a pedotransfer function that could be used to determine the C mineralization rate of other RT and CT fields based on the OC present in the different fractions isolated according to the physical fractionation method of Six *et al.* (2000a). The highest correlation between the C mineralization rate undisturbed and OC fractions was found with the OC present in the coarse + fine fPOM fraction. However, based on our results of the OC content in the fractions of the physical fractionation we can not improve the prediction of the C mineralization rate of the undisturbed soil cores compared to measurements of % SOC. The lack of correlation between the C mineralization rate and OC content in the fractions of the physical fractionation in this research is obviously related to the small range in soil texture and as a consequence OC content in the different fractions.

Table 4.2 Pearson correlation of microbial biomass carbon (MB-C) content (0-10 cm depth layer) in the field, clay (0-10 cm depth layer), soil organic carbon (SOC) (0-5 cm depth layer) and total C mineralization rate (day 7-day 91) (0-5 cm depth layer) of undisturbed (U) and disturbed-refilled (D) tubes of the reduced (RT) and conventional tillage (CT) fields

		Clay (%)	SOC (%)	C mineralization rate U (mg C kg^{-1} dry soil day^{-1})	C mineralization rate D (mg C kg^{-1} dry soil day^{-1})
RT	MB-C (mg C kg^{-1} dry soil)	-0.681 *	-0.406	0.602	0.194
	Clay (%)		0.448	-0.331	0.235
	SOC (%)			0.339	0.653 *
CT	MB-C (mg C kg^{-1} dry soil)	-0.541	0.009	0.809 *	0.269
	Clay (%)		0.060	-0.161	0.204
	SOC (%)			0.065	0.717 *

Significant differences *: P = 0.05; **: P = 0.01

4.6. CONCLUSION

The % SOC in the surface layer of silt loam soils was higher under RT than CT agriculture. The amount of OC in three different POM fractions was found to be (significantly) higher both on an absolute as well as relative basis in the RT compared to the CT fields. In general the difference was the highest for the coarse fPOM fraction, which is the most labile fraction. The higher percentage of (labile) SOC in the surface layer of RT fields resulted in a higher C mineralization rate in undisturbed tubes under controlled conditions in the laboratory. Simulating an intensive tillage operation resulted in both lower and higher C mineralization rates of the RT fields indicating that ploughing RT fields will have a limited effect on the SOC stock. The relatively intense soil disturbance of the tillage operations of the RT fields and disturbance on the occasion of harvest of root and tuber crops every 2 to 3 years might explain why little effect of additional disturbance on C mineralization was observed.

Although the EOC from manure application and crop residues was comparable or higher for the RT compared to CT fields, this research suggests that no change in SOC stock occurs in the 0-60 cm depth layer under RT agriculture, even after 20 years of not ploughing the soil. The frequent soil disturbances of the RT fields might decrease the potential positive effects of RT agriculture on SOC accumulation.

Chapter 5:

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

Villers-le-Bouillet:
Field 13 with winter wheat and residues of potatoes in March 2005
Soil sampling for measuring the nitrogen mineralization rate

Left under: continuous flow auto-analyser

Modified from:

D’Haene, K., Vandenbruwane, J., De Neve, S., Gabriels, D., Salomez, J., Hofman, G., 2008. The effect of reduced tillage on nitrogen dynamics in silt loam soils. Eur. J. Agron. http://dx.doi.org/10.1016/j.eja.2007.11.007

D’Haene, K., De Neve, S., Gabriels, D., Hofman, G., 2006. The influence of 10 years of reduced tillage on the nitrogen stock and mineralization of soils under a temperate climate. In: Proceedings of 5th international symposium Agro Environ “Agricultural constraints within the soil-plant-atmosphere continuum”, 04-07/09/2006, Ghent, p. 281-287.

5.1. ABSTRACT

Crop rotations in Western Europe contain crops that seem not suitable for 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 agriculture on the stratification and stock of TN in the 0-40 cm depth layer and the N mineralization in the upper 0-15 cm depth layer of silt loam soils in Belgium was evaluated. For doing so, ten fields at seven locations representing the important types of RT systems applied for a different number of years, and eight fields under CT agriculture 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 C:N ratio was more pronounced under RT than CT fields. The TN stock in the RT_C was comparable to CT fields, even after 20 years. No trend could be found in the change in TN stock of RT_{DD} compared to CT agriculture. 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 on average 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 (MB-N) content. Disturbing the soil resulted in a decreasing trend in N mineralization rate compared to the undisturbed soil, on average 0.19±0.04 mg N kg^{-1} dry soil day^{-1} and 0.11±0.04 mg N kg^{-1} dry soil day^{-1} for RT and CT fields, respectively, but the differences between disturbed and undisturbed soils were rarely significant due to the high variability of the N mineralization rate.

5.2. INTRODUCTION

Since the 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. Vlassak, 1970; Coppens *et al.*, 2002) and in the field (e.g. Hofman, 1988; Neeteson *et al.*, 1988; Demyttenaere, 1991; Smit, 1994). However, all these data were pertaining to CT soils. While RT agriculture is gaining momentum in Western Europe, the research on RT agriculture was focused on the effects of the change of field management on soil erosion and SOC stock changes. The change of N dynamics under a temperate climate due the shift to RT agriculture was researched in the large arable regions in America, Canada 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 agriculture 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 agriculture.

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 agriculture. No significant differences in the TN stock compared to CT agriculture were measured of two sandy loam soils after 4 or 5 years RT_{DD} agriculture and one loam soil after 8 years RT_C agriculture in eastern Canada (Angers *et al.*, 1997), of a silty clay loam soil after 8 years RT_{DD} or RT_C agriculture in central Ohio (Puget & Lal, 2005) and of a silt loam soil after 21 years of RT_C agriculture in Germany (Stockfisch *et al.*, 1999). However, Etana *et al.* (1999) measured a decreased TN stock compared to CT after 17 years RT_C agriculture of a silt loam soil in Sweden.

Next to the change in TN stock, it is important to know whether the TN is stable or will be released in case RT fields are ploughed. Occasionally ploughing of RT fields is sometimes used as a remedy for infestation with weeds of RT fields. Kandeler & Böhm (1996) and Kandeler *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 agriculture. The N mineralization rate of the upper depth layer showed a decreasing trend in the order: $RT_{DD} > RT_C >$ CT agriculture. Deeper in the soil profile a significant decrease in N mineralization was determined under

RT compared to CT agriculture. Doran (1987) found a (significant) increase of potentially mineralizable N in the upper depth layer of silt and silt loam fields under 5 to 11 years RT_{DD} agriculture. The same trend was observed by Friedel *et al.* (1996) after 14 years RT_C agriculture in Germany and by Kristensen *et al.* (2000) after 20 years RT_{DD} agriculture in Maryland.
N mineralization research is most often studied on sieved soil, which can strongly effect the measured N mineralization (Stenger *et al.*, 1995; Balesdent *et al.*, 2000). Sieving results in a destruction of both macro- and micro-aggregates and a release of large amounts of physically protected SOM. In a literature review Balesdent *et al.* (2000) mostly found a higher N mineralization after sieving the soil of virgin, RT_{DD} and CT fields. The largest differences were found for RT_{DD} fields with a high % clay.

The objective of this study was to look into the short and long term effects of RT agriculture on stratification and stocks of N, 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), and to asses the effect of soil disturbance on the N mineralization of RT and CT fields.

5.3. MATERIALS AND METHODS

5.3.1. Soil sampling

Fields 1-8 and 17-18 were sampled in December 2004, whereas fields 9-16 were sampled in March 2005 for the determination of % TN and for measuring the N mineralization rate in lab incubations (see 3.3.1).

5.3.2. Total nitrogen and soil organic carbon

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 layer into one composite sample, thoroughly mixed and let to dry to the air in the laboratory. The percentage of TN was measured with a CNS elemental analyzer (Vario Max, Elementar, Germany) whereas SOC content was analysed according to the method of Walkley & Black (1934).

5.3.3. Nitrogen mineralization rate

N mineralization rate was measured under controlled conditions in the laboratory for both undisturbed and disturbed 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 before sampling. The 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. Fourteen tubes were taken from each plot. Seven tubes per plot were incubated "undisturbed". In order to simulate the effect of an intensive tillage operation, the soil from the other seven tubes was removed and the tube was then refilled with the "disturbed soil", adjusted to the same bulk density. The moisture content of fields 1-8 and 17-18 at the time of sampling was 50±5% WFPS (see Eq. 3), which is considered to be within the optimum soil moisture content range for N mineralization (De Neve & 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.

Every two weeks soils were sampled destructively by removing the soil from one tube of the U and D treatment for each plot. The soil was mixed thoroughly and 30 g moist soil was analysed for mineral N (NO_3^--N and ammonium nitrogen (NH_4^--N)) by extraction with a 1M 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: $N_t = N_0 + k_N \,.\, t$, where N_t is the amount of mineral N at time t (mg N kg^{-1} dry soil), N_0 is the initial amount of mineral N (mg N kg^{-1} dry soil), t is the time (in days) and k_N is the nitrogen mineralization rate (mg N kg^{-1} dry soil day^{-1}).

5.3.4. Microbial biomass nitrogen

Eight weeks after the start of the incubation, the 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 analyzed with a TOC analyzer (TOC-V CPN, Shimadzu, Japan). To correct for the incomplete release and extraction of MB-C a K_{EC} factor is needed (Voroney *et al.*, 1993). As suggested by Voroney *et al.* (1993) an extraction efficiency K_{EC} value of 0.25 was used. The MB-N was obtained assuming a C:N ratio of 6 for microbial biomass (Chaves, 2006; Chaves *et al.*, 2006).

5.3.5. Physical fractionation

Sub samples from every replicate of the different treatments were separately used for the physical fractionation. The fractionation procedure was carried out in triplicate, yielding a total of twelve repetitions per tillage treatment and per soil depth (see 4.3.5). Sub samples of the separated soil fractions were analyzed for TN with a CNS elemental analyzer (Vario Max, Elementar, Germany).

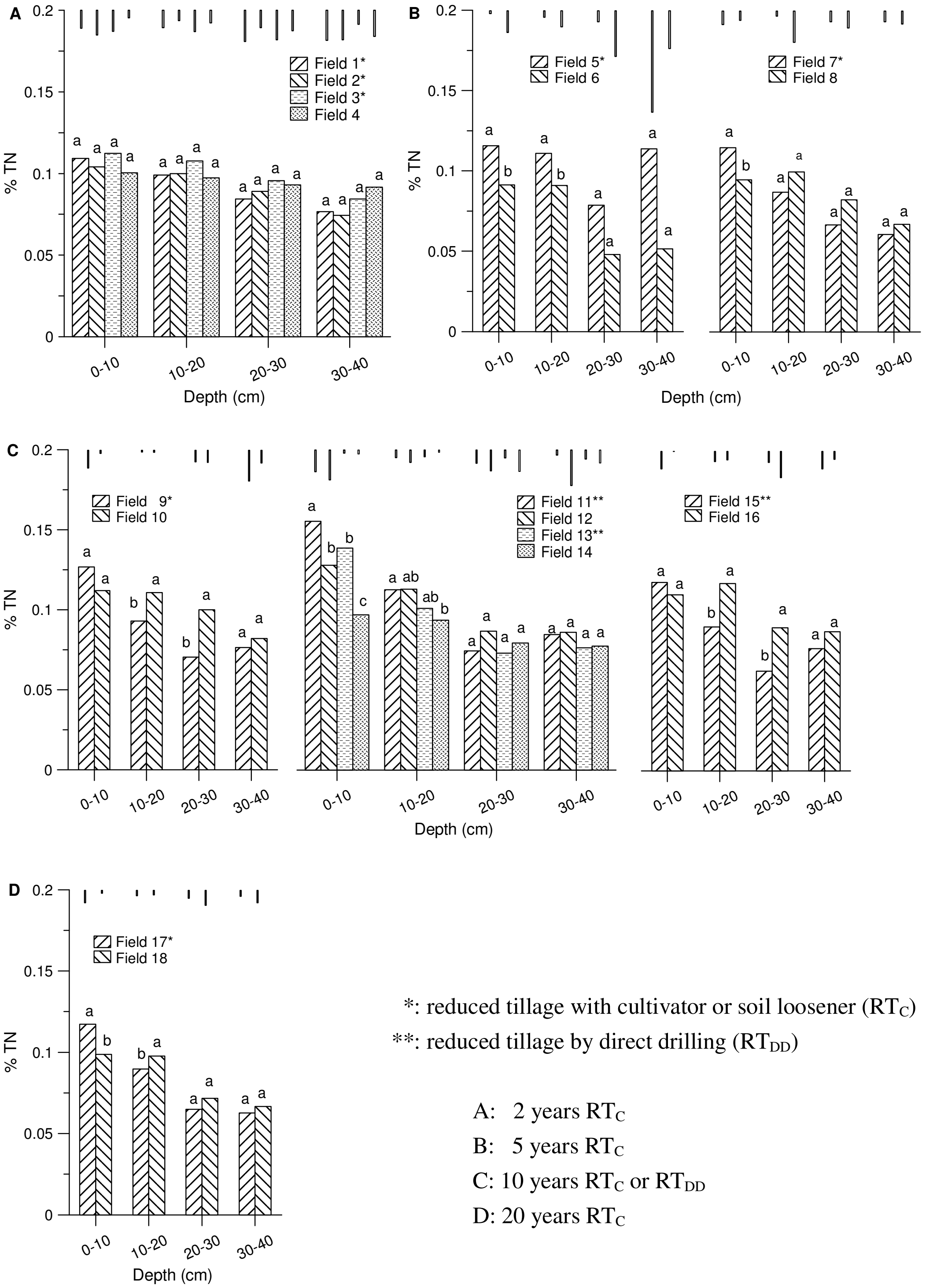
5.3.6. Statistical analysis

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, physical fractionation results and TN stock for locations with only 2 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 2 fields for homogeneous and heterogeneous variances, respectively. The N mineralization was calculated with linear regression in SPSS. A correlation analysis was performed using a Pearson's correlation matrix in SPSS (SPSS version 12.0, SPSS Inc., Chicago).

5.4. RESULTS

5.4.1. Total nitrogen percentage and stock

There were no significant differences in % TN in the different layers of fields 1-4 in Heestert (Figure 5.1A). However, the % TN decreased more gradually with depth in field 4. After 5 years RT_C agriculture, the % TN in the 0-10 and 10-20 cm depth layer in the RT_{C_5} field 5 was significantly ($P = 0.05$) higher than field 6 under CT but not significantly higher deeper in the soil profile (Figure 5.1B).



*: reduced tillage with cultivator or soil loosener ($\mathrm{RT_C}$)

**: reduced tillage by direct drilling ($\mathrm{RT_{DD}}$)

A: 2 years $\mathrm{RT_C}$
B: 5 years $\mathrm{RT_C}$
C: 10 years $\mathrm{RT_C}$ or $\mathrm{RT_{DD}}$
D: 20 years $\mathrm{RT_C}$

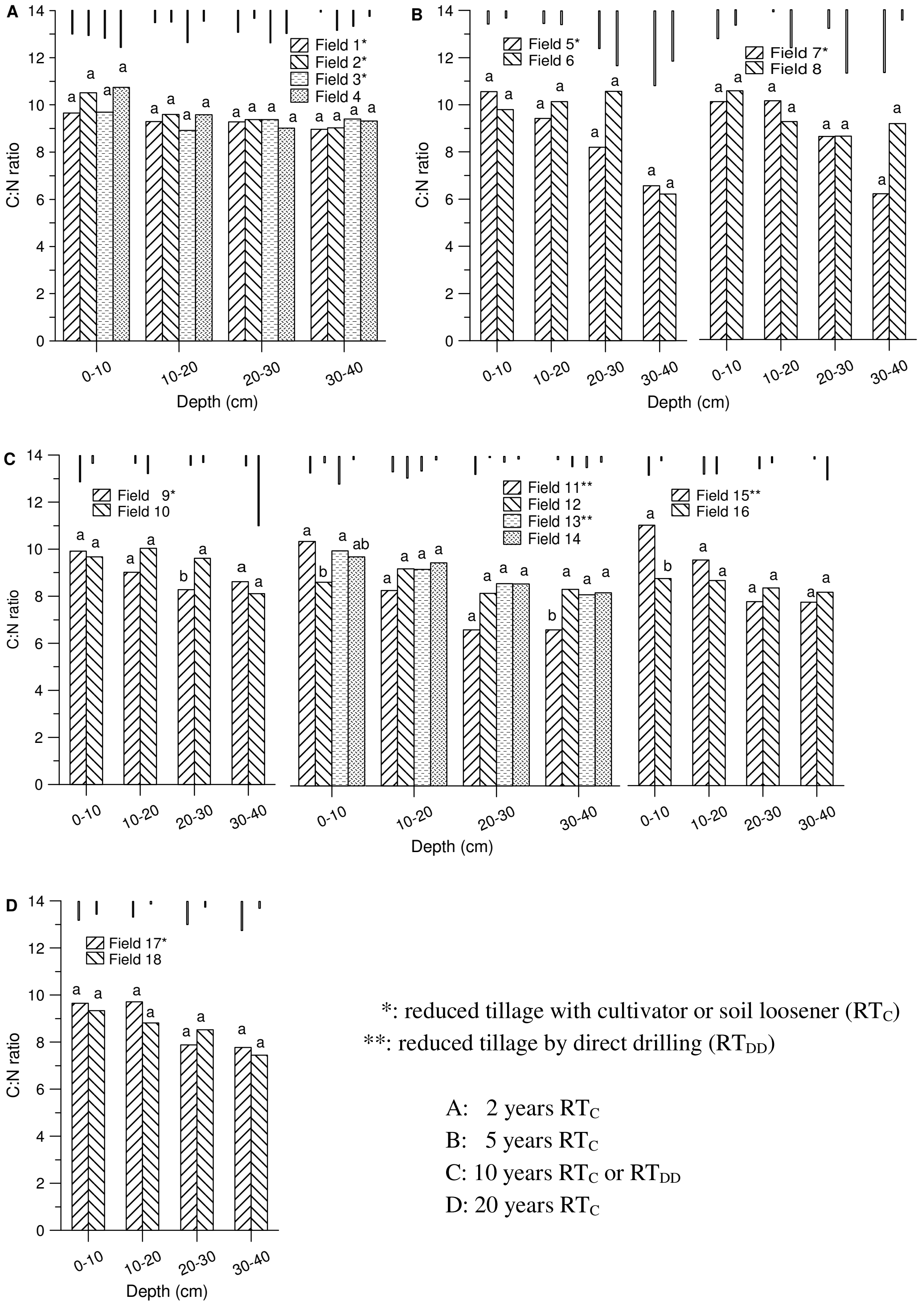
same letters indicate no significant differences between tillage treatments per location and per depth (P = 0.05) (one way ANOVA/Duncan post hoc test, Welch/Games-Howell post hoc test or *t*-Test)

Figure 5.1 Total nitrogen (TN) (%) in the 0-10, 10-20, 20-30 and 30-40 cm depth layers (vertical lines = standard deviation) of the 18 selected fields

The % TN in the 0-10 cm depth layer in RT_{C_5} field 7 was significantly higher than in CT field 8 and lower deeper in the soil profile. A (significant) higher % TN in the 0-10 cm depth layer was observed after 10 years RT agriculture (Figure 5.1C). The % TN of the 10-20 cm depth layer was significantly lower in RT_{C_10} field 9 compared to CT field 10 and in RT_{DD_10} field 15 compared to CT field 16, while the % TN of the 10-20 cm depth layer was lower in CT field 14 compared to RT_{DD_10} fields 11 and 13. In the 20-30 cm depth layer, the % TN after 10 years RT agriculture was (significantly) lower than under CT agriculture. The % TN in the 30-40 cm depth layer after 10 years RT was comparable to CT agriculture. The % TN in RT_{C_20} field 17 was significantly higher in the 0-10 cm depth layer and significantly lower ($P = 0.05$) in the 10-20 cm depth layer compared to CT field 18 (Figure 5.1D). 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 to 8 between ≤5 years RT_C and CT agriculture (Figure 5.2). After 10 years RT agriculture, the C:N ratio was (significantly) higher in the 0-10 cm depth layer and mostly lower in the 10-20 and 20-30 cm depth layer than under CT agriculture. 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 TN stock of the 0-40 cm depth layer calculated with the measured bulk densities was on average 5.4±0.6 Mg TN ha^{-1} for the 18 fields. The TN stock was similar for all fields in Heestert (Figure 5.3). A higher TN stock was measured after 5 years RT_C agriculture. The TN stock, however, was lower after 10 years RT agriculture in Maulde (field 9 compared to field 10) and in Kuttekoven (field 15 compared field 16). Conversely, CT field 14 had a significantly lower ($P = 0.05$) TN stock compared to fields 11-13. The TN stock of RT_{C_20} field 17 was lower (but not significantly) than CT field 18.

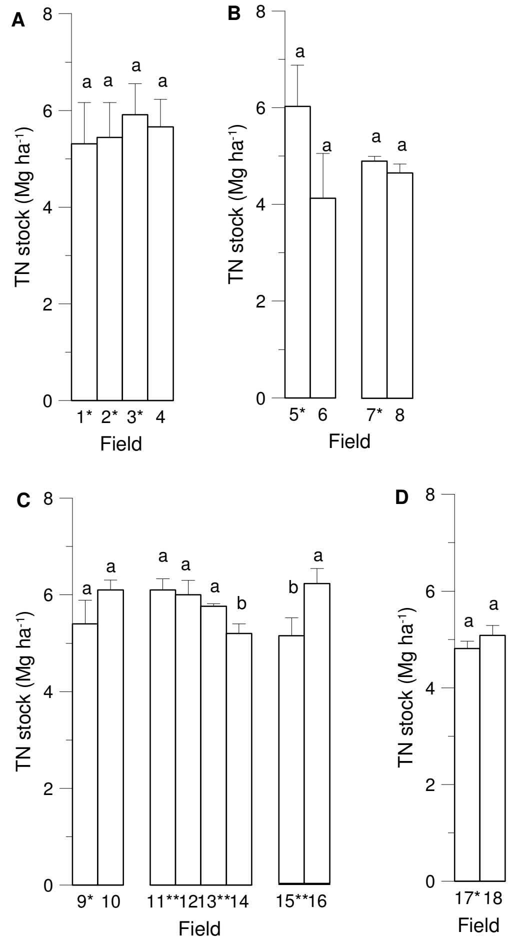


*: reduced tillage with cultivator or soil loosener (RT_C)
**: reduced tillage by direct drilling (RT_{DD})

A: 2 years RT_C
B: 5 years RT_C
C: 10 years RT_C or RT_{DD}
D: 20 years RT_C

same letters indicate no significant differences between tillage treatments per location and per depth ($P = 0.05$) (one way ANOVA/Duncan post hoc test, Welch/Games-Howell post hoc test or *t*-Test)

Figure 5.2 C:N ratio in the 0-10, 10-20, 20-30, and 30-40 cm depth layers (vertical lines = standard deviation) of the 18 selected fields



*: reduced tillage
with cultivator or soil loosener (RT$_C$)
**: reduced tillage with
direct drilling (RT$_{DD}$)

A: 2 years RT$_C$
B: 5 years RT$_C$
C: 10 years RT$_C$ or RT$_{DD}$
D: 20 years RT$_C$

same letters indicate no significant differences per location (P = 0.05) (One way ANOVA/Duncan post hoc test or *t*-Test)

Figure 5.3 Total nitrogen (TN) stock (Mg ha^{-1}) in the 0-40 cm depth layer (vertical lines = standard deviation) of the 18 selected fields

5.4.2. Nitrogen mineralization rate and microbial biomass nitrogen

As an example in Figure 5.4 the evolution of NH_4^+-N and mineral N (NO_3^--N + NH_4^+-N) of the disturbed and undisturbed soil cores of field 7 are given. The amount of NH_4^+-N increased until week 4 and then decreased but was low in general. The amount of mineral N increased linearly with time (Figure 5.4). However, a very large variability between replicates was observed. The N mineralization rate of the undisturbed soil samples varied from 0.032 to 0.329 mg N kg^{-1} dry soil day^{-1} (Table 5.1).

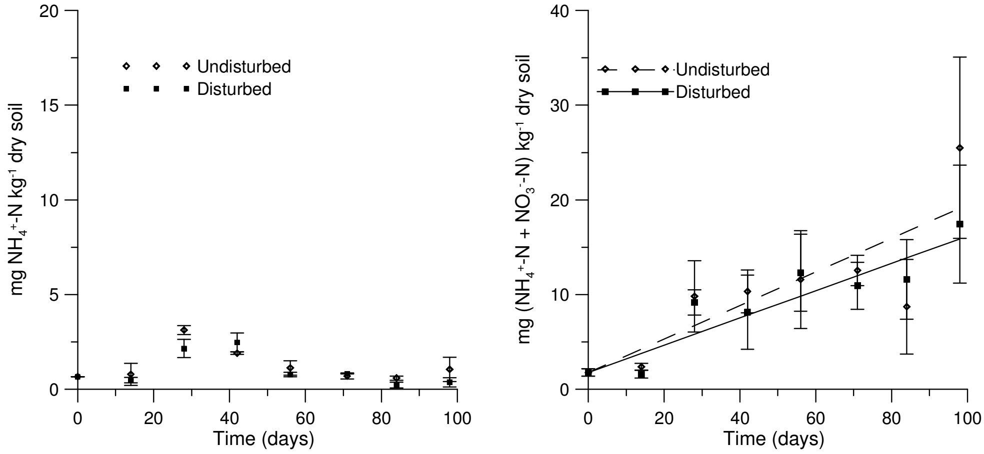


Figure 5.4 Evolution ammonium nitrogen (NH_4^+-N) (mg kg^{-1} dry soil) and mineral nitrogen (NH_4^+-N+NO_3^--N) (mg kg^{-1} dry soil) (vertical lines = standard deviation) of undisturbed and disturbed soil cores of the 0-15 cm depth layer of reduced tillage field 7

At each location, the N mineralization rate of the RT fields was higher than of CT fields, with the exception of fields 5 and 6 (Table 5.1). The N mineralization rates of the RT_C and RT_{DD} fields was on average 1.55 and 1.76 times 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} than for the CT fields, respectively.

For most fields we found only small and inconsistent differences (either higher or lower) in the N mineralization rate between disturbed and undisturbed soil (Table 5.1). There was an obvious higher N mineralization rate of the RT_{DD} fields 11 and 13 compared to CT fields 12 and 14 but not for RT_{DD} field 15 compared to CT field 16. Although we removed winter wheat residues left at the soil surface before taking samples, the immobilization in fields 15 and 16 upon disturbance may have been due to small amounts of winter wheat residues that were still present in the tubes and that started to immobilize N from the moment they were mixed with the soil. The maize residue of RT_{C_5} field 5 possibly caused some N immobilization in the course of the incubation compared to CT field 6.

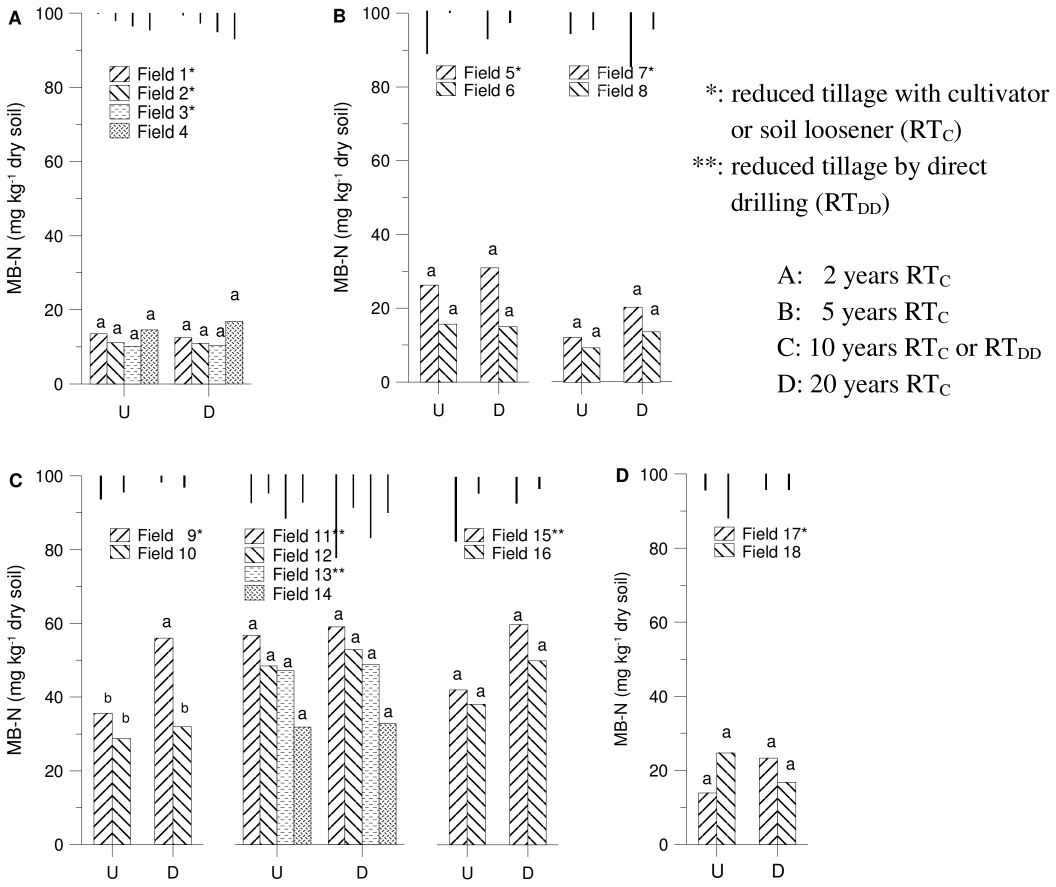
Table 5.1 Nitrogen mineralization rate k_N * of the undisturbed and disturbed soil cores with standard deviation between brackets of the 0-15 cm depth layer of the 18 selected fields to be compared per location

Field		Undisturbed samples k_N (mg N kg^{-1} dry soil day^{-1})		R²	sign	Disturbed samples k_N (mg N kg^{-1} dry soil day^{-1})		R²	sign
1	RT_{C_2}	0.108	(0.028)	0.395	0.001	0.045	(0.023)	0.143	0.069
2	RT_{C_2}	0.107	(0.015)	0.705	0.000	0.033	(0.025)	0.072	0.205
3	RT_{C_2}	0.082	(0.032)	0.235	0.016	0.039	(0.022)	0.180	0.039
4	CT	0.084	(0.027)	0.308	0.005	0.068	(0.040)	0.114	0.107
5	RT_{C_5}	0.032	(0.024)	0.065	0.229	-0.025	(0.039)	0.020	0.531
6	CT	0.069	(0.020)	0.364	0.002	0.049	(0.025)	0.162	0.051
7	RT_{C_5}	0.177	(0.036)	0.525	0.000	0.144	(0.023)	0.642	0.000
8	CT	0.131	(0.088)	0.094	0.145	0.131	(0.031)	0.451	0.000
9	RT_{C_10}	0.275	(0.056)	0.606	0.000	0.255	(0.035)	0.710	0.000
10	CT	0.109	(0.034)	0.187	0.035	0.108	(0.030)	0.374	0.001
11	RT_{DD_10}	0.095	(0.038)	0.218	0.021	0.179	(0.034)	0.559	0.000
12	CT	0.242	(0.031)	0.741	0.000	0.162	(0.028)	0.596	0.000
13	RT_{DD_10}	0.224	(0.069)	0.325	0.004	0.242	(0.036)	0.676	0.000
14	CT	0.178	(0.018)	0.817	0.000	0.140	(0.025)	0.589	0.000
15	RT_{DD_10}	0.329	(0.027)	0.872	0.000	0.207	(0.039)	0.556	0.000
16	CT	0.091	(0.022)	0.427	0.001	0.140	(0.018)	0.732	0.000
17	RT_{C_20}	0.099	(0.030)	0.330	0.003	0.116	(0.019)	0.626	0.000
18	CT	0.033	(0.018)	0.129	0.085	0.091	(0.024)	0.407	0.001

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

* The N mineralization rate k was calculated using zero-order kinetics: $N_t = N_0 + k_N \, . \, t$, where t is the time (in days), N_t is the amount of mineral N at time t (mg N kg^{-1} dry soil), N_0 is the initial amount of mineral N (mg N kg^{-1} dry soil), and k_N the mineralization rate (mg N kg^{-1} dry soil day^{-1}). The R² of the regression and significance (sign) of N mineralization rate k_N are given.

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 (Figure 5.5). The MB-N contents in the disturbed tubes after 8 weeks incubation were higher than the MB-N contents of the undisturbed tubes. The MB-N content in the disturbed tubes was also (significantly) higher in the RT fields (≥5 years) (42.6±17.3 mg MB-N kg^{-1} dry soil) than in the CT fields (30.4±16.3 mg MB-N kg^{-1} dry soil).



*: reduced tillage with cultivator or soil loosener (RT_C)

**: reduced tillage by direct drilling (RT_{DD})

A: 2 years RT_C

B: 5 years RT_C

C: 10 years RT_C or RT_{DD}

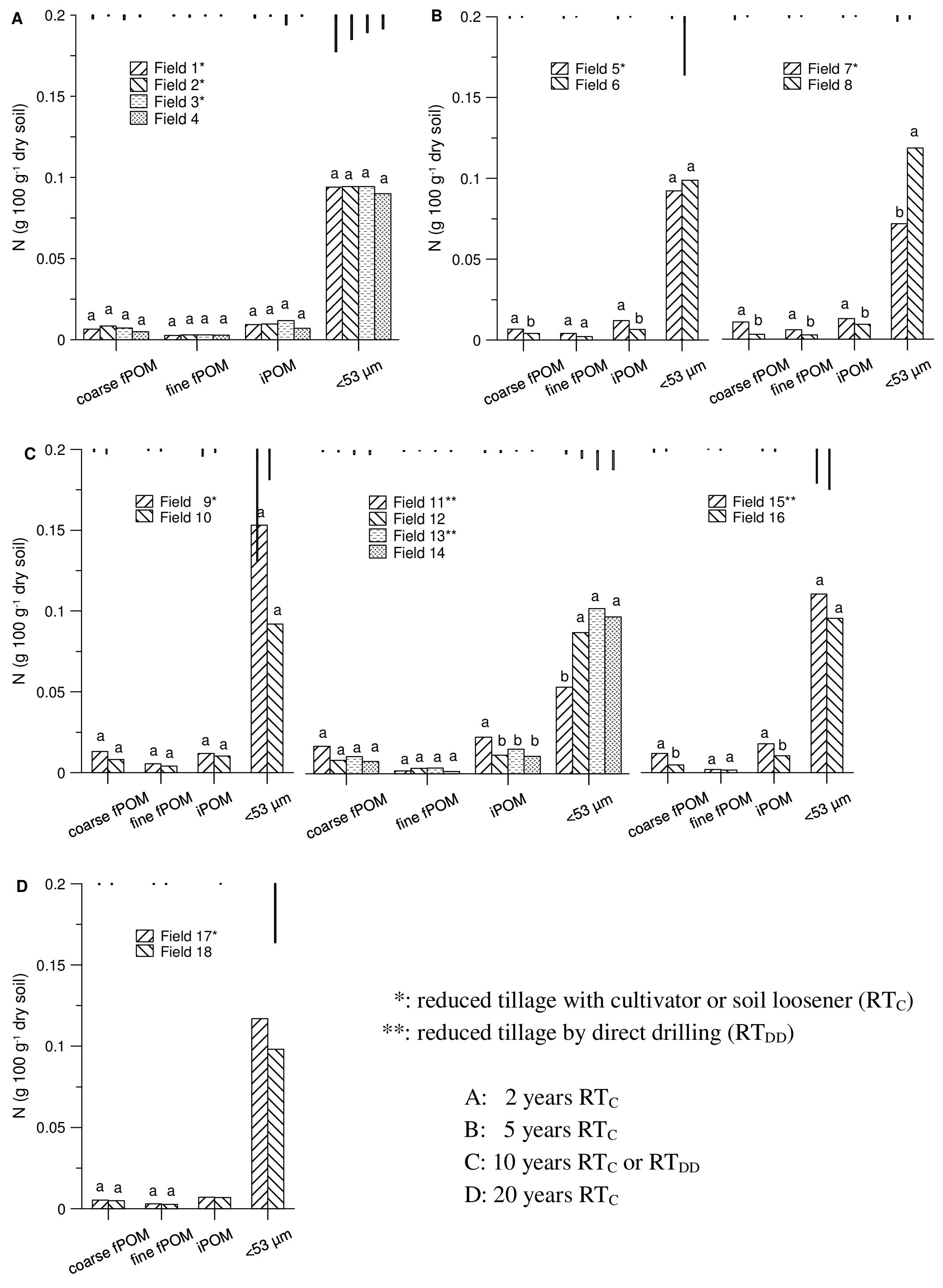
D: 20 years RT_C

same 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)

Figure 5.5 Microbial biomass nitrogen (MB-N) content (mg kg^{-1} dry soil) in the undisturbed (U) and disturbed (D) soils (vertical lines = standard deviation) of the 0-15 cm depth layer of the 18 selected fields

5.4.3. Nitrogen from physical fractionation

The N present in the three POM fractions of the upper 0-10 cm depth layer was comparable or higher in the RT than in the CT fields at the same location, both on an absolute (Figure 5.6) as well as on a relative basis (Appendix III - Figure III.1). No trend in differences in the N present in the free silt and clay fraction between the RT and CT fields could be observed (Figure 5.6).



*: reduced tillage with cultivator or soil loosener (RT_C)
**: reduced tillage by direct drilling (RT_{DD})

A: 2 years RT_C
B: 5 years RT_C
C: 10 years RT_C or RT_{DD}
D: 20 years RT_C

same 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)

Figure 5.6 Absolute distribution of the nitrogen (N) content (g 100 g^{-1} dry soil) in the coarse free particulate organic matter (fPOM) (>250 µm), fine fPOM (53-250 µm), intra-aggregate organic matter (iPOM) (53-250 µm) and <53 µm fraction (vertical lines = standard deviation) of the 0-10 cm depth layer of the 18 selected fields

Although the C:N ratio of the upper 0-10 cm depth layer was higher under RT >5 years compared to the CT fields (Figure 5.2), this was not correlated with a higher C:N ratio of the different fractions obtained with the physical fraction method of Six *et al.* (2002b) (Appendix III - Figure III.1).

5.5. DISCUSSION

5.5.1. Total nitrogen percentage and stock

In the study area, very little experimental sites exist where CT can be compared to RT practices. Therefore, we had to include farmers' fields, where inevitably there is no perfect match in management between CT and RT fields. However, in the selection of the fields much care was taken to select paired fields which were similar from a soil type and management point of view. Therefore, when assessing the effect of the change of management to RT agriculture 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 (see 2.1).

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 by water calculated with the Revised Universal Soil Loss Equation (RUSLE) (Renard *et al.*, 1991) is more than 20 Mg soil ha^{-1} y^{-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 (Figure 5.3).

The application of composted manure and green waste manure resulted in a high amount of EOC and TN in RT_{C_5} field 7, 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.

Results from experiments under temperate climate with cereal, maize and soybean rotations indicated that TN stocks tend to decrease under RT_C agriculture while TN stocks remain unchanged under RT_{DD} agriculture (e.g. Doran, 1987, Angers *et al.*, 1997; Etana *et al.*, 1999; Stockfisch *et al.*, 1999; Puget & Lal, 2005). We found similar or lower TN stocks under RT_C compared to CT agriculture. No trend could be found in the change in TN stock of RT_{DD} fields. The significant higher TN stock of fields 11 and 13 after 10 years RT agriculture, of which 4 years RT_{DD}, compared to CT field 14 suggests a higher TN stock after long term RT_{DD} compared to CT agriculture, but the TN stock of RT_{DD} field 15 was significantly lower compared to CT field 16 ($P = 0.05$). 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 layer of RT_{DD} fields was higher compared to CT fields (Figure 5.2). The higher % TN and C:N ratio in the upper 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 micro flora, crop residues and nutrients (Stemmer *et al.*, 1999). Mineralization results in a decrease of % SOC since CO_2 is lost but N remains mostly in the soil and as a consequence results in a lower C:N ratio in CT fields (Van Hove, 1969; Murty *et al.*, 2002; McLauchlan, 2006).

A higher C:N ratio was measured in the upper depth layer in Nebraska under 5 to 11 years RT_{DD} agriculture (Doran, 1987) and in Ohio after 8 years RT_{DD} compared to CT and RT_C agriculture (Puget & Lal, 2005). In most cases, the C:N ratio of the upper layer of RT_C fields remained unchanged or was higher compared to CT fields. A comparable C:N ratio in the upper layer was measured under CT agriculture and after 8 to 17 years of RT_C agriculture in eastern Canada by Angers *et al.* (1997), in Sweden by Etana *et al.* (1999), in central Ohio by Puget & Lal (2005) while a higher C:N ratio was measured after 9 and 21 years RT_C agriculture 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 agriculture become apparently after short term RT_{DD} agriculture but only after long term RT_C agriculture.

5.5.2. Nitrogen mineralization and microbial biomass nitrogen

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

Soils under RT agriculture often have a lower temperature and higher moisture content (Drury *et al.*, 1999; Balesdent *et al.*, 2000; Larney *et al.*, 2003; Six *et al.*, 2004a). In general these differences in soil temperature and moisture content slow down the N mineralization of RT compared to CT fields (Franzluebbers *et al.*, 2001; Al-Kaisi *et al.*, 2005a & b). After 7 years RT_C and RT_{DD} agriculture of a clay soil in Pennsylvania the N mineralization rate in the laboratory was highest under RT_{DD} and lowest under CT agriculture. 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} agriculture. 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 higher gaseous N losses as a result of a higher moisture content rather than a lower N mineralization rate under RT agriculture in field conditions.

We used the temperature correction function determined for Flemish CT fields by De Neve *et al.* (1996) to recalculate the N mineralization rate obtained in the laboratory to N mineralization per ha and per year using the monthly average temperatures. This resulted in an estimated in situ N mineralization of on average 52, 73 and 114 kg N ha^{-1} y^{-1} 15 cm^{-1} for CT, RT_C and RT_{DD} fields, respectively, if the soil temperature and moisture content would 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 will be twice the N mineralization of the 15 cm depth layer, namely 104 kg N ha^{-1} y^{-1} 30 cm^{-1}. However, the N mineralization of RT_{DD} fields is negligible in the 15-30 cm depth layer due to the high stratification of the % of TN resulting in a N mineralization of 114 kg N ha^{-1} y^{-1}

30 cm^{-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 too small to adapt the N fertilization for RT fields.

It is important to know to what extent the N will be released when RT fields are ploughed. Disturbance had a limited effect on the N mineralization rate in our experiment, while sieving in other experiments in most cases resulted in a higher N mineralization rate (Balesdent *et al.*, 2000). It has to be mentioned that in these experiments the soil was disturbed by sieving, which is far more extreme than the disturbance in our experiment or than an intensive tillage operation in the field. Sieving results in a destruction of both macro- and micro-aggregates and a release of large amounts of physically protected SOM. The release of physically protected SOM caused by disturbance in our experiment was probably minimal resulting in a small effect or no effect of disturbance, except for the RT$_{DD}$ fields 11 and 13. The frequent disturbance of these silt loam fields with crop rotations including root and tuber crops under RT agriculture on the occasion of harvest might be an important reason why little effect of additional disturbance on the N mineralization rate was observed.

The MB-N in the disturbed soil cores was on average higher than in the undisturbed soil cores but the differences were not significant. A higher N mineralization rate was correlated with a higher MB-N content (Table 5.2). The higher MB-N contents under RT compared to CT fields are similar with the results of other researches. After only 3 years RT$_C$ agriculture in a clay loam soil in Germany, the MB-N was higher in the 0-10 cm depth layer compared to CT agriculture (Hoffmann *et al.*, 1996 & 1997). The MB-N of a sandy loam field from Austria was higher in the 0-10 cm depth layer 7 years after changing to RT$_C$ and RT$_{DD}$ agriculture (Kandeler *et al.*, 1999a). After 20 years RT$_C$ agriculture, the MB-N in the upper 15 cm of a silt loam soil was significantly higher compared to CT agriculture in Maryland (McCarty *et al.*, 1995).

The sampling method of undisturbed tubes resulted in a high variability of N mineralization rates making the detection of correlations with soil parameters more difficult. The N mineralization rate (kg N ha^{-1} day^{-1}) of the undisturbed and disturbed soil cores of the fields was positively correlated with % loam and negatively with % sand (Table 5.2). There was also a positive correlation with % TN and MB-N and a negative correlation with C:N ratio (Table 5.2). The higher correlations for the N mineralization in the disturbed compared to the undisturbed soil with these soil parameters indicate a stronger aggregation and physical protection of SOM and TN in micro- and macro-aggregates in the undisturbed as compared in the disturbed state while a part of the TN physically protected in the undisturbed samples was mineralized in the disturbed samples.

Table 5.2 Pearson correlation of nitrogen mineralization rate of the undisturbed (U) and disturbed (D) tubes with microbial biomass nitrogen (MB-N) of the U and D tubes, clay, loam, sand, total nitrogen (TN) and C:N ratio of reduced tillage (RT) and conventional tillage (CT) fields

Mineralization rate (kg N ha^{-1} day^{-1})			MB-N (kg MB-N ha^{-1} day^{-1})		Clay (%)	Loam (%)	Sand (%)	TN (%)	C:N ratio
		D	U	D					
RT	U	0.838 **	0.493	0.677 *	0.241	0.630	-0.590	0.215	-0.108
	D		0.735 *	0.829 *	0.482	0.881 **	-0.869 **	0.662 *	-0.368
CT	U	0.813 *	0.863 **	0.733 *	0.451	0.418	-0.460	0.666	-0.413
	D		0.910 **	0.868 **	0.513	0.699	-0.718 *	0.694	-0.650

Significant differences *: $P = 0.05$; **: $P = 0.01$

5.5.3. Nitrogen of physical fractionation

The high C:N ratios of the POM fractions (13-32) can be explained by the fact that they are relatively fresh. Less or undecomposed OM consists of large proportions of lignin-derived monomers and dimers and of carbohydrate and are poor in N-containing compounds (Appendix III – Figure III.2). The low C:N ratio of the clay and silt fraction (5-11) reflect the presence of the relative higher proportion of N compared to OC in the <53 µm fraction. Indeed N containing compounds and recalcitrant N heterocycles have been reported to be enriched with decreasing particle size which may be explained by the selective accumulation of microbial N containing metabolites in the finer soil fractions (Leinweber & Schulten, 1995). The C:N ratio of the iPOM was lower than the C:N ratio of the fPOM fraction for most fields. This indicates that the iPOM is an intermediate decomposed fraction of OM which is more stabilized inside the micro-aggregates than the fPOM but more labile than the silt and clay OM (Leinweber & Schulten, 1995; Sleutel *et al.*, 2007b).

The amount of N in the coarse and fine fPOM fractions were on average 96% and 53% higher in the RT compared to CT fields, which was higher than for OC in these fractions (Figure 5.6 and Appendix III – Figure III.2). The amount of N in the iPOM fraction was on average 50% higher in RT than CT fields, which is comparable as for OC in this fraction. The amount of N in the <53 µm fraction was comparable for the RT and CT fields. This indicates on average a lower/ comparable and comparable C:N ratio for the POM and <53 µm fraction of RT compared to CT fields, respectively.

5.6. CONCLUSION

Crop rotations in Western Europe often include beets or potatoes. Despite the soil disturbance at the harvest of these crops a more pronounced stratification of % TN in the soil profile was found for these rotations under RT agriculture. However, the TN stock in the RT_C fields was lower or similar compared to CT fields, even after 20 years RT_C agriculture. 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 RT fields 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 ha 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.

Chapter 6:

The effect of reduced tillage agriculture on nitrous oxide emissions in silt loam soils

VILLERS-LE-BOUILLET:
FIELD 13 WITH WINTER WHEAT RESIDUES IN SEPTEMBER 2005
SOIL SAMPLING FOR MEASURING THE NITROUS OXIDE EMISSIONS

UPPER RIGHT: GC-ECD

Modified from:

D'Haene, K., Van den Bossche, A., Vandenbruwane, J., De Neve, S., Gabriels, D., Hofman, G. The effect of reduced tillage on nitrous oxide losses from silt loam soils. Biol. Fertil. Soils, submitted.

6.1. ABSTRACT

RT agriculture is an effective measure to reduce soil loss from soils susceptible to erosion in the short term but has often been found to increase N_2O emissions from soils. Three silt loam fields under RT agriculture running for a different number of years and three fields under CT agriculture with comparable soil type and crop rotation were selected for measuring N_2O-N emissions. Therefore, undisturbed soil samples taken in September 2005 and February 2006 were incubated in the laboratory at 80% WFPS and N_2O emissions were measured. N_2O-N emissions from RT fields tended to be slightly higher than the N_2O emissions from CT fields. The increase in N_2O-N emissions of RT compared to CT fields was correlated with an increase in % TN and MB-N. Denitrification and nitrification are microbial processes that indeed strongly depend on the availability of OC and TN. Leaving the straw on the field, as is a typical feature for RT agriculture, possibly resulted in low mineral N content in the soil and a reduction of the potential N_2O-N emissions from RT fields.

6.2. INTRODUCTION

Denitrification, a form of anaerobic respiration during which NO_3^- or nitrite (NO_2^-) is reduced to gaseous N oxides (NO and N_2O) and N_2, is important not only because N_2O is a greenhouse gas and affects the stratospheric ozone layer but also with respect to N use efficiency (Hofman & Van Cleemput, 2001). Denitrification strongly depends on soil NO_3^- concentrations and the availability of OC present in SOM, crop residues or green manure. Denitrification rates in the field tend to increase with increasing soil moisture content (e.g. Bremner, 1978; Firestone, 1982; Aulakh *et al.*, 1983; Sextone *et al.*, 1985; Colbourn & Harper, 1987, Klemedtsson *et al.*, 1988; Bergstrom & Beauchamp, 1993; Clayton *et al.*, 1997; Colbourn, 1998). Nitrification can also result in the formation and loss of N_2O. N_2O emissions from nitrification mainly depend on the availability of NH_4^+, easily available OC and soil moisture content. The percentage of WFPS in soils is a useful indicator of the relative aerobic and anaerobic microbial activities in soils. Nitrification declines rapidly with increasing water content above 60% WFPS in favour of denitrification because aeration is a major factor regulating nitrification (e.g. Linn & Doran, 1984; Firestone & Davidson, 1989; Aulakh *et al.*, 1991a, b & 1992; Abassi & Adams, 2000).

On the one hand, RT agriculture under a temperate climate increases the % TN in the surface soil (see 5.4.1). Soil moisture content is often higher under RT fields covered with crop residues than CT fields (e.g. Stockfisch *et al.*, 1999; Balesdent *et al.*, 2000). Since these factors both increase N_2O emissions, fertilization during the growing season were reported to result in high peaks of N_2O emissions from RT fields (Granli & Bøckman, 1994; Johnson *et al.*, 2005). On the other hand, CT fields often have a slightly higher surface temperature and this in combination with more aerated conditions has been reported to result in higher N mineralization and a higher amount of NO_3^--N which in turn can promote N_2O emissions under CT fields (Johnson *et al.*, 2005). Aggregate stability and drainage conditions tend to be better under RT compared to CT agriculture (Hussain *et al.*, 1999; Strauss *et al.*, 2003). A higher aggregate stability and better drainage result in lower N_2O emissions. Since all the above mentioned factors are strongly interrelated, it is difficult to predict the effects of RT agriculture on N_2O emissions and conflicting results are reported in literature (Johnson *et al.*, 2005).

Research on N_2O emissions in RT agriculture under temperate climates has been focused mainly on cereal crop rotations under RT_{DD} agriculture. From intact soil cores in the laboratory Liu *et al.* (2007) observed a greater potential for N_2O loss after 5 years RT_{DD} than CT agriculture in a clay loam soil in Canada. One to 4 years after the change to RT_{DD} agriculture higher N_2O emissions were measured under RT_{DD} than CT agriculture in a silt loam soil in New Zealand (Choudhary *et al.*, 2002) and in a silty clay loam soil in Quebec under field conditions which was attributed to the higher soil moisture content and BD (Fan *et al.*, 1997). Robertson *et al.* (2000) and Drury *et al.* (2006) did not measure significant differences in N_2O-N emissions the first 3 and 8 years after changing to RT_{DD} agriculture on a clay loam soil in Canada and on a loam soil in Michigan, respectively. Kessavalou *et al.* (1998) weekly measured lower N_2O emissions for a RT_{DD} (23 to 25 years) than a CT and RT_C field. The differences in N_2O emissions were highest during spring and became gradually smaller throughout the year. Based on the output of linear mixed-effect modelling Six *et al.* (2004b) estimated that the first 5 year after the shift to RT_{DD} agriculture of cereal crop rotations under temperate climate N_2O-N emissions are 3.8±0.8 kg N_2O-N ha^{-1} y^{-1} higher for RT_{DD} compared to CT fields but after long term RT_{DD} agriculture (>20 years) the N_2O-N emissions are 4.2±1.8 kg N_2O-N ha^{-1} y^{-1} lower in RT_{DD} compared to CT fields.
No trend in differences of N_2O-N emissions between RT_C, RT_{DD} and CT fields with a maize and soybean crop rotation was found by Hilton *et al.* (1994), Elmi *et al.* (2003) and Venterea *et al.* (2005). They concluded that the type, timing and amount of fertilizers and organic manure applications have a larger effect on the yearly N_2O-N emissions under field conditions than the type of tillage.

While RT agriculture is gaining momentum in Western Europe, to date research on RT agriculture was focused mainly on the reduction of soil erosion and changes in SOC stocks. Little is known about the influence of RT_{DD} and RT_C agriculture on N_2O-N emissions under the specific Western European climatic and soil conditions, with crop rotations containing crops that are rather uncommon under RT agriculture including an important share of root and tuber crops. Therefore, the objective of this study was to looked into the effects of RT agriculture on N_2O-N emissions for these specific conditions.

6.3. MATERIALS AND METHODS

6.3.1. Nitrous oxide emissions

N_2O emissions were measured on undisturbed soil samples during incubations under controlled circumstances in the laboratory on soil samples taken in September 2005 and February 2006.

For the measurements of the N_2O-N emissions, soil cores inside PVC tubes with a 6.8 cm inner diameter and 7 cm height were used. On each field, visible crop residues were removed before sampling. The PVC tubes were pushed into the soil to a depth of 5 cm. The tubes were carefully dug out, excess soil from the bottom of the core was removed, and the bottom was covered with a PVC cap. Duplicate samples from each plot were taken. Two replicate undisturbed soil cores with a volume of 98 cm³ were additionally taken from the 0-5 cm depth layers close to each PVC tube for the determination of the % WFPS at the time of sampling. Oven dry weight was determined after drying at 105 °C (24 hours). The BD was based on the soil dry weight and volume of the soil core.

The soil samples taken in September were not dried prior to incubation because the moisture content was on average only 46% WFPS (see Eq. 3) at sampling (Table 6.1). The moisture content of the soil samples taken in February 2006 was on average 74% WFPS (Table 6.2). These soil samples were dried to ±50% WFPS prior to the incubation.

On day 0 the undisturbed PVC tubes were placed in glass jars and preincubated at a temperature of 15 °C. After 8 hours, demineralised water was added to obtain a WFPS of 80% and the jars were closed airtight and incubated at a temperature of 15 °C. On day 1, 16 and 24 hours after closure of the jars, the concentration of N_2O-N in the headspace was measured by sampling 1 ml with a gas-tight syringe. The measurements of the concentration of N_2O-N in the headspace continued twice a day till the production of N_2O-N in the headspace became undetectable. Every day after the second analysis of the concentration of N_2O-N in the headspace the jars were left open for 30 minutes to allow replenishment of O_2.

The N_2O-N concentrations were immediately measured with a gas chromatograph equipped with an electron capture detector and 2 packed columns (15 and 10 meters respectively, Porabond Q) (Trace GC-ECD, Interscience, the Netherlands). The operating conditions were as follows: carrier gas N_2 (29.9 ml min^{-1}), injector temperature 200 °C, column and oven temperature 30 °C and detector temperature 310 °C. The chromatograms were calibrated using N_2O-N standard gas (23±1.5 µl l^{-1} in He). The N_2O emissions were calculated in g N ha^{-1} by extrapolating the area of the tube to 1 ha.

The moisture content of the undisturbed soil samples taken in September 2005 was checked on day 3 and adjusted if needed. Since the addition of water to the undisturbed soil samples taken in September 2005 stimulated the N_2O emissions, the moisture content of the undisturbed soil samples taken in February 2006 was not adjusted to avoid extra N_2O emissions.

6.3.2. Microbial biomass nitrogen and mineral nitrogen

The MB-N and mineral N content of the incubated soil samples were measured at the end of the incubation.
The MB-N content was determined with the chloroform fumigation extraction method (Voroney *et al.*, 1993). Total soluble nitrogen was extracted with 0.5 M K_2SO_4 (1:2 soil weight (g): extractant volume (ml)) and NO_3^--N measured colorimetrically after oxidization with the persulfate oxidation method (Koroleff, 1983) with a 'continuous flow auto-analyzer' (Chemlab System 4, Skalar, the Netherlands). MB-N was calculated as the difference between NO_3^--N after and before the fumigation and corrected for the extraction efficiency. As suggested by Joergensen & Mueller (1996) an extraction efficiency K_{EN} value of 0.54 was selected.

Mineral N (NO_3^--N and NH_4^--N) was extracted from the soil samples with 1 M KCl (1:2 soil weight (g): extractant volume (ml)) and measured colorimetrically with a 'continuous flow auto-analyzer' (Chemlab System 4, Skalar, the Netherlands).

6.3.3. Statistical analysis

A *t*-Test was used to determine significant differences between the fields per location and sampling time (P = 0.05). A correlation analysis was performed using a Pearson's correlation matrix in SPSS (SPSS version 12.0, SPSS Inc., USA).

6.4. RESULTS

6.4.1. Soil samples taken in September 2005

The % WFPS and BD were higher in fields 1 and 4 in Heestert compared to fields 13 and 14 in Villers-le-Bouillet and fields 17 and 18 in Court-Saint-Etienne (Table 6.1). The amount of mineral N was low in fields 1, 4, 13, 14 and 17 but high in field 18. In Court-Saint-Etienne, the amount of mineral N of RT_{C_20} field 17 was significantly lower (P = 0.05) than CT field 18. At each location, the MB-N content of the RT fields was (significantly) higher than the MB-N contents of CT fields.

Table 6.1 Bulk density (BD), water filled pore space (WFPS) at sampling, N_2O-N emission, microbial biomass N (MB-N) and mineral N of the 0-5 cm depth layer at the end of the incubation of fields 1 and 4 in Heestert, fields 13 and 14 in Villers-le-Bouillet and fields 17 and 18 in Court-Saint-Etienne in the soil samples from September 2005

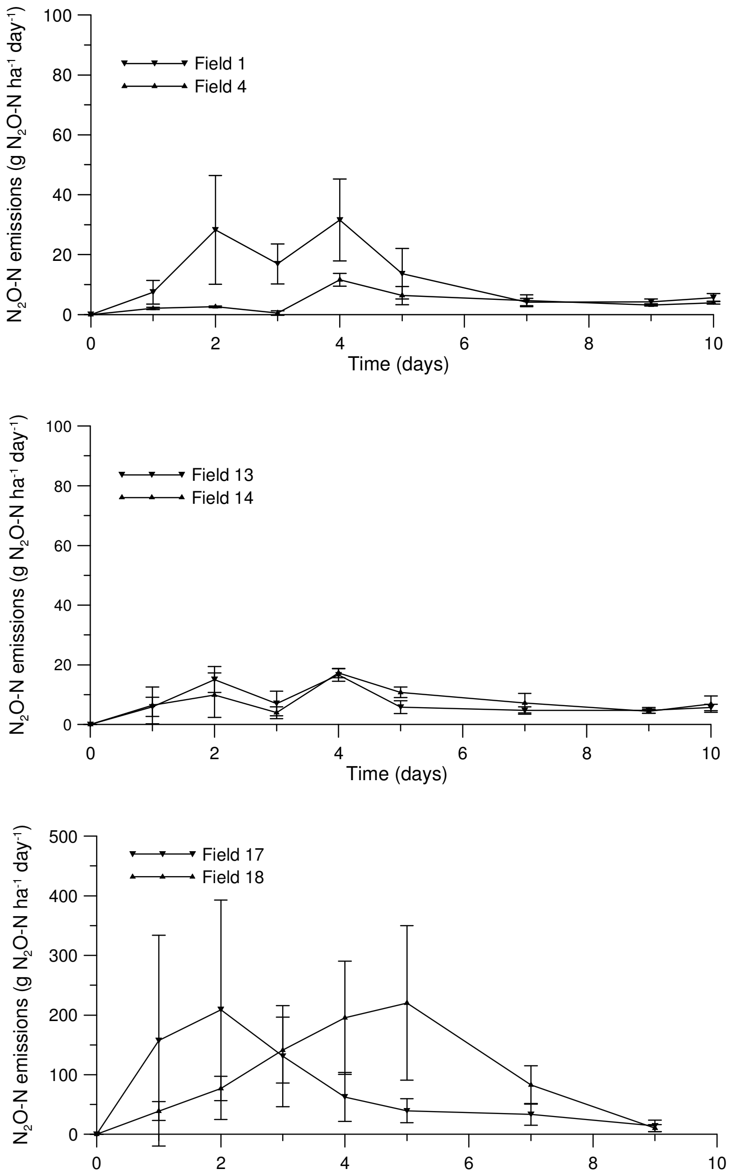
Field		BD ($Mg\ m^{-3}$)	WFPS at sampling (%)	N_2O-N emission ($\mu g\ N\ kg^{-1}$ dry soil day^{-1})	MB-N ($mg\ N\ kg^{-1}$ dry soil)	Mineral N ($mg\ N\ kg^{-1}$ dry soil)
1	RT_{C_2}	1.32 (0.09)	72 (8)	16.0 (4.9) *	9.5 (1.4) *	3.4 (0.9)
4	CT	1.41 (0.08)	65 (7)	5.0 (1.8)	5.8 (1.7)	3.4 (1.4)
13	RT_{DD_10}	1.16 (0.08)	37 (6)	9.4 (3.9)	19.6 (0.8) *	2.4 (0.6)
14	CT	1.15 (0.10)	31 (7)	9.6 (4.3)	3.3 (1.2)	4.0 (1.7)
17	RT_{C_20}	1.06 (0.13) *	32 (6)	92.6 (118.4)	11.7 (3.4)	7.1 (2.3) *
18	CT	1.19 (0.06)	38 (7)	109.5 (56.6)	4.6 (2.2)	51.0 (12.1)

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

Standard deviation between brackets

*: Significant differences per location (P = 0.05) (*t*-Test)

Two days after the start of the incubation of the samples taken in September 2005 an increase in N_2O-N emissions was measured on fields 1 and 13, 14, 17 and 18, while there was practically no increase in N_2O-N emission in field 4 (Figure 6.1). The N_2O-N emission decreased on day 3, except for field 18. After adjusting the soil moisture content on day 3, an increase in N_2O-N emission was observed in fields 1, 4, 13, 14 and 18. After 10 days of incubation, the N_2O-N emission became undetectable. The total N_2O-N emission after 10 days for field 1 (112 g N_2O-N ha^{-1}) was significantly higher than for field 4 with only 35 g N_2O-N ha^{-1} emitted. The total N_2O-N production of fields 13 and 14 in Villers-le-Bouillet was similar, namely 66 and 67 g N_2O-N ha^{-1}, respectively. The total N_2O-N emission of fields 17 and 18 from Court-Saint-Etienne were higher than for any of the other fields, namely 647 and 766 g N_2O-N ha^{-1}, respectively.



Significant differences are indicated with different letter (P = 0.05) (*t*-Test)
Bars indicate standard deviation

Figure 6.1 N_2O-N emission (g ha^{-1} day^{-1}) (vertical lines = standard deviation) of the 0-5 cm depth layer of fields 1 (reduced tillage field with cultivator since 2003 (RT_{C_2})) and 4 (conventional tillage (CT)) in Heestert, fields 13 (reduced tillage field by direct drilling since 1995 (RT_{DD_10})) and 14 (CT) in Villers-le-Bouillet and fields 17 (RT_{C_20}) and 18 (CT) in Court-Saint-Etienne in the soil samples from September 2005

6.4.2. Soil samples taken in February 2006

The BD of the sampled fields varied from 1.23 to 1.33 Mg m^{-3}. At the three locations, the amount of mineral N of the RT fields was low but (significantly) higher than that of the CT fields. The MB-N content of the RT fields was significantly higher (P = 0.05) than the CT fields (Table 6.2).

Table 6.2 Bulk density (BD), water filled pore space (WFPS) at sampling, N_2O-N emission, microbial biomass N (MB-N) and mineral N of the 0-5 cm depth layer at the end of the incubation of fields 1 and 4 in Heestert, fields 13 and 14 in Villers-le-Bouillet and fields 17 and 18 in Court-Saint-Etienne in the soil samples from February 2006

Field		BD (Mg m^{-3})	WFPS at sampling (%)	N_2O–N emission (µg N kg^{-1} dry soil day^{-1})	MB-N (mg N kg^{-1} dry soil)	Mineral N (mg N kg^{-1} dry soil)
1	RT_{C_2}	1.30 (0.08)	74 (8)	/	11.4 (0.9) *	1.9 (0.2)
4	CT	1.30 (0.11)	70 (10)	/	4.6 (0.6)	1.2 (0.2)
13	RT_{DD_10}	1.30 (0.07)	81 (6)	12.9 (7.1)	14.0 (1.6) *	5.2 (0.7) *
14	CT	1.31 (0.04)	77 (5)	8.0 (4.5)	5.6 (0.7)	2.6 (0.3)
17	RT_{C_20}	1.23 (0.11) *	68 (8)	24.7 (21.7)	10.9 (2.9) *	7.5 (2.5)
18	CT	1.33 (0.06)	74 (8)	6.5 (3.4)	5.3 (1.7)	5.0 (0.6)

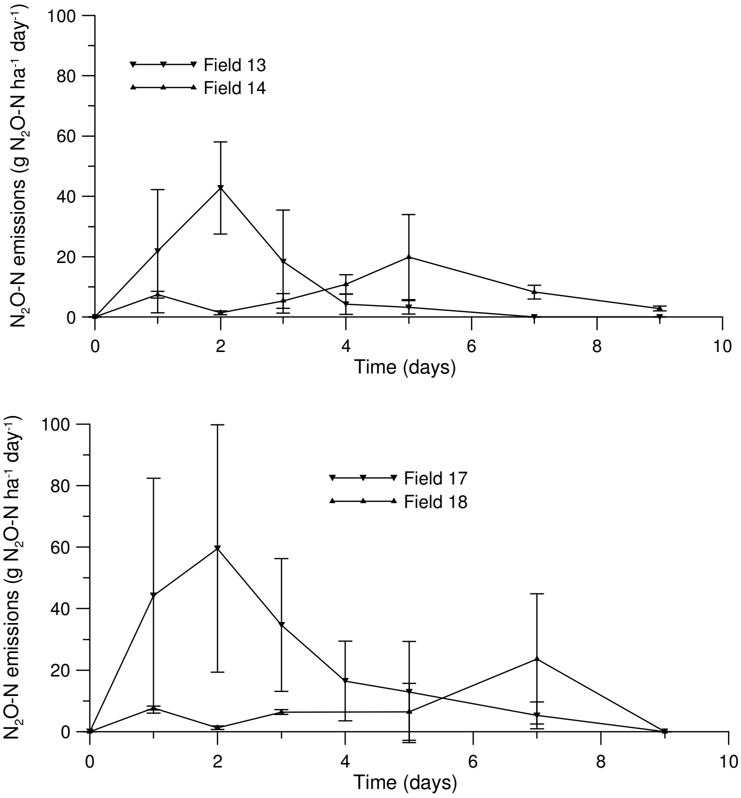
RT_C: reduced with cultivator or soil loosener, RT_{DD}: by direct drilling with in subscript the period in years; CT: conventional tillage

Standard deviations between brackets

/: not available

*: Significant differences per location (P = 0.05) (*t*-Test)

No measurable N_2O-N emissions were observed from fields 1 and 4 in the samples taken in February 2006. Two days after the start of the incubation a peak of N_2O-N emission was measured for fields 13 and 17, while the N_2O-N emission was slightly increased in fields 14 and 18 on day 5 and 7, respectively (Figure 6.2). The N_2O-N emission after 8 days incubation of RT fields 13 and 17 was 91 and 173 g N_2O-N ha^{-1}, respectively, while only 56 and 45 g N_2O-N ha^{-1} was emitted from fields 14 and 18, respectively.



Significant differences are indicated with different letter (P = 0.05) (*t*-Test)
Bars indicate standard deviation

Figure 6.2 N_2O-N emission (g ha^{-1} day^{-1}) (vertical lines = standard deviation) of the 0-5 cm depth layer of fields 13 (reduced tillage field by direct drilling since 1995 (RT_{DD_10})) and 14 (CT) in Villers-le-Bouillet and fields 17 (reduced tillage field with cultivator since 1985 (RT_{C_20})) and 18 (CT) in Court-Saint-Etienne in the soil samples from February 2006

6.5. DISCUSSION

In situ studies of N_2O-N emissions are difficult because of the extreme temporal and spatial variability associated with nitrification and denitrification processes (Well & Myrold, 2002). Spatial variability results from a non-homogeneous distribution of available C, NO_3^--N and NH_4^+-N and soil moisture content resulting in “hot spots” of microbial activity (Luo *et al.*, 2000). Even in apparently well-aerated soils anaerobic hot spots may be present where denitrification occurs. The spatial variability of RT fields tends to be even higher than in CT fields. Soil loosening instead of ploughing indeed was found to result in a less physical homogeneous soil, because lower soil moisture conditions and BD are created on the locations where the tines have worked the soil compared to the unworked part of the soil (Perfect & Caron, 2002; Duiker & Beegle, 2006; Roisin, 2007).

Under field conditions, variables having a strong effect on N_2O-N emissions, such as soil moisture content and temperature, often override the effect of soil variables such as texture and availability of C and N. Part of the high variability of N_2O-N emissions was controlled in this study by measuring in the laboratory under fixed conditions, namely at 80% WFPS and 15 °C. Due to the sampling protocol adapted here (undisturbed tubes), the variability in N_2O-N emissions between the different tubes remained high, especially in RT_{C_20} field 17 (Table 6.1 and Table 6.2). 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. The use of disturbed soil cores for measuring and comparing N_2O emissions could have resulted in decomposition of physically protected OM resulting in a higher amount of available C and N and as a consequence possibly higher N_2O-N emissions.

Under field conditions a big part of the variability in N_2O-N emission is caused by the alternation of drying and wetting cycles (Priemé & Christensenn, 2001). After adjusting the soil moisture content on day 3 of the samples of September 2005, a second small peak of N_2O-N emissions was observed in fields 1, 4, 13, 14 and 18 but not in field 17 (Figure 6.1). The small increase in soil moisture content seemed to be high enough to cause a detectable increase in N_2O-N emissions. Since it was thought that this would induce additional variability, no water was added during the incubation of the samples of February 2006.

N_2O-N emissions were measured on soil samples taken in September 2005 and February 2006 in order to determine if the potential N_2O-N emissions are different in summer and winter. The amount of mineral N was low at the end of the incubation in the samples from September 2005, except for field 18 with 51 mg N kg^{-1} dry soil (equivalent to 182 kg N ha^{-1} 30 cm^{-1}) (Table 6.1). The high amount of mineral N in that field can be a result from the application of organic manure after the harvest of winter wheat in August 2005. Both fields received organic manure in the month prior to sampling. The application of 30 tons of cattle manure ha^{-1} on CT field 18 contained approximately 250 kg N ha^{-1}, of which 60 kg N ha^{-1} was directly available in mineral form. The organic manure application (7 Mg chicken manure ha^{-1}) of RT_{C_20} field 17 contained approximately 230 kg N ha^{-1}, including 55 kg mineral N ha^{-1} (Table 2.15). Although similar amounts of N were applied on both fields, a large portion of the N that became available was probably immobilized by the straw left on

RT_{C_20} field 17, whereas little immobilization occurred in the CT field where straw was removed. Leaving the straw on the field is a typical feature of RT agriculture and these inherent differences in RT and CT management should explicitly be taken into account when comparing overall N_2O emissions between both systems. The low mineral N content in the soil samples from CT field 18 taken in February 2006 was probably to a large extent due to the N uptake by the green manure during the autumn and earlier N emissions (Table 2.4).

A positive and significant Pearson correlation of the N_2O-N emissions with mineral N was found (P = 0.05) (Table 6.3).

Table 6.3 Pearson correlation between the N_2O-N emissions, clay, bulk density (BD), total nitrogen (TN), microbial biomass nitrogen (MB-N) and mineral nitrogen

	Clay (%)	BD (Mg m^{-3})	TN (%)	MB-N (mg N kg^{-1} dry soil)	Mineral N (mg N kg^{-1} dry soil)
N_2O-N (mg N kg^{-1} dry soil day^{-1})	0.143	-0.375 **	-0.035	-0.010	0.391 **
Clay (%)		-0.345 **	0.335	0.159	0.209
BD (Mg m^{-3})			-0.233 *	-0.037	-0.094
TN (%)				0.761 **	-0.172
MB-N (mg N kg^{-1} dry soil)					-0.264 *

Significant differences *: P = 0.05; **: P = 0.01

Low N_2O-N emissions were measured, independent of the sampling time, for the fields with a low amount of NO_3^--N, except for RT_{C_20} field 17 sampled in September 2005 with a low amount of NO_3^--N but high N_2O-N emissions (Table 6.1 and Table 6.2).

In situations very favourable to denitrification, namely application of organic manure, green manure or crop residues under high soil moisture conditions, large peaks up to a few kg N_2O-N emissions ha^{-1} can occur (Schloemer, 1991; Beauchamp *et al.*, 1996). If the moisture conditions become favourable for denitrification several weeks after the application of organic manure, green manure or crop residues smaller peaks of N_2O-N emission can occur (±0.05 kg N_2O-N ha^{-1}) (Aulakh *et al.*, 1984; Vermoesen, 1999; Goossens *et al.*, 2001; Stevens & Laughlin, 2002; Rochette *et al.*, 2004). The application of organic manure in fields 17 and 18 in August 2005 probably resulted in sufficiently large amounts of easily mineralizable C and N in the soil samples taken in September 2005, which in combination with the increase of the moisture content up to 80% WFPS, resulted in somewhat higher N_2O-N emissions in the soil samples from fields 17 and 18 taken in September 2005 than the background N_2O-N emissions.

The BD in fields 13, 14, 17 and 18 for the soil samples taken in September 2005 were low because tillage was done only a few weeks prior to sampling (Table 6.1). The BD in the soil samples of fields 13, 14, 17 and 18 taken in February 2006 were significantly larger than in September 2005 due to the stabilization of the soil. A higher BD can increase the N_2O-N emissions. Ball *et al.* (1999) measured higher N_2O-N emissions in a CT field in Scotland on the area compacted by a roller than on the uncompacted area. Ruser *et al.* (2006) took undisturbed tubes from differently compacted areas (the ridges, the interrow area and wheel compacted interrow area) of a silt loam CT field with potatoes in Germany to the laboratory, adjusted to different soil moisture contents and measured N_2O-N emissions. The results showed that for the same % WFPS more compacted areas emitted more N_2O-N than the less compacted areas. Although BD can explain differences in N_2O-N emissions within one field, other factors may be more important between fields. The BD of RT_C field 17 was lower than CT field 18 in February 2006 (Table 6.2) while the SOC content and % TN of RT_C field 17 was higher than CT field 18. The higher % TN, in combination with the higher MB-N and mineral N content, most probably contributed to the higher N_2O-N emissions in RT_C field 17 compared to CT field 18 in the samples taken in February 2006.

A higher amount of SOM and crop residues in the upper layer result in a higher C availability for the micro-organisms and as a consequence in a higher MB amount in the RT compared to the CT fields (e.g. Höflich *et al.*, 1999; Stockfisch *et al.*, 1999). At each location the MB-N contents of the RT fields were (significantly) higher than the CT fields (Table 6.1 and Table 6.2). After the shift from CT to RT agriculture a relative increase in fungal to bacterial biomass is observed under RT fields because more crop residues are at the surface and the C:N ratio of the upper layer is higher of RT fields (Beare *et al.*, 1997; Frey *et al.*, 1999; Bossuyt *et al.*, 2001). Moreover, the hyphens of the fungi are destroyed at ploughing resulting in a decrease of fungi under CT fields. The expected increase in the ratio fungal to bacterial biomass in RT compared to CT fields could partly explain why the increase in N_2O-N emissions was not proportional with the MB-N increase. Per location, the higher N_2O-N emissions of the RT fields were correlated with a higher MB-N amount.

N_2O-N emissions are also enhanced with increasing fineness of soil texture (Chaterpaul *et al.*, 1980; Groffman & Tiedje, 1989 & 1991; Arah *et al.*, 1991; Liang & MacKenzie, 1997). D'Haene *et al.* (2003) found that the denitrification potential of the upper horizons of Flemish arable fields and pastures could be divided into three groups: soils with a high clay content (>30% clay) were characterised by a high denitrification potential; soils with medium texture had a medium denitrification potential and soils with a high sand content (>80% sand) had a low denitrification potential. Within each textural group a higher % TN resulted in higher denitrification potentials. It looks as if the second factor influencing the denitrification potential, % TN, can explain the higher N_2O-N emissions in RT compared to CT fields. The increase in % TN in the upper layer of RT compared to CT fields in this research was, however, lower than expected. The Western European crop rotation with sugar beets or potatoes causes heavy soil disturbance every 2 or 3 years at harvest. The frequent soil disturbance possibly resulted in a lower increase in % SOC and TN under RT fields compared to the increase in % TN in the upper layer in experimental fields on the shift of management to RT agriculture in America, Canada and Australia with cereal - soybean crop rotations (see 5.5.1). As a consequence of the lower increase in % TN, even after 21 years RT agriculture, a limited increase in N_2O-N emissions was measured for RT fields in this research compared to the increase in N_2O-N emissions measured in experiments on the shift of management to RT in America, Canada and Australia.

6.6. CONCLUSION

RT agriculture is an effective measure to reduce soil loss from soils susceptible to erosion in the short term but is often claimed to increase the N_2O emissions. N_2O-N emissions from RT fields tended to be slightly higher than the N_2O emissions from CT fields. The higher N_2O-N emissions were correlated with a higher % TN and MB-N. Under field conditions, the type, timing and amount of fertilizers and organic manure applications will have the largest effect on the N_2O-N emissions. Especially organic manure with easily available C and N can result in a peak of N_2O-N emission. Leaving the straw on the field, as is a common practice for RT fields, results in a lower mineral N content in the soil and might reduce the potential N_2O-N emissions from RT fields. Next to leaving straw on the field, composting of manure to stabilize the available C and N may reduce potential N_2O-N emissions in the field.

Chapter 7:

General discussion and conclusions: Is there potential for reduced tillage agriculture in Flanders?

WORKSHOP "REDUCED TILLAGE AGRICULTURE IN FLANDERS"

27 OCTOBER 2006

7.1. INTRODUCTION

CsT agriculture was first introduced on a large scale as a very effective measure to reduce erosion and store water into the soil (Arshad, 1999; Six *et al.*, 2002b; Bautista *et al.*, 2004; Derpsch, 2007). To date the research on the effects of CsT compared to CT agriculture were mainly focussed on the crop rotations under the climate and soil conditions in the USA, Latin America and Australia. In these large arable areas mainly cereals, soybean and sunflower are grown under a warm and dry climate (Arshad, 1999; Uri, 1999; Six *et al.*, 2002b; D'Emden & Llewellyn, 2004; Derpsch, 2007). The crop rotations in Western Europe with a maritime temperate climate often include beets and potatoes, resulting in a high disturbance of the soil at the formation of the ridges and at harvest. Erosion problems mostly occur with beets, potatoes and maize (Esteve *et al.*, 2004; Geelen, 2006) impelling on-site measurements.

In this research, we studied the effect of the shift of management from CT to RT agriculture, a type of CsT agriculture which refers to tilling the whole soil surface but eliminating one or more of the operations that would otherwise be done in a CT system. We've researched the effect of the shift of management from CT to RT agriculture on the physical and chemical soil properties of soils under the specific Western European climatic and soil conditions, with crop rotations containing crops that seem less suitable under RT agriculture, including an important share of root and tuber crops. However, other factors than physical and chemical soil properties have to be taken into account before sensible conclusions can be drawn on the potential for RT agriculture in this study area. Therefore, we summarized our results and combined them with existing data on other aspects of RT agriculture in order to obtain an integrated picture of the advantages and drawbacks for RT agriculture in Flanders.

We combined data from literature and experiences from RT farmers concerning yields, overall C and N dynamics, control of weeds, diseases and pests and economics with the effects on the physical and chemical soil properties measured in this study in order to put our results in a wider perspective and to conclude whether there is potential for RT agriculture in Flanders.

7.2. PHYSICAL SOIL PROPERTIES

In order to investigate the effect of RT on runoff and erosion, the aggregate stability and infiltration rate were measured, while the PR and WRC were determined to find out if the soil structure and potential for water stockage are optimal for root and crop growth in RT fields.

The short term (≤5 years) effect of RT agriculture on the reduction of soil erosion and runoff of crop rotations with root and tuber crops had been demonstrated before with rainfall simulations under field conditions (Gillijns *et al.*, 2002 & 2004; Goyens *et al.*, 2005; Leys *et al.*, 2007; Vermang *et al.*, 2007). The residues of the crops or green manure at the soil surface indeed intercept the rain and protect the soil against crusting of the soil surface. Moreover, the coverage slows down the runoff flow velocity (Layton *et al.*, 1993; Vandergeten & Roisin, 2004; Gillijns *et al.*, 2005). The aggregate stability of the upper 10 cm depth layer measured with the method of De Leenheer & De Boodt (1959) and the three methods of Le Bissonnais (1996) was a short time after the shift to RT agriculture higher than under CT agriculture which helps to reduce erosion losses (chapter 3).

The trend of a higher infiltration rate under RT compared to CT agriculture can be explained by the higher aggregate stability, the canals made by earthworms and roots which are not (RT_{DD}) or less (RT_C) destroyed compared to ploughing (CT) and the vertical cracks from loosening the soil (RT_C). The tines of the machines used to loosen the soil indeed make vertical cracks in the soil which transport the water fast to the deeper depth layers. These vertical cracks can be detected for several years with measurements of the PR (chapter 3) (Franzluebbers, 2002; Baritz *et al.*, 2004; Vandergeten & Roisin, 2004).

Since roots provide the crops with water and nutrients, a good rooting system is necessary for plant nutrition. For an optimal root growth a homogeneous and loose soil is needed. Compacted zones and cavities in the soil cause a branching or deformation of the roots and as a consequence decrease the crop yield (Pardo *et al.*, 2000; Nevens & Reheul, 2003; Vandergeten & Roisin, 2004). If the tillage operation and harvest can occur under optimal soil moisture conditions, RT agriculture including root and tuber crops (and green manure) can maintain but not improve the soil structure (Vandergeten, 2005 & 2006). As a consequence it is necessary that the soil structure is optimal before changing the management to RT agriculture (Vandergeten & Roisin, 2004; Thomas, 2006).

The BD of the 5-10 cm depth layer tended to be lower under RT than CT agriculture. The PR was higher in the upper depth layers (10-30 cm) under RT_{DD} than CT agriculture and often was higher than the maximum PR of roots (= 3 MPa). The PR in the 20-30 cm depth layer was only higher under RT_C than CT agriculture if the working depth was lower (chapter 3). The farmers with RT_C fields find that the upper depth layers are easier to work compared to CT fields. However, if the farmers can not harvest the beets and potatoes under optimal soil moisture conditions the soil structure is reduced for several years (D'Haene *et al.*, 2007).

An optimal soil structure not only facilitates oxygen and water infiltration but can also improve water storage (Franzluebbers, 2002). Since the crop yield under RT agriculture is often lower in wet years and higher in dry years than under CT agriculture (see 7.4), it was assumed that a higher PASW under RT compared to CT agriculture was partly responsible for differences in crop yields. However, the fact that no differences in PASW were found between RT and CT fields, indicated that other factors were responsible for the differences in crop yields. Soil temperature and evaporation under RT agriculture are lower than under CT agriculture due to the presence of crop residues or green manure at the surface (Drury *et al.*, 1999; Balesdent *et al.*, 2000; Larney *et al.*, 2003; Six *et al.*, 2004a) which may result in higher soil moisture contents under RT agriculture (chapter 3).

7.3. CARBON DYNAMICS AND BUDGET

A good soil structure is strongly related with SOM. Higher SOM and microbial biomass result in a better aggregate stability and a lower risk of erosion and therefore it is essential to maintain a high SOM content in the upper depth layer (Broninck & Lal, 2005). Maintaining or increasing the SOC stock is also important in the framework of "global change" (IPCC, 2000).

The objective of chapter 4 was to study the effect of RT agriculture on the C dynamics. RT agriculture resulted in a higher stratification of the % SOC but not in higher SOC stocks in the 0-60 cm depth layer of the RT compared to the CT fields. The potential to increase C in soils under RT agriculture in Western Europe is probably limited because the RT fields are periodically heavily disturbed (harvesting of beets and potatoes) which possibly limits the potential positive effect of RT (chapter 4). Moreover, although tillage intensity in this study was lower under RT than CT agriculture, the soil disturbance caused by tillage remained relatively intense under RT agriculture (chapter 2).

The higher amount of SOC at the soil surface was most pronounced in the labile fraction, which may result in a fast loss of SOC when RT fields are ploughed. However, the C mineralization rates measured in the laboratory on undisturbed and disturbed soil indicated that an intensive soil operation did not result in higher C mineralization rates of those silt loam RT fields.

Looking at the overall C budget, the amount of C from fuel use emitted by tractors, e.g. during tillage operations, also has to be considered. Due to the lower needed tractor time, loosening the stubble, preparing the seedbed and sowing RT_C fields resulted in a reduction of 33 l ha^{-1} y^{-1} (75 compared to 108 l ha^{-1} y^{-1} under CT) or 24 kg C ha^{-1} y^{-1} compared to the field work when sowing CT fields in France (Thomas, 2006). If loosening the soil, harrowing and sowing were done in one passage the reduction of fuel use under RT_C agriculture was sometimes twice as high in France and Wallonia (Haan, 2006; Thomas, 2006). A reduction of 59 l ha^{-1} y^{-1} or 43 kg C ha^{-1} y^{-1} was calculated under RT_{DD} compared to CT agriculture (Lal, 2002; West & Marland, 2002; Thomas, 2006).

7.4. CROP YIELDS

Ploughing results in a higher soil temperature and dries out the soil under CT compared to RT agriculture. As a consequence CT fields can be sown earlier and the early season growth of RT fields is delayed compared to CT fields (Drury *et al.*, 1999; Balesdent *et al.*, 2000; Larney *et al.*, 2003; Six *et al.*, 2004a).

The only difference between the RT and CT fields of field experiments is the type of tillage. The timing of soil cultivation and harvest and the choice of the crop variety are because of practical considerations the same which facilitates the comparison of soil properties (Powlson, 2007). Due to the delayed growth of crop yields of RT agriculture an underestimation can be observed in field experiments.

The inferiority in the crop growth under RT_C compared to CT agriculture is decreased rather fast. The crop yields of beets, potatoes and cereal crops were comparable (85-115%) for RT_C and CT agriculture if the soil structure is optimal and tillage operations were done correctly and non superficial (0-25/30 cm depth layer) (Ekeberg & Riley 1996; Mehdi *et al.*, 1999; El Titi, 2001; Debout, 2004; Rücknagel *et al*, 2004; Vandergeten & Roisin, 2004; Dam *et al.*, 2005; Riley *et al.*, 2005; Paauw, 2006; Vermang *et al.*, 2007). In dry and wet years slightly higher and lower crop yields could sometimes be observed, respectively (Debout, 2004). If the tillage operations were not done under optimal soil conditions, the crops, especially root crops, could have large amounts of branched roots which resulted in a higher amount of soil tare and resulted in lower yields, especially in dry years (Vandergeten & Roisin, 2004). Undeep loosening of the soil (0-15 cm depth layer) could result in a yield decrease under RT compared to CT agriculture (Debout, 2004; Gillijns *et al.,* 2004; Serlet, 2004; Vandergeten, 2005; Govers *et al.,* 2006).

The crop yields under RT_{DD} agriculture were comparable or lower than CT agriculture. The reductions in crop yields under RT_{DD} agriculture were probably correlated with the higher PR in the soil profile (Debout, 2004; Gillijns *et al.,* 2004; Vandergeten, 2005).

7.5. NITROGEN DYNAMICS

Crop growth not only depends on a good soil structure but also an optimal nutrient supply. To avoid nutrient losses from plant production or deficiency problems, fertilization has to be based on plant needs and consider the input through mineral N in the soil, mineralization and deposition (Hofman, 1983; Pálmai *et al.*, 1998; Hofman *et al.*, 2000). Since 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 CT soils.

The objective of chapter 5 was to indicate whether the higher stratification of N under RT compared to the CT agriculture results in a higher N mineralization rate. Recalculation of the N mineralization rate obtained in the laboratory to N mineralization per ha 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 (chapter 5).

To limit NH_3 losses, organic manure has to be worked into the soil but this can cause higher N_2O losses under RT than CT agriculture due to a higher soil moisture content and easily available C in the upper layer. This research has shown, however, that the background emissions of N_2O remain limited under RT agriculture (chapter 6). Under field conditions, the type, timing and amount of fertilizers and organic manure applications will have a larger effect on the N_2O-N emissions than the type of tillage. Composting can stabilize the OM before application (Baritz *et al.*, 2004) and reduce peaks of N losses after application. Compost also has a positive influence on the formation of aggregates and soil structure (Broninck & Lal, 2005).

Experiments in Belgium showed that N fertilization for sugar beets does not have to be changed for (short term) RT_C compared to CT fields (Vandergeten & Roisin, 2004). Farmers in Flanders and Wallonia confirm that the N efficiency is as good under RT as CT agriculture (D'Haene *et al*, 2007). However, the lower aeration and temperature of the soil of RT fields under field circumstances can result in a lower N mineralization rate in the spring which can explain the slower germination and early season growth under RT compared to CT agriculture (Rieger, 2001).

Another important consideration is the loss of NO_3^--N by leaching. In Western Europe, the NO_3^--N leaching losses mainly occur during winter time and will be at least partly determined by the residual NO_3^--N in the soil profile in autumn. We have measured the nitrate content at the start of October 2006 which gives a rough idea of the potential NO_3^--N by leaching in the winter 2006-2007. The NO_3^--N content (kg NO_3^--N ha^{-1}) of the 0-90 cm depth layer was comparable (RT_{C_2} field 1 compared to CT field 4 and RT_{DD_10} field 13 compared to CT field 14) or lower (RT_{C_20} field 17 compared to CT field 18) under RT than CT agriculture (Table 7.1).

A provisional allowed target value of 90 kg NO_3^--N ha^{-1} (0-90 cm) between 1 October and 15 November has been introduced (Anonymous, 2006c) (see 1.1.3). Only fields 1 and 4, located in Flanders, met the target value of MAP. However, not only the residual nitrate nitrogen in the soil profile in autumn and weather circumstances effect the NO_3^--N leaching. The canals formed by roots, earthworms and cracks from loosening the soil result in a good infiltration rate of the rainwater under RT agriculture limiting the contact of the rainwater with NO_3^--N in the soil and resulting in a low NO_3^--N leaching of RT fields (Holland, 2004; Thomas, 2006).

The high amount of mineral N in field 18 can be a result from the application of organic manure after the harvest of winter wheat in August 2005 (Table 2.15). Although similar amounts of N were applied on fields 17 and 18, a large portion of the N that became available was probably immobilized by the straw left on RT_{C_20} field 17, whereas little immobilization occurred in the CT field 18 where straw was removed. Leaving the straw on the field is a typical feature of RT agriculture.

Table 7.1 Nitrate nitrogen content (kg NO_3^--N ha^{-1}) of the 0-90 cm depth layer of some fields sampled on 05/10/2005 (fields 1 and 4) and 06/10/2005 (fields 13, 14, 17 and 18)

Depth layer (cm)	1 RT_{C_2}	4 CT	13 RT_{DD_10}	14 CT	17 RT_{C_20}	18 CT
0-20	5	5	52	34	33	102
20-40	5	4	25	37	19	34
40-60	3	0	10	18	10	21
60-80	1	0	13	7	7	16
80-90	0	0	4	4	2	4
Total average	13	9	105	100	72	176
Standard deviation	6	3	15	17	14	21

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

7.6. CROP PROTECTION

One of the main reasons for farmers to plough is to control the weed population. As a consequence of changing the management to RT agriculture, the abundancy and diversity of weeds can change (Carter *et al.*, 2002; D'Emden & Llewellyn, 2004). The germination of weeds that require no burial is limited after the shift to RT_C or RT_{DD} agriculture by sowing in the crop residues or green manure (Johnson *et al.*, 1993; Streit *et al.*, 2002; 2003). Seeds that need a period of burial to break dormancy loose their germinative capacity under RT_{DD} agriculture (Yenish *et al.*, 1992). A large part of the seeds under RT_{DD} agriculture is eaten by mice (van der Weide *et al.*, 2003).

Some RT fields are overgrown with weeds. The weeds and especially the grass vegetation can hamper the seedbed preparation. An extra superficial mechanical cultivation of the soil with a harrow or cultivator after the emergence of the crop or green manure is a possibility to loosen up and dry out the weeds. Mechanical cultivation can also be used to prepare a false seedbed and reduce weeds with a broad germination (Drinkwater *et al.*, 2000; Vandergeten & Roisin, 2004; Carter *et al.*, 2005; Thomas, 2006; Anonymous, 2007b). The choice to prepare a false seedbed depends on the weeds on the field and moment of emergence with regard to the sowing time (Thomas, 2006).

Both the presence of more mulch on the soil surface as well as the higher soil moisture content can result in more bacterial and fungal infections of the main crops under RT compared to CT agriculture. A restricted crop rotation appears to include a larger risk for bacterial and fungal infections of the main crops under RT compared to CT agriculture (Sturz *et al.*, 1997; Carter & Sanderson, 2001; Peters *et al.*, 2004 & 2005). RT farmers do not or can not consider the specific susceptibilities for bacterial and fungal infections of crops under RT agriculture choosing the variety of their crops because seeds for crop varieties are selected for an optimal crop yield under CT agriculture.

Reducing the number of passages and the higher concentration of OM at the soil surface also results in a higher number of hiding places and cavities in the soil and increases the risks of pests. The major pests under RT agriculture are snails, mice and larvae (Petheram, 2000; Vandergeten & Roisin, 2004).

Since the presence of mulch at the soil surface of RT fields is expected to result in a reduced efficiency of the pesticides (Sadeghi *et al.*, 1998; Streit *et al.*, 2003), more or more expensive pesticides are often used to control the weed population, diseases and pests the first years after the shift of the management to RT compared to CT agriculture as a precaution measure (Gillijns *et al.*, 2004; 2005). Since pesticides can have direct negative effects on the environment by affecting unintended target organisms and thus disturbing the functioning of ecosystems, other management measures can be selected. An extra mechanical cultivation for RT fields to resolve problems with weeds appears contradictory at first sight but it does not reduce the anti erosion effect of the mulch and the infiltration rate if the mechanical cultivation is not too deep and enough mulch remains at the soil surface (Vandergeten & Roisin, 2004). The choice of the sowing date, crop rotation and the correct choice of the green manure can also minimize problems with weeds and diseases (Guisson, 2006; Legrand & Vandergeten, 2006; Thomas, 2006). The green manure has to be selected so that diseases and pests are not passed on to the following main crop (Timmer *et al.*, 2004; Thomas, 2006). Changing the crop rotation is, however, often a theoretical but not a practical solution.

7.7. SOIL BIOLOGICAL ACTIVITY AND BIODIVERSITY

As a general rule, disease-causing bacteria and fungi make up only a very small proportion of the total number of species in root zone soil. Most bacterial and fungal species are beneficial and even crucial for soil functioning and soil quality (Sturz *et al.*, 1997).

In this research MB in the upper 10 cm depth layer was 1.5 to 3 times higher under RT compared to CT agriculture at the same location (chapter 3 and 4). Sometimes more symbiotic relations are observed which results in higher yields of these crops (Höfflich *et al.*, 1999). However, no biodiversity measurements were done in this study.

The higher amount of earthworms under RT compared to CT agriculture (Rasmussen, 1999; Tebrügge & Düring, 1999; Emmerling, 2001; Carter *et al.*, 2002; Katsvairo *et al.*, 2002; Boonen, 2004; Cunningham *et al.*, 2004; Van den Bossche *et al.*, 2007) increases the amount of canals in the soil and has a positive influence on the formation of aggregates through the binding ability of their excrements (Werner & Dindall, 1990). Earthworms increase soil N availability and cycling by stimulating the transfer of N from plant material to inorganic forms that can be utilized by microorganisms and plants (Brown *et al.*, 2000; Cortez *et al.*, 2000). Research from Switzerland, however, suggested that crop rotation has a bigger influence on the earthworm population than the type of tillage. Crop rotations without root and tuber crops have more earthworms than crop rotations including beets and potatoes (Hofer *et al.*, 2002; Maurer-Troxler *et al.*, 2006).

Other important soil organisms such as nematodes are very sensitive indicators of soil quality and essential players in the soil food web. Although this research did not deal with these organisms, they are often reported to be much more numerous under RT agriculture, and are therefore an indicator of a more healthy soil food web under RT agriculture (Holland, 2004).

RT agriculture benefits wildlife mainly by leaving crop residue on the soil surface which may be used as cover (Uri *et al.*, 1999).

7.8. FINANCIAL IMPACT

Next to the effect on the soil and crop yield, the financial impact of conversion to RT agriculture has to be considered. Haan (2006) calculated that the RT_C farmers save 10 to 25 euro y^{-1} by using less fuel compared to CT farmers. Gillijns *et al.* (2004) calculated the costs for tillage operations, fertilization and use of pesticides and profits of short term RT_C compared to CT agriculture. For short term RT_C agriculture (with soil loosening >15 cm) the financial output of RT_C rotations with beets, winter wheat and maize was similar or slightly higher to comparable CT rotations despite the more or more expensive pesticides that were often unnecessarily used. However, the financial output of short term RT_C (with soil loosening <15 cm) and RT_{DD} fields could be up to 50% lower than CT fields (Gillijns *et al.*, 2004).

Sowing green manure has many advantages, however, there are extra expenses for buying the seeds, tillage operations and killing (Timmer *et al.*, 2004; Huybrechts, 2006). The costs for sowing green manure decrease as for the main crop from CT > RT_C > RT_{DD} agriculture (Thomas, 2006).

Management agreements for obtaining subsidies for sowing green manure (50 euro ha^{-1} y^{-1}) can no longer be obtained in Flanders. The farmers receive money for reducing erosion as they receive the “single farm payment” of the MTR (Anonymous, 2005a & b). A soil conservation policy recently emerged in Flanders subsidising farmers, partly paid with European funds, who implement erosion control measures, e.g. grass buffers and RT agriculture, on their fields (Anonymous, 1999, 2003a & 2004a). Flemish farmers can receive 80 euro ha^{-1} y^{-1} for RT_C fields through a 5 year RT_C management agreement. The subsidies for a 5 year RT_{DD} management agreement are 200 euro ha^{-1} y^{-1}. Subsidising obviously makes RT agriculture more positive than mentioned before. RT_C agriculture results in a comparable or better financial output than CT agriculture, while RT_{DD} agriculture often leads up to a lower financial output.

Although the financial output of RT_{DD} farming is per ha lower than CT fields, the farmers spend less time per ha cultivating their fields (Uri, 2000; FAO, 2001; Bautista *et al.*, 2003; Wadsworth *et al.*, 2003; Cunnigham *et al.*, 2004) which gives them the opportunity to cultivate larger areas. Whereas CT farmers work on average 7 to 8 hours ha^{-1} y^{-1} with their tractors, this time is reduced by 3 to 4 hours ha^{-1} y^{-1} for RT_C farmers (Haan, 2006). Calculations of Velghe & Velghe (2004) and the CRA Gembloux confirm the reduction of work time of 4 to 5 hours ha^{-1} y^{-1} for RT_C compared to CT fields. The farmer, however, has to invest time to collect the knowledge to adapt his management (van Essen *et al.*, 2006) since changing the management to RT agriculture also can imply sowing green manure, adapting the sowing and harvesting time, changing crop rotation, etc.

To get an overall financial picture, we also have to look at the investments e.g. sowing into residue crops under RT agriculture requires adapted machinery (Timmer *et al.*, 2004). Since the subsidies are only 10% of the total cost, Flemish farmers often indicate the need of adapted machinery as a reason why they don't shift to RT agriculture (D'Haene *et al.*, 2007).

7.9. THE GREENHOUSE GAS BALANCE

The "Global Warming Potential" (GWP) is an index for estimating relative global warming contribution due to the atmospheric emission of greenhouse gases compared to the emission of a kg of CO_2. The GWP of a kg of CH_4 and N_2O is 21 and 310, respectively. One kg CO_2-C, CH_4-C and N_2O-N corresponds with 3.3, 28.0 and 476.9 CO_2 equivalents, respectively (IPCC, 2000 & 2005). Using GWP one can evaluate how much the greenhouse gases CO_2, CH_4 and N_2O emitted by RT and CT fields contribute to the greenhouse balance.

The difference in emissions of the greenhouse gases was calculated assuming an equal amount of fertilization and pesticides (see 5.5.2, 7.5 and 7.6) and an equal SOC stock (see 4.4.1 and 7.3) of RT and CT fields under Western European soil and climate conditions.

No trend in differences in N_2O-N emissions between RT_C, RT_{DD} and CT fields with maize and soybean crop rotation was observed under field conditions by Hilton *et al.* (1994), Elmi *et al.* (2003) and Venterea *et al.* (2005). They concluded that the type, timing and amount of fertilizers and organic manure applications have a larger effect on the yearly N_2O-N emissions than the type of tillage. Therefore we assumed no changes in N_2O-N emissions between RT and CT fields under field conditions.

The CH_4 uptake is comparable for RT_C and CT fields, while the CH_4 uptake on average is 0.4±0.1 kg CH_4-C ha^{-1} y^{-1} higher under RT_{DD} compared to CT fields (Six *et al.*, 2002b).

The change in C losses through fuel use depends on the type of RT agriculture and on whether green manure is sown or not (West & Marland, 2002 and Thomas, 2006).

The change of CO_2 equivalents ha^{-1} of arable fields without green manure results in lower emissions for RT_C and RT_{DD} compared to CT fields (Table 7.2):

for RT_C fields: 157 – 244 = -87 CO_2 equivalents ha^{-1} y^{-1}
RT_{DD} fields: 76 – 244 = -168 CO_2 equivalents ha^{-1} y^{-1}

When green manure is sown under RT but not CT, higher emissions for RT_C and lower emissions for RT_{DD} are found compared to CT fields (Table 7.2):

for RT_C fields: 359 – 244 = 115 CO_2 equivalents ha^{-1} y^{-1}
RT_{DD} fields: 208 – 244 = -36 CO_2 equivalents ha^{-1} y^{-1}

Table 7.2 Yearly CH_4 uptake and C losses through fuel use at sowing expressed in kg ha^{-1} y^{-1} en CO_2 equivalents ha^{-1} y^{-1} and total emissions expressed as CO_2 equivalents ha^{-1} (CO_2 eq. ha^{-1} y^{-1}) of conventional tillage (CT), reduced tillage with cultivator or soil loosener (RT_C) and direct drilling (RT_{DD}) fields without or with green manure (without or with gm)

	CH_4[†]		C use in fuel[‡]		Total
	(kg C ha^{-1} y^{-1})	(CO_2 eq. ha^{-1} y^{-1})	(kg C ha^{-1} y^{-1})	(CO_2 eq. ha^{-1} y^{-1})	(CO_2 eq. ha^{-1} y^{-1})
CT without gm	1.6	-45	79	289	244
CT with gm	1.6	-45	158	578	533
RT_C without gm	1.6	-45	55	202	157
RT_C with gm	1.6	-45	110	404	359
RT_{DD} without gm	2.0	-56	36	132	76
RT_{DD} with gm	2.0	-56	72	264	208

[†]: based on Six *et al.* (2002b)
[‡]: based on West & Marland (2002) and Thomas (2006)

The GWP calculated with yearly CH_4 uptake and N_2O-N emissions from fields with maize and soybean crop rotations suggest that RT fields have a lower GWP than CT fields (Table 7.2). However, the N_2O-N emissions from RT fields measured under controlled conditions in the laboratory tended to be slightly higher than the N_2O emissions from CT fields (chapter 6). Therefore, research on the effect of yearly CH_4 uptake and N_2O-N emissions of fields with crop rotations including root and tuber crops under RT and CT agriculture is needed in order to correctly compare their GWP.

7.10. CONCLUSION

Nowadays farmers shift more and more to RT agriculture, which can partly be explained by the gradual improvements in machinery, especially sowing machines. Moreover, the economical circumstances force the farmers to reduce production costs, while the pressure on the environment stimulates the farmer to manage his soil capital better and reduce his runoff and erosion (Vandergeten & Roisin, 2004). A few years after the shift to RT farmers often plough once, every three years or shift to CT agriculture again. RT agriculture can not decrease the plough pan or reduce pests or diseases whereas problems with weeds can increase if no control measures are taken. Moreover, there is no general cultivation plan that can be followed because management has to be adapted to the specific circumstances. RT fields are generally cultivated later in spring and have to be harvested later. Farmers with long term RT experience advise to first eliminate the plough pan and solve other problems related to soil structure before the shift to RT agriculture.

A correct adoption of RT agriculture is beneficial for the environment by reducing erosion, fuel use, while the N efficiency is comparable. However, higher overall emissions of greenhouse gases can occur under RT agriculture, especially for RT_{DD} agriculture. RT agriculture is also socially more sustainable. The lower work pressure allows the farmer to spend more time with his family and friends, but can even improve the general perception of agriculture e.g. by avoiding contact mud flows on roads because of reduced erosion.

We can conclude that RT_C is a form of agriculture that is more sustainable then CT agriculture in these loamy soils and that there is actually a potential for RT_C agriculture in Flanders. RT_C agriculture seems to benefit the farmers, society and the environment. However, still some improvements are necessary. E.g. dedicated selection of crops and green manure for RT_C agriculture, better subsidies upon conversion from CT to RT_C agriculture, and more knowledge on the effect of RT_C on pests and diseases could further increase the potential for RT_C agriculture.

This research indicates that short term RT_{DD} agriculture under crop rotations with root and tuber crops often result in a lower crop yield, which is probably correlated with the higher PR in the 10-30 cm depth layer. No data is available for long term RT_{DD} agriculture. Therefore, the potential of RT_{DD} agriculture in Flanders is probably limited because of the typical crop rotations that are less compatible with this type of agriculture.

SUMMARY

HEESTERT:
FIELD 1 WITH MUSTARD IN DECEMBER 2004

SOIL SAMPLING WITH AUGUR

Untill recently, modern agriculture was focused on maximum food production without considering the long term impact on soil fertility or environment. As a consequence modern agriculture is nowadays confronted with a number of pressing problems. The main problems agriculture experiences in industrialised societies are the degradation of physical soil structure resulting in erosion and soil compaction, decline in SOM and N losses.

Conservation tillage (CsT) agriculture was first introduced on a large scale on fields with mainly cereals, soybean and sunflower in the USA, Latin America and Australia as a very effective measure to reduce erosion and store water into the soil (Arshad, 1999; Six *et al.*, 2002b). To date research on the positive and negative effect of CsT compared to CT agriculture mainly focussed on the soil conditions and crop rotations under the warm and dry climatic of the USA, Latin America and Australia. The climatic and soil conditions and crop rotations in Western Europe are, however, very different. Western Europe has a maritime temperate climate and the crop rotations contain crops that seem less suitable under CsT 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 (Anonymous, 2006d). The major erosion problems in Belgium are found with these root and tuber crops and maize in the loess belt (Anonymous, 2000; Geelen, 2006).

Nowadays farmers in Western Europe shift more and more to reduced tillage (RT) agriculture, a type of CsT agriculture which refers to tilling the whole soil surface but eliminating one or more of the operations that would otherwise be done in a CT system. This shift can partly be explained by the progress in machines, especially sowing machines, and because of its proven effects on reduction of soil erosion (Vandergeten & Roisin, 2004). However, very little information is available on the evolution of important soil properties e.g. related to C dynamics in RT agriculture under the specific Western European climatic and soil conditions and crop rotations.

In this thesis, eighteen fields with a silt loam texture were selected, including the different types of RT agriculture running for a different number of years. In the study area, very little experimental sites exist where CT practices are compared to RT practices. Therefore, we had no choice but to include farmers' fields, where inevitably there is no perfect match between CT and RT fields.

Despite the high disturbance of the soil every 2 or 3 years of crop rotations including sugar beets or potatoes, RT agriculture had a positive effect on the measured physical soil properties. The aggregate stability of the upper 10 cm depth layer measured with the method of De Leenheer & De Boodt (1959) and the three methods of Le Bissonnais (1996) were higher a short time after the shift to RT compared to CT agriculture. At each location, bulk density (BD) of the 5-10 cm depth layer was mostly lower and saturated soil water content (θs) was mostly higher under RT than CT agriculture. The penetration resistance (PR) of the upper depth layer under RT by direct drilling (RT_{DD}) is higher than under CT agriculture, while the PR in the 20-30 cm depth layer is only higher under RT agriculture by cultivator or soil loosener (RT_C) if the working depth is lower. The trend was a higher field-saturated hydraulic conductivity (K_{fs}) under RT compared to CT agriculture (chapter 3).

RT agriculture resulted in a higher stratification of soil organic carbon (SOC) and total nitrogen (TN) in the soil profile. However, the total SOC and TN stock was not changed, even after a period of 20 years of RT agriculture. The amount of organic carbon and TN in three different particulate organic matter (POM) fractions of the 0-10 cm depth layer were found to be (significantly) higher both on an absolute and relative basis in the RT compared to the CT fields. In general the difference was the highest for the coarse free POM fraction, which is the most labile fraction. The higher SOC, TN and microbial biomass (MB) content in the upper depth layer of RT fields resulted in a higher carbon (C) and nitrogen (N) mineralization rate in undisturbed soil under controlled conditions in the laboratory. Simulating ploughing by disturbing the soil resulted both in lower and higher mineralization rates of the silt loam soils, but due to the large variability of the estimated mineralization parameters, the differences were not significant. It seems that under the specific management and climatic conditions of Western Europe, RT agriculture increase the SOC and TN content and microbial activity in the top layers, but do not result in enhanced sequestration when the entire soil profile is considered (chapter 4 and 5).

Nitrous oxide nitrogen (N_2O-N) emissions from RT fields tended to be slightly higher than CT fields. The higher N_2O-N emissions of RT compared to CT fields were correlated with a higher % TN and MB-N (chapter 6).

This study indicates that RT_C agriculture is beneficial for the farmers, society and environment. However, the potential for RT_{DD} agriculture in Flanders is probably limited because of the typical crop rotations that are less compatible with this type of agriculture (chapter 7).

SAMENVATTING

COURT-SAINT-ETIENNE:
FIELD 17 WITH WINTER WHEAT IN JUNE 2005

SOIL SAMPLING WITH AUGUR

Omwille van de bevolkingexplosie was de moderne landbouw van de 20ste eeuw gericht op maximale voedselproductie zonder rekening te houden met de langetermijn effecten op het milieu en de bodemvruchtbaarheid. Daarom wordt de moderne landbouw in West-Europa momenteel met verschillende problemen geconfronteerd. Het belangrijkste negatieve gevolg van de moderne productiemethodes voor de landbouwer is waarschijnlijk de degradatie van de fysische bodemstructuur, resulterend in erosie en compactie. De economische schade aangericht door erosie heeft niet alleen betrekking op het landbouwbedrijf zelf (on-site) (wegspoelen van zaaigoed, meststoffen en bestrijdingsmiddelen…). Er worden ook belangrijke off-site problemen veroorzaakt. Erosie komt in België vooral voor bij wortel- en knolgewassen en maïs geteeld op de leembodems (Verstraeten & Poesen, 1999; Esteve *et al.*, 2004). Naast erosie vormt ook diepe compactie onder de normale werkdiepte een ernstige bedreiging voor de bodemproductiviteit (Ide *et al.*, 1984 & 1987; Ide & Hofman, 1990).

Erosie en compactie hangen sterk af van het management. De voornaamste menselijke oorzaken van de degradatie van de fysische bodemstructuur zijn eenzijdige teeltrotaties, het frequent betreden van percelen met zware landbouwvoertuigen ook in ongunstige omstandigheden, intensieve bodembewerkingen, en een tekort aan organische stof (OS) in de bodem (Esteve *et al.*, 2004; Jones *et al.*, 2004). Recente studies toonden aan dat het gehalte OS van akkerbouwbodems in Vlaanderen significant gedaald is tussen 1990 en 1999 (Sleutel *et al.*, 2003a & b). Zodoende valt het te vrezen dat de problematiek van erosie en compactie in de komende jaren nog nijpender zal worden.

Door het overvloedige gebruik van minerale en organische meststoffen heeft de degradatie van de fysische bodemstructuur nog niet geleid tot een daling van de chemische bodemvruchtbaarheid. Stikstof (N), het belangrijkste nutriënt voor het bekomen van een gewasproductie en -kwaliteit, heeft via verliezen een belangrijke impact op de kwaliteit van het milieu (De Clercq *et al.*, 2001).

Conserveringslandbouw (ConsL) werd op grote schaal in Amerika, Latijns-America en Australië geïntroduceerd als een effectieve maatregel tegen erosie en om water in de bodem op te slaan (Arshad, 1999; Six *et al.*, 2002b). De resten van de teelten en groenbemester aan de oppervlakte beschermen immers de bodem tegen de rechtstreekse regeninslag, verminderen de verslemping van de bodem en vertragen de snelheid van het afstromend water (Vandergeten & Roisin, 2004).

Tot op heden werden de effecten van CsL in vergelijking met conventionele (Conv) landbouw voornamelijk onderzocht onder de klimaats- en bodemomstandigheden in Amerika, Latijns-America en Australië. Meestal worden in deze grote akkerbouwgebieden graangewassen, soja enz. onder een warm en droog klimaat geteeld (Arshad, 1999). In West-Europa met een maritiem gematigd klimaat komen in de teeltrotaties vaak bieten en aardappelen voor (Anonymous, 2006d), die bij de aanmaak van de ruggen bij aardappelen en de oogst van bieten en aardappelen voor een grote verstoring van de bodem zorgen.

Momenteel wordt landbouw met gereduceerde bodembewerkingen (Red), een vorm van ConsL waarbij één of meerdere bodembewerkingen geëlimineerd worden die onder Conv landbouw zouden plaatsvinden, ook in West-Europa omwille van zijn positief effect op erosie gepromoot (o.a. Gillijns *et al.*, 2002 & 2004; Goyens *et al.*, 2005). De overschakeling van het management van Conv naar Red landbouw wordt ook verklaard door de vooruitgang in machines, voornamelijk de zaaimachines (Vandergeten & Roisin, 2004). Er is echter weinig informatie over de effecten van de verandering van het management van Conv naar Red landbouw op de fysische en chemische bodemvruchtbaarheid onder de West-Europese klimaats- en bodemomstandigheden en teeltrotaties met wortel- en knolgewassen.

Er werden achttien percelen met een leemtextuur geselecteerd. Ze omvatten de verschillende types van Red landbouw lopende gedurende 2 tot 20 jaar. In het studiegebied zijn er weinig experimenten waar Red en Conv management met elkaar vergeleken worden. Daarom moesten er percelen van landbouwers geselecteerd waardoor onvermijdelijk de Red en Conv percelen geen perfect evenbeeld zijn. Bij de selectie van de gepaarde percelen werd ervoor gezorgd dat het bodemtype en management vergelijkbaar zijn.

Ondanks de regelmatige verstoring van de bodem bij teelrotaties met bieten en aardappelen blijkt dat aggregaatstabiliteit bepaald met de methode van De Leenheer & De Boodt (1959) en de drie methoden van Le Bissonnais (1996), van de bodemlaag 0-10 cm al op een korte termijn na omschakeling naar Red landbouw hoger waren dan onder Conv landbouw wat gedeeltelijk de lagere erosieverliezen verklaart (hoofdstuk 3). De trend was een verhoogde infiltratiesnelheid onder Red landbouw in vergelijking met Conv landbouw wat mogelijk te verklaren is door de hogere aggregaatstabiliteit, omdat de regenworm- en wortelgangen niet (Red met directe inzaai [$\mathrm{Red}_{\mathrm{DI}}$]) of minder (Red met cultivator of woeler [$\mathrm{Red}_{\mathrm{C}}$]) verstoord worden in vergelijking met het keren van de bodem bij ploegen (Conv) en door de verticale scheuren gevormd tijdens de bodembewerkingen ($\mathrm{Red}_{\mathrm{C}}$). Deze verticale scheuren gevormd tijdens het losbreken van de bodem waren zichtbaar bij de metingen van de penetratieweerstand (hoofdstuk 3) (Franzluebbers, 2002; Vandergeten & Roisin, 2004).

Voor een optimale wortelgroei is een homogene en losse bodemstructuur nodig. Verhoogde penetratieweerstand door verslempingen (zelfs lichte), verdichte zones en holten kunnen tot een vervorming van de wortels leiden, wat nadelig kan zijn voor de opbrengst van gevoelige teelten zoals bieten (Vandergeten & Roisin, 2004; Vandergeten, 2005 & 2006). Ons onderzoek toonde aan dat de penetratieweerstand toeneemt bovenaan het profiel onder $\mathrm{Red}_{\mathrm{DI}}$ landbouw, vaak ook boven de maximum penetratieweerstand (= 3MPa) die een wortel kan overwinnen. De penetratieweerstand in de bodemlaag 20-30 cm was alleen hoger onder $\mathrm{Red}_{\mathrm{C}}$ dan Conv landbouw indien de bodembewerkingen ondieper waren (hoofdstuk 3). De BD van de bodemlaag 5-10 cm was meestal lager onder Red dan Conv landbouw terwijl het vochtgehalte bij verzadiging meestal hoger was.

De stratificatie van het % organische koolstof (OC) in de bodemlaag 0-60 cm was groter voor de Red dan Conv percelen maar de totale OC stock in de bodem was niet noodzakelijk hoger. Het potentieel voor koolstof (C) opslag in Red percelen in Vlaanderen is dan ook wellicht minimaal. De bodems onder Red landbouw zijn immers periodisch onderhevig aan vrij zware verstoringen (oogstwerkzaamheden van bieten en aardappelen) wat mogelijk het potentiële positieve effect van Red landbouw beperkt (hoofdstuk 4). Bovendien zijn de bodembewerkingen onder Red landbouw nog steeds relatief intensief. Over het algemeen was de OC toename aan de oppervlakte het meest uitgesproken in de meest labiele fractie, namelijk de fractie grof vrij particulair organisch materiaal. Het opnieuw overschakelen naar Conv landbouw zou kunnen resulteren in een snel verlies van de OC. Metingen van de C mineralisatie snelheid van onverstoorde en verstoorde bodems geven echter aan dat na een sterke eenmalige verstoring van de bodem er geen directe toename is van de C mineralisatie snelheid.

Naast de verandering aan C in de bodem moet er ook gekeken worden naar de hoeveelheid C in de diesel verbruikt door de tractoren vb. tijdens de bodembewerkingen. Door de verminderde tijd nodig voor het veldwerk onder Red landbouw is het diesel- en dus C verbruik lager (West & Marland, 2002; Thomas, 2006).

De stratificatie van het percentage TN in de bodemlaag 0-40 cm was ook groter onder Red dan Conv landbouw. Onder labo omstandigheden nam de N mineralisatie snelheid van de bodemlaag 0-15 cm toe. Herberekening van de N mineralisatie snelheid bepaald in het labo naar N mineralisatie snelheid per ha en per jaar gebruik makend van de gemiddelde maandtemperaturen en rekening houdend met de verschillende stratificatie onder Red en Conv landbouw gaf aan dat de verschillen in N mineralisatie snelheid van de bodemlaag 0-30 cm te klein zijn om de N bemesting van Red percelen aan te passen (hoofdstuk 5). Proeven in België tonen aan dat het bij Red landbouw niet noodzakelijk is om het N bemestingsniveau aan te passen (Vandergeten & Roisin, 2004).

Dit onderzoek toonde aan dat de N verliezen in de vorm van N_2O beperkt blijven onder Red landbouw. De iets hogere N_2O-N verliezen in het labo waren gecorreleerd met een hogere % TN en MB-N hoeveelheid. Onder veldomstandigheden heeft de hoeveelheid, soort en tijdstip van bemesting een grotere invloed op de N_2O-N verliezen dan het type landbouw (hoofdstuk 6).

Het gehalte MB-C en MB-N in de bovenste 10 cm was 1.5 tot 3 maal hoger in de percelen onder Red in vergelijking met de Conv percelen op dezelfde locatie (hoofdstuk 4 en 5).

Om te kunnen besluiten of er potentieel voor Red landbouw is in Vlaanderen werden de bekomen resultaten van de fysische en chemische bodemvruchtbaarheid samengevoegd met een C en N budget, onkruid- en ziektedruk, opbrengsten en financieel rendement om een geïntegreerd beeld te krijgen van de voor- en nadelen van Red landbouw in Vlaanderen.

Eén van de belangrijkste redenen om te ploegen is de onkruiddruk beperken. Onder Red landbouw kan zowel de onkruiddruk toenemen als de onkruidflora veranderen. Een bijkomende bewerking met een rotoreg of ontstoppelaar is een mogelijkheid om de grassen los te maken en te laten uitdrogen of om een vals zaaibed aan te leggen en kan nuttig zijn om het potentieel van onkruiden met een gespreide opkomst, te verminderen (Drinkwater *et al.*, 2000; Vandergeten & Roisin, 2004; Thomas, 2006; Anonymous, 2007b).

De aanwezigheid van oogresten aan de oppervlakte en het hogere vochtgehalte kunnen de kans op bacteriële en schimmelinfecties verhogen onder Red in vergelijking met Conv landbouw (Sturz *et al.*, 1997; Carter & Sanderson, 2001; Peters *et al.*, 2004 & 2005). Landbouwers gebruiken dan ook vaak preventief meer of duurdere gewasbeschermingsmiddelen (Gillijns *et al.*, 2004 & 2005).

Onder Red landbouw werden meestal meer regenwormen dan onder Conv landbouw gemeten (e.g. Boonen, 2004; Van den Bossche *et al.*, 2007) wat een positieve invloed heeft op de vorming van horizontale gangen en de aggregaatstabiliteit (Werner & Dindall, 1990).

De opbrengsten van bieten, aardappelen en granen waren vergelijkbaar onder $\mathrm{Red}_{\mathrm{C}}$ en Conv landbouw op voorwaarde dat de bodemstructuur goed was en de teeltbewerkingen correct en niet oppervlakkig (0-25/30 cm) uitgevoerd werden. In droge jaren was er een kleine meeropbrengst terwijl in natte jaren een kleine minderopbrengst werd vastgesteld. Wanneer $\mathrm{Red}_{\mathrm{C}}$ landbouw echter niet op optimale wijze gebeurde, vertoonden de bieten grote hoeveelheden vertakte wortels. Bij ondiep (0-10 cm) losbreken en een slechte bodemstructuur werden er opbrengstverliezen tot 20% onder $\mathrm{Red}_{\mathrm{C}}$ t.o.v. Conv percelen gemeten (Debout, 2004; Vandergeten & Roisin, 2004; Vandergeten, 2005).
De opbrengsten onder $\mathrm{Red}_{\mathrm{DI}}$ waren vergelijkbaar of lager met Conv percelen. De lagere opbrengsten bij $\mathrm{Red}_{\mathrm{DI}}$ percelen zijn waarschijnlijk gecorreleerd met de hogere penetratieweerstand bovenaan het profiel (Debout, 2004; Gillijns *et al.,* 2004; Vandergeten, 2005).

Naast de verlaagde werkdruk en het financiële voordeel voor de landbouwer, vermindert $\mathrm{Red}_{\mathrm{C}}$ landbouw ook de maatschappelijke kosten van de landbouw omdat de kosten voor het opruimen van de wegen en uitbaggeren van de waterlopen verlaagd worden.

We kunnen besluiten dat Red_C landouw een meer duurzame vorm van landbouw is dan ConvL en dat er potentieel is voor Red_C landouw in de leembodems in Vlaanderen. Red_C landbouw is zowel voordelig voor de landbouwer, de maatschappij als het milieu. Er zijn echter nog een aantal zaken die verbeterd kunnen worden vb. de selectie van de variëteiten van de teelten en tussenteelten rekening houdend met de specifieke gevoeligheden onder Red_C landouw, betere subsidies bij omschakeling van Conv naar Red_C landbouw en een meer uitgebreide kennis van de effecten van Red_C landbouw op ziektes en onkruiddruk onder de Vlaamse teeltrotaties zouden het potentieel voor Red_C landbouw nog kunnen doen toenemen.

Uit onderzoek naar Red_{DI} landbouw onder de Vlaamse teeltrotatie blijkt er op korte termijn vaak een daling van de opbrengst onder Red_{DI} ten opzichte van Conv landbouw,wat mogelijk gecorreleerd is met de hogere penetratieweerstand in de bodemlaag 10-30 cm. Over langetermijn Red_{DI} landbouw zijn er geen gegevens. Een betere kennis van het microbiële leven en hun invloed op de bodemstructuur en ziektes kan mogelijk de negatieve gevolgen van Red_{DI} landbouw verlagen.

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APPENDICES

Table I.1 Granulometric composition and pH_{KCl} (with standard deviation between brackets) of the 10-20, 20-30 and 30-40 cm layer of the 18 selected fields

Depth layer	Field		Sand (%)	Silt (%)	Clay (%)	pH_{KCl}	
10-20 cm	1	RT_{C_2}	34.0	52.4	13.6	7.0	(0.5)
	2	RT_{C_2}	37.4	50.1	12.5	6.5	(0.3)
	3	RT_{C_2}	28.8	59.3	12.0	6.7	(0.4)
	4	CT	37.8	49.8	12.4	6.4	(1.1)
	5	RT_{C_5}	33.2	48.4	18.4	6.4	(0.0)
	6	CT	25.0	58.3	16.7	5.3	(0.2)
	7	RT_{C_5}	28.1	60.6	11.3	6.7	(0.1)
	8	CT	28.3	60.3	11.4	6.7	(0.2)
	9	RT_{C_10}	8.8	69.9	21.3	5.9	(0.2)
	10	CT	10.5	76.1	13.4	6.2	(0.2)
	11	RT_{DD_10}	7.4	71.8	20.8	6.6	(0.4)
	12	CT	6.5	74.8	18.7	6.6	(0.0)
	13	RT_{DD_10}	5.9	76.8	17.3	6.6	(0.2)
	14	CT	9.0	75.7	15.3	5.7	(0.1)
	15	RT_{DD_10}	13.8	70.7	15.5	5.9	(0.1)
	16	CT	10.3	72.3	17.4	6.3	(0.0)
	17	RT_{C_20}	12.4	72.5	15.1	6.3	(0.4)
	18	CT	8.4	74.9	16.6	5.7	(0.2)
20-30 cm	1	RT_{C_2}	34.5	51.0	14.5	7.1	(0.5)
	2	RT_{C_2}	32.2	55.5	12.3	6.6	(0.2)
	3	RT_{C_2}	28.4	59.6	12.0	6.9	(0.4)
	4	CT	32.8	52.9	14.3	6.3	(0.9)
	5	RT_{C_5}	30.8	47.3	21.9	6.2	(0.1)
	6	CT	23.8	58.7	17.5	5.4	(0.1)
	7	RT_{C_5}	28.8	58.2	13.0	6.6	(0.2)
	8	CT	28.6	59.6	11.8	6.7	(0.3)
	9	RT_{C_10}	7.4	70.8	21.8	5.9	(0.1)
	10	CT	9.3	76.6	14.1	6.3	(0.3)
	11	RT_{DD_10}	5.7	68.8	25.6	6.4	(0.5)
	12	CT	5.5	69.8	24.7	6.5	(0.1)
	13	RT_{DD_10}	5.5	69.6	24.9	6.5	(0.2)
	14	CT	7.5	75.7	16.8	5.8	(0.1)
	15	RT_{DD_10}	8.3	69.8	21.9	5.7	(0.1)
	16	CT	8.9	71.1	20.0	6.4	(0.4)
	17	RT_{C_20}	10.9	71.8	17.3	6.4	(0.6)
	18	CT	7.4	74.2	18.4	5.8	(0.1)

Table I.1 (continuation) Granulometric composition and pH_{KCl} (with standard deviation between brackets) of the 10-20, 20-30 and 30-40 cm layer of the 18 selected fields

Depth layer	Field		Sand (%)	Silt (%)	Clay (%)	pH_{KCl}	
30-40 cm	1	RT_{C_2}	35.8	47.3	16.9	7.1	(0.6)
	2	RT_{C_2}	34.4	52.4	13.2	6.5	(0.2)
	3	RT_{C_2}	32.1	55.2	12.8	6.8	(0.4)
	4	CT	31.9	54.1	14.0	6.4	(1.0)
	5	RT_{C_5}	31.1	46.9	22.0	6.2	(0.1)
	6	CT	25.3	57.6	17.1	5.4	(0.1)
	7	RT_{C_5}	27.5	59.7	12.8	7.0	(0.3)
	8	CT	29.2	58.1	12.7	6.6	(0.2)
	9	RT_{C_10}	8.5	69.6	21.9	5.8	(0.1)
	10	CT	8.4	76.2	15.4	6.1	(0.1)
	11	RT_{DD_10}	7.4	67.5	25.1	6.1	(0.0)
	12	CT	4.5	72.8	22.7	6.4	(0.1)
	13	RT_{DD_10}	4.9	71.5	23.6	6.3	(0.1)
	14	CT	8.0	74.3	17.6	5.8	(0.1)
	15	RT_{DD_10}	8.8	70.9	20.3	5.7	(0.1)
	16	CT	10.4	69.4	20.2	6.4	(0.1)
	17	RT_{C_20}	12.8	69.3	17.9	6.3	(0.4)
	18	CT	35.8	47.3	16.9	5.8	(0.1)

Table II.1 Total and readily plant available soil water (TPASW and RPASW) and S of 5-10 cm depth layer of the selected fields (with standard deviation between brackets)

Field		TPASW ($m^3\ m^{-3}$)			RPASW ($m^3\ m^{-3}$)			S		
1	RT_{C_2}	0.135	(0.018)	ab	0.017	(0.002)	a	0.042	(0.003)	a
2	RT_{C_2}	0.143	(0.014)	ab	0.018	(0.001)	a	0.044	(0.004)	a
3	RT_{C_2}	0.140	(0.006)	a	0.018	(0.001)	a	0.045	(0.003)	a
4	CT	0.106	(0.005)	b	0.014	(0.001)	b	0.036	(0.004)	a
5	RT_{C_5}	0.129	(0.043)	a	0.012	(0.003)	a	0.038	(0.014)	a
6	CT	0.111	(0.018)	a	0.012	(0.000)	a	0.032	(0.005)	a
7	RT_{C_5}	0.161	(0.016)	a	0.022	(0.002)	a	0.055	(0.005)	a
8	CT	0.135	(0.019)	a	0.018	(0.001)	b	0.046	(0.001)	b
9	RT_{C_10}	0.105	(0.017)	b	0.013	(0.002)	b	0.033	(0.006)	b
10	CT	0.174	(0.008)	a	0.021	(0.003)	a	0.053	(0.003)	a
11	RT_{DD_10}	0.145	(0.044)	a	0.014	(0.003)	a	0.042	(0.013)	a
12	CT	0.168	(0.028)	a	0.017	(0.003)	a	0.049	(0.010)	a
13	RT_{DD_10}	0.156	(0.012)	a	0.017	(0.002)	a	0.045	(0.004)	a
14	CT	0.169	(0.011)	a	0.016	(0.004)	a	0.050	(0.004)	a
15	RT_{DD_10}	0.158	(0.021)	a	0.019	(0.003)	a	0.048	(0.007)	a
16	CT	0.144	(0.006)	a	0.017	(0.001)	a	0.042	(0.002)	a
17	RT_{C_20}	0.115	(0.020)	a	0.013	(0.001)	a	0.033	(0.005)	a
18	CT	0.135	(0.008)	a	0.015	(0.001)	a	0.039	(0.001)	a

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

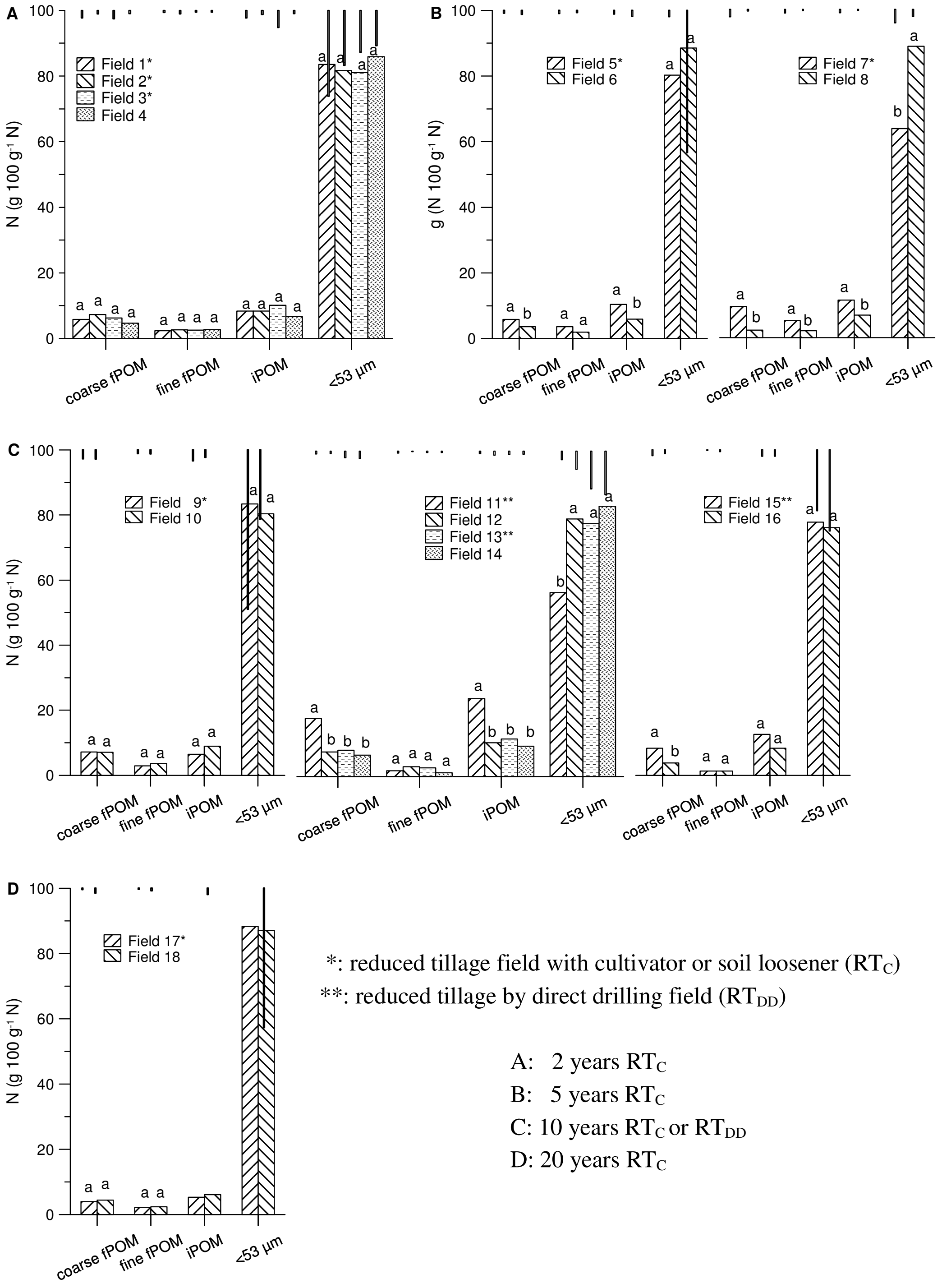
same letters indicate no significant differences between tillage treatments per location (P=0.05) (one way ANOVA/Duncan post hoc test, Welch/Games-Howell post hoc test or *t*-Test)

Table II.2 Total and readily plant available soil water (TPASW and RPASW) and S of 25-30 cm depth layer of the selected fields (with standard deviation between brackets)

Field		TPASW ($m^3\ m^{-3}$)			RPASW ($m^3\ m^{-3}$)			S		
1	RT_{C_2}	0.127	(0.006)	a	0.016	(0.001)	b	0.038	(0.002)	b
2	RT_{C_2}	0.129	(0.015)	a	0.017	(0.001)	ab	0.043	(0.001)	ab
3	RT_{C_2}	0.148	(0.004)	a	0.019	(0.001)	a	0.047	(0.002)	a
4	CT	0.120	(0.014)	a	0.016	(0.002)	b	0.040	(0.005)	b
5	RT_{C_5}	0.133	(0.045)	a	0.014	(0.003)	a	0.039	(0.013)	a
6	CT	0.126	(0.009)	a	0.016	(0.002)	a	0.040	(0.005)	a
7	RT_{C_5}	0.163	(0.009)	a	0.023	(0.001)	a	0.056	(0.002)	a
8	CT	0.166	(0.004)	a	0.022	(0.001)	a	0.054	(0.002)	a
9	RT_{C_10}	0.119	(0.030)	b	0.015	(0.004)	b	0.036	(0.009)	b
10	CT	0.170	(0.005)	a	0.020	(0.001)	a	0.052	(0.001)	a
11	RT_{DD_10}	0.125	(0.013)	a	0.015	(0.001)	a	0.037	(0.003)	a
12	CT	0.145	(0.032)	a	0.016	(0.004)	a	0.042	(0.011)	a
13	RT_{DD_10}	0.134	(0.011)	a	0.016	(0.002)	a	0.039	(0.004)	a
14	CT	0.165	(0.026)	a	0.017	(0.004)	a	0.050	(0.009)	a
15	RT_{DD_10}	0.149	(0.003)	a	0.018	(0.002)	a	0.045	(0.003)	a
16	CT	0.146	(0.006)	a	0.016	(0.000)	a	0.042	(0.002)	a
17	RT_{C_20}	0.115	(0.015)	a	0.013	(0.002)	a	0.034	(0.005)	a
18	CT	0.127	(0.011)	a	0.015	(0.002)	a	0.037	(0.004)	a

RT_C: reduced 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 between tillage treatments per location (P=0.05) (one way ANOVA/Duncan post hoc test, Welch/Games-Howell post hoc test or *t*-Test)



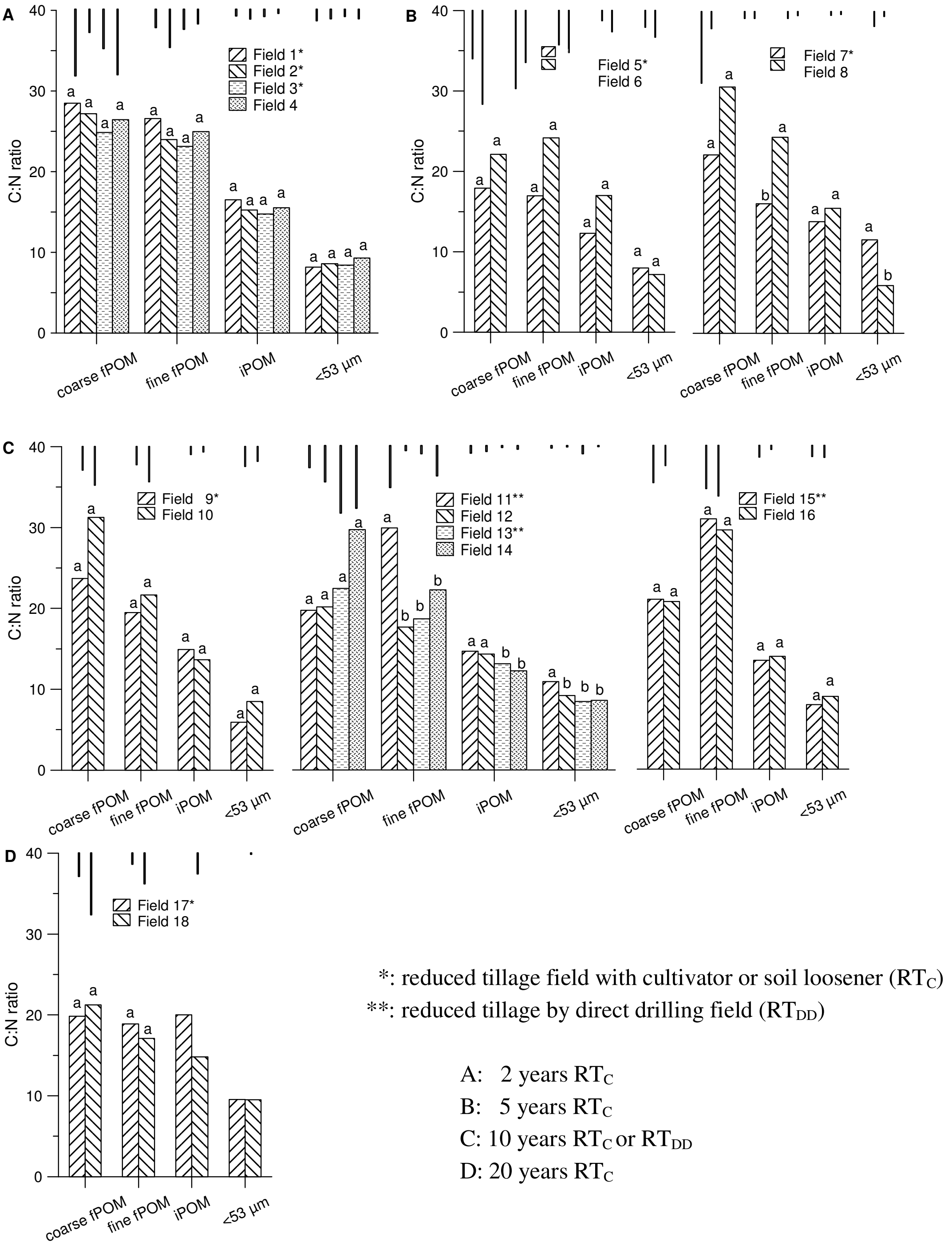
*: reduced tillage field with cultivator or soil loosener (RT_C)

**: reduced tillage by direct drilling field (RT_{DD})

A: 2 years RT_C
B: 5 years RT_C
C: 10 years RT_C or RT_{DD}
D: 20 years RT_C

same 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)

Figure III.1 Relative distribution of the nitrogen (N) content (g 100 g^{-1} N) in the coarse free particulate organic matter (fPOM) (>250 µm), fine fPOM (53-250 µm), intra-aggregate organic matter (iPOM) (53-250 µm) and <53 µm fraction isolated according to physical fractionation method of Six *et al.* (2000a) (vertical lines=standard deviation) of the 0-10 cm depth layer of the 18 selected fields



*: reduced tillage field with cultivator or soil loosener (RT_C)
**: reduced tillage by direct drilling field (RT_{DD})

A: 2 years RT_C
B: 5 years RT_C
C: 10 years RT_C or RT_{DD}
D: 20 years RT_C

same 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)
only one measurement of iPOM and <53µm was done for field 7

Figure III.2 Ratio of the organic carbon to nitrogen content (C:N ratio) in the coarse free particulate organic matter (fPOM) (>250 µm), fine fPOM (53-250 µm), intra-aggregate organic matter (iPOM) (53-250 µm) and <53 µm fraction isolated according to physical fractionation method of Six *et al.* (2000a) (vertical lines=standard deviation) of the 0-10 cm depth layer of the 18 selected fields

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