Op de akkerlijnen schrijft de boer

vele gewassen diep en ver

door weer en wind getergd

zijn eigen woordeloos gedicht

in zijn ogen groeien de vier seizoenen

die hij steeds met vaste hand door de dagen begeleidt

laat ons worden als hij die lucht en aarde eert

en ook de kleine vogels in de bomen niet vergeet.

Promoters: Prof. dr. ir. Stefaan De Neve

Department of Soil Management

Faculty of Bioscience Engineering

Ghent University

Dr. ir. Bart Vandecasteele

Plant Sciences Unit

The Institute for Agricultural and Fisheries Research (ILVO)

Dean: Prof. dr. ir. Marc Van Meirvenne

Rector: Prof. dr. Anne De Paepe

Ir. Koen WILLEKENS

Nitrogen dynamics in relation to soil management and soil quality in field vegetable cropping systems

Thesis submitted in fulfillment of the requirements for the degree of Doctor (PhD) in Applied Biological Sciences: Land and Water Management

Dutch translation of the title:

Stikstofdynamiek in relatie tot bodembeheer en bodemkwaliteit in de vollegrondsgroenteteelt

Illustration on the front cover:

Soil management experiment in Meulebeke (October, 2011)

Illustration on the back cover:

Soil management experiment in Melle (August, 2013)

Citation:

Willekens, K., 2016. Nitrogen dynamics in relation to soil management and soil quality in field vegetable cropping systems. PhD thesis, Ghent University, Ghent, Belgium, p. 178

ISBN 978-90-5989-872-1

Summary

Introduction

Soil quality in conventional field vegetable cropping systems is seriously threatened by intensive tillage and fertilization practices and by a limited number of crops in the crop rotation. A decrease in soil quality will jeopardize yield security and product quality. Inclusion of cover crops, compost application and reduced tillage help to sustain soil quality. Nitrogen (N) is a key element in crop productivity and at the same time, N losses by leaching are the main environmental issue in intensive field vegetable cropping systems in Europe. N leaching losses are presumed to be primarily caused by a high fertilizer N input in combination with a low fertilizer N recovery by the crop. The question was how soil quality and soil quality improving management practices influence the N supply and N recovery in the plant-soil system. Do soil quality improving management practices enable an increase of the fertilizer N recovery by the crop and a reduction of the N losses? And how does N input by mineral or organic fertilizers interact with the soil organic matter (SOM) content and phosphorous (P) status of the soil?

The objectives of this study were (i) assessing the effects of specific management practices on soil quality, and (ii) understanding N dynamics in relation to soil quality and soil quality improving management practices, i.e., reduced tillage, compost application and green manuring. The study work was based on a combination of a field survey and dedicated field trials. Farmers' practice was applied on the surveyed fields. The soil management field trials were performed in both conventional and organic field vegetable cropping systems. The main hypotheses of this study were (i) soil management affects soil quality, (ii) soil quality affects N dynamics in the plant-soil system, (iii) soil management affects N dynamics and (iv) soil management, soil quality and N dynamics affect crop performance. The aim was to (i) gain better knowledge on N dynamics allowing for fine-tuning N fertilization to specific soil quality characteristics or certain soil management practices in order to optimize N utilization in the plant-soil system and minimize N losses to the environment, and (ii) define soil management strategies for field vegetable production systems that allow to improve soil quality while maintaining a balanced nutrient availability.

Field Survey 2009-2011

In the first year, N dynamics in the plant-soil system were assessed on about thirty conventional horticultural fields with leek (*Allium porrum*) as a test crop. In the first half of the growing season, N availability in the soil, as a result of the N release from SOM, was related to the total N content in the arable layer (Ntot) and base mineral N dressing. Ntot is a proxy for SOM. Ntot apparently reflected the N release from SOM. Excessive base mineral dressing was found to positively affect N release from SOM, which is a priming effect. Ntot was decisive for crop N uptake probably due to its effect on N availability. In the second half of the growing season, a better soil quality (higher SOM) resulted in a higher biomass yield and lower residual mineral N due to a better utilization of the plant available N by the crop. Hot water extractable carbon (HWC) was significantly positively correlated with Ntot and closely related to crop productivity. So, HWC appeared to be a good indicator for soil quality on the surveyed fields.

In both 2010 and 2011, the field survey was continued assessing the effects of a broad range of crop related and soil quality defining factors on the amount of residual soil mineral N, distinguishing for residual soil mineral N in the arable layer (0-30 cm) and the nitrate N residue, i.e., the residual NO_3^--N amount in the 0-90 cm soil profile. Flanders established a nitrate N residue threshold of 90 kg ha^{-1} in order to restrict the risk of nitrate leaching. The nitrate N residue level was related to crop group (i.e., cereals, potatoes and vegetables) since fertilizer effective N doses differed between crop groups. Nitrate N residue was not affected by Ntot. Fields of farms with livestock seemed to bear an inherent risk for high nitrate N residues, i.e., 50 kg NO_3^--N ha^{-1} extra. A higher Ntot resulted in a higher residual mineral N amount in the arable layer. Residual mineral N in the arable layer was also affected by growing season, i.e., a year-to-year variation. A high level of mineral N input by fertilization (> 200 kg ha^{-1}) resulted in excess residual soil mineral N. However, at a low to medium level of mineral N input, residual soil mineral N seemed to be unaffected by that input.

Field trial on soil improving practices and N dynamics 2008-2011

A three-year soil management trial in a conventional field vegetable cropping system was set up to explore combined effects on soil quality by (i) farm compost amendment at three rates (three doses, 0, 15 and 45 Mg ha^{-1} $year^{-1}$, resp. C_0, C_{15} and C_{45}) and (ii) reduced, non-inversion tillage (RT) versus conventional ploughing (CT). The crop rotation (2009-2011) consisted of broccoli (*Brassica oleracea*, var. Italica Group), carrots (*Daucus carota*) and leek (*Allium porrum*). N dynamics were studied to assess whether N fertilization should be adapted in the short term when these soil quality improving management practices are adopted.

The highest compost dose clearly supported the initial level of total organic carbon (TOC) in the arable layer, i.e., ca 1%. The decrease in soil acidity (pH-KCl) in the arable layer was considerably smaller in case of compost application than for the treatment without compost, irrespective of the compost dose applied. RT resulted in a favorable stratification for different soil quality indicators both by placement of organic residues near the soil surface and by a reduction of leaching of base cations and organic carbon compounds. Differences between tillage practices and compost doses were most striking in the 0-10 cm top soil layer. Compared to C_0, C_{45} enhanced total biomass of soil microbiota in the 0-10 cm soil layer by 27%. Compared to CT, RT realized an increase of the microbial biomass by 44%. Conversion to RT allowed for sustaining vegetable production in this intensive cropping system. Compost application and RT counteracted soil degradation. In this particular field, it was feasible to reach a balance between decomposition and build up of SOM by a yearly compost application of 15 Mg ha^{-1} without surpassing fertilization limits for N and P_2O_5. A yearly compost dose of 45 Mg ha^{-1} was apparently not desirable since such a high dosage lowered apparent C recovery in SOM stock and supplied an excessively high P amount to the soil.

Small differences in N dynamics were found between soil management treatments. Broccoli showed a significantly higher N uptake and biomass yield under RT, however < 10% higher compared to CT. In contrast, leek biomass yield tended to be higher under CT, compared to RT, which was in line with a tendency for a higher amount of residual soil mineral N. In the carrot crop, a 16% higher amount of mineral N in the arable layer under CT did not increase root yield. Compost application sustained SOM content and did not result in a higher amount of residual soil mineral N. Only in the carrot growing season, the highest compost dose increased the soil mineral N amount in the arable layer to a limited extent (+20%). The introduction of RT and compost application do not necessitate a change in the N fertilizer application on the short term since the changes in soil N availability are small in the first years applying these practices.

Organically managed field trial on soil quality and nutrient dynamics 2012-2013

In a two-year soil management trial in an organic vegetable cropping system, the effects of tillage practice (non-inversion tillage versus conventional ploughing), green manure termination strategy and use of organic amendments on N and P availability and crop

performance were investigated. Different strategies of grass-clover termination were evaluated in the first year, whereas in the second year, the effect of cut-and-carry fertilizer (ensilaged grass-clover) was assessed and farm compost application was included as an additional factor. Off-farm nutrients were supplied with compost to the system, whereas nutrients from the grass-clover cut-and-carry fertilizer (on-farm amendment) circulated internally on the farm level.

Termination strategy was decisive for the level and timing of N release from the grass-clover residues and for the N utilization by the subsequent leek crop. Tillage practice did not affect leek N uptake and biomass yield. Compared to late destruction of the grass-clover sward in May after repeated mulching, early destruction of the sward in March resulted in a 30% higher mineral N amount in the arable layer at the start of the leek growing period (half of June). However, this higher N availability did not result in a better crop performance since leek crop N demand and N availability in the soil were badly synchronized. Late destruction of the grass-clover sward after repeated mulching showed the highest N input from aboveground plant parts, which did neither result in a higher leek N uptake, compared to early destruction, nor in excess mineral N. Late destruction of the grass-clover sward after removal of a full-grown cut lowered leek biomass yield and residual mineral N in the soil profile. Late destruction of the grass-clover sward after repeated mulching showed an intermediate risk of N leaching losses in between both other strategies, and offered a good yield and probably the highest storage of N in SOM. In the second experimental year, cut-and-carry fertilizer and compost application additively improved celeriac (*Apium graveolens, var. rapaceum*) crop performance. Each of these fertilization factors interacted with tillage practice affecting N and P availability. However, their positive effect on tuber yield was not related to enhanced N and P availability, but probably to their K input, and in case of compost to its benefits to general soil quality. RT was not effective in relieving soil compaction in the lower part of the arable layer that originated from the leek harvest in wet soil conditions. This resulted in a 14% lower tuber yield under RT. Both green manuring and compost application sustained the SOM level.

General findings

Both the field survey and the soil management trials generated new knowledge allowing to fine-tune N fertilization to specific soil quality characteristics or certain soil management practices. When recurrent compost application and green manuring result in a higher SOM content and a better soil quality, this may enhance plant N availability, by soil N mineralization, and ameliorate N utilization by the crop. The positive effect of soil quality on utilization of plant available N should be generally recognized establishing fertilizer N recommendations. Soil quality clearly affects crop yield potential and N uptake. Estimation of yield potential should be based on (i) soil quality characteristics (e.g., Ntot and HWC, as revealed by this study), (ii) field history with regard to yields and (iii) visual soil assessment. Also other aspects revealed by this study should be recognized for formulating fertilizer N recommendations, i.e., higher net N mineralization rates in case of early cultivation and extra N mineralization from SOM due to excessive base mineral N dressing. A more favorable stratification of mineral N in the soil profile by recurrent RT will probably also increase N utilization, thus reducing the need for N fertilizers.

By distinguishing between the first and second half of the growing season while calculating balances of plant available N, it was found that N availability was characterized by a cyclic pattern, i.e., net N mineralization in the first half of the growing season (spring - early summer) and net N immobilization in the second half of the growing season (late summer - autumn). To the best of our knowledge this finding is new. Assessing N availability in order to decide on N fertilization should reckon on this cyclic pattern over the growing season. The commonly used mineral N measurements and mineralization tests allow for a reliable N availability assessment before the establishment of the crop or during its youth stage. However, another type of soil test should be developed to assess potentially plant available N during the second half of the growing season, i.e., under a well-established crop.

Besides providing a better insight in N dynamics in relation to soil quality and soil management, the outcome of this study also allows to define soil management strategies for both conventional and organic field vegetable cropping systems in order to improve soil quality while keeping good balance between N availability on one hand and the P and SOM content of the arable layer, on the other hand.

Samenvatting

Inleiding

In de gangbare groenteteelt wordt de bodemkwaliteit ernstig bedreigd door intensieve bodembewerking en bemesting, en door een nauwe vruchtwisseling. Een afname in bodemkwaliteit zal de opbrengstzekerheid en productkwaliteit hypothekeren. Het inschakelen van groenbedekkers, de toepassing van compost en gereduceerde bodembewerking helpen de bodemkwaliteit te ondersteunen. Stikstof is een sleutelelement voor de gewasproductie en tegelijkertijd zijn stikstofverliezen door uitspoeling het belangrijkste milieuprobleem in de intensieve groenteteelt binnen Europa. Verondersteld wordt dat stikstofverliezen door uitspoeling in de eerste plaats veroorzaakt worden door de combinatie van een hoge stikstofbemesting en een lage benutting van de stikstof uit die bemesting door het gewas. De onderzoeksvraag was hoe bodemkwaliteit en bodemverbeterende maatregelen de stikstofvoorziening en stikstofbenutting in het bodem-plant systeem beïnvloeden. Kan bodembeheer gericht op de verbetering van de bodemkwaliteit de benutting van de stikstofbemesting door het gewas verhogen? Wat zijn de linken tussen stikstofaanvoer via minerale of organische bemesting enerzijds en het bodem organische stofgehalte (BOS-gehalte) en de fosfortoestand van de bodem anderzijds?

De objectieven van deze studie waren (i) analyse van de effecten van specifieke beheermaatregelen op de bodemkwaliteit, en (ii) het begrijpen van de stikstofdynamiek in relatie tot de bodemkwaliteit en bodemverbeterende maatregelen, met name gereduceerde bodembewerking, composttoepassing en groenbemesting. De studie was een combinatie van een driejarige perceelsopvolging en meerjarige veldproeven bodembeheer. Op de praktijkpercelen die opgevolgd werden pasten de landbouwers hun gebruikelijke teeltmaatregelen toe. De veldproeven lagen aan in zowel een biologisch als een gangbaar groenteteeltsysteem. De belangrijkste hypotheses van deze studie waren (i) het bodembeheer is bepalend voor de bodemkwaliteit, (ii) de bodemkwaliteit heeft een effect op de stikstofdynamiek in het bodem-plant systeem, (iii) het bodembeheer heeft een effect op de stikstofdynamiek, (iv) bodembeheer, bodemkwaliteit en stikstofdynamiek zijn bepalend voor de gewasprestaties. Het doel was (i) een beter inzicht te verwerven in de stikstofdynamiek die het mogelijk maakt de stikstofbemesting af te stemmen op specifieke kwaliteitskenmerken van de bodem of op bepaalde maatregelen qua bodembeheer ter optimalisatie van de stikstofbenutting in het bodem-plant systeem en ter beperking van de stikstofverliezen naar het milieu toe, en (ii) het bepalen van bodembeheerstrategieën die het

mogelijk maken om in de vollegrondsgroenteteelt in volle grond de bodemkwaliteit te verbeteren en tegelijkertijd een goede voedingsstoffenbalans te verzekeren.

Perceelsopvolging 2009-2011

In het eerste jaar werd op een dertigtal gangbare tuinbouwpercelen de stikstofdynamiek in het bodem-plant systeem opgevolgd met prei (*Allium porrum*) als testgewas. De stikstofbeschikbaarheid in de bodem, als resultante van de netto stikstofvrijstelling uit BOS, was in de eerste helft van het groeiseizoen gerelateerd aan het stikstofgehalte in de bouwvoor (Ntot) en aan de voorjaarsbemesting met minerale N. Ntot is een indicator voor BOS. Ntot reflecteerde blijkbaar de stikstofvrijstelling uit BOS bij deze percelen. Een overmatige stikstofbemesting versterkte de stikstofvrijstelling uit BOS (priming effect). Ntot was bepalend voor de stikstofopname door het gewas, wellicht door het effect van Ntot op de stikstofbeschikbaarheid. In de tweede helft van het groeiseizoen resulteerde een betere bodemkwaliteit (hogere BOS) in een hogere gewasopbrengst en een kleinere hoeveelheid minerale reststikstof door een betere benutting van de voor de plant beschikbare stikstof door de prei. Heet water extraheerbare koolstof (HWC) was significant positief gecorreleerd met Ntot en sterk gerelateerd aan gewasproductiviteit, en bleek dus een goede indicator voor bodemkwaliteit te zijn op deze percelen.

In 2010 en 2011 werd de perceelsopvolging verder gezet. Diverse factoren gerelateerd aan gewas- en bodemkwaliteit werden onderzocht voor hun effect op de hoeveelheid minerale reststikstof, enerzijds de minerale reststikstof in de 0-30 cm bouwvoor en anderzijds de resterende hoeveelheid NO_3^--N in het 0-90 cm bodemprofiel (nitraatstikstofresidu). Om het risico op nitraatuitspoeling te beperken, werd in Vlaanderen de grenswaarde voor het nitraatstikstofresidu ingesteld op 90 kg stikstof ha^{-1}. Het nitraatstikstofresidu was gerelateerd aan de gewasgroep (i.e., granen, aardappelen en groenten) aangezien de toegepaste hoeveelheid werkzame stikstof verschillend was tussen de gewasgroepen. Het nitraatstikstofresidu was niet gerelateerd aan Ntot. Velden van bedrijven met vee vertoonden een inherent risico voor een te hoog nitraatstikstofresidu, i.e., 50 kg NO_3^--N ha^{-1} extra. Een hogere Ntot resulteerde in een grotere hoeveelheid minerale reststikstof in de bouwvoor. De minerale reststikstof in de bouwvoor werd ook beïnvloed door het groeiseizoen, met name een jaareffect. Een hoog niveau van minerale stikstofinput via bemesting (> 200 kg ha^{-1}) resulteerde in een overmaat aan minerale reststikstof, terwijl bij een laag tot gemiddeld niveau van minerale stikstofinput de minerale reststikstof blijkbaar niet beïnvloed werd door die input.

Veldproef aangaande bodemverbeterende maatregelen en stikstofdynamiek 2008-2011

In een gangbaar groenteteeltsysteem werd een driejarige veldproef bodembeheer opgezet om gecombineerde effecten op bodemkwaliteit te onderzoeken, uitgaande van (i) de toepassing van boerderijcompost (drie dosissen, 0, 15 en 45 ton ha^{-1} $jaar^{-1}$, resp. C_0, C_{15} en C_{45}) en (ii) niet-kerende bodembewerking (NKB) ten opzichte van het conventionele ploegen. De vruchtopvolging (2009-2011) bestond uit broccoli (*Brassica oleracea*, var. Italica Group), wortelen (*Daucus carota*) en prei (*Allium porrum*). De stikstofdynamiek werd bestudeerd om te achterhalen of de stikstofbemesting op korte termijn dient aangepast te worden bij toepassing van deze bodemverbeterende maatregelen.

Het initiële totale organische koolstofgehalte (TOC) in de bouwvoor (ca 1%) bleef behouden bij de hoogste compostgift. De daling van de zuurtegraad (pH-KCl) in de bouwvoor was aanzienlijk kleiner bij composttoepassing dan voor de behandeling zonder compost, ongeacht de toegepaste compostdosis. NKB gaf aanleiding tot een gunstige stratificatie voor verschillende bodemkwaliteitskenmerken zowel door de plaatsing van organische resten dicht bij het bodemoppervlak als door een reductie van de uitspoeling van alkali-elementen en organische koolstofverbindingen. Verschillen tussen methodes van bodembewerking en compostdosering kwamen het sterkst tot uiting in de 0-10 cm toplaag van de bodem. In vergelijking met C_0, verhoogde C_{45} de totale biomassa aan micro-organismen in de 0-10 cm bodemlaag met 27%. Vergeleken met ploegen verhoogde NKB de microbiële biomassa met 44%. Bij omschakeling naar NKB in dit intensieve teeltsysteem bleef de productie van de verbouwde groenten op peil. Composttoepassing en NKB voorkwamen bodemdegradatie. Met een jaarlijkse compostgift van 15 ton ha^{-1} was het op dit perceel mogelijk om een evenwicht te bereiken tussen afbraak en opbouw van BOS zonder de bemestingsnormen voor stikstof en fosfaat te overschrijden. Een jaarlijkse compostgift van 45 ton ha^{-1} was blijkbaar niet gewenst aangezien de efficiëntie van de composttoepassing voor koolstofopbouw afnam bij die hoge dosering (C_{45}) in vergelijking met de lage dosering (C_{15}) en aangezien de hoge compostdosering excessief veel fosfor aanbracht in een bodem met een al hoge fosforvoorraad.

Kleine verschillen in stikstofdynamiek werden vastgesteld tussen de behandelingen qua bodembeheer. De stikstofopname en biomassaopbrengst van broccoli waren significant hoger bij NKB, echter wel minder dan 10% hoger ten opzichte van ploegen. Daartegenover neigden preiopbrengst en minerale reststikstof in het bodemprofiel iets hoger te zijn bij ploegen dan bij NKB. De 16% hogere hoeveelheid minerale stikstof in de bouwvoor bij ploegen verhoogde de opbrengst van de wortelen niet. Composttoepassing onderhield het

BOS-gehalte maar resulteerde niet in hogere waarden voor minerale reststikstof. Enkel in het groeiseizoen van de wortelen werd een beperkte verhoging vastgesteld van de hoeveelheid minerale stikstof in de bouwvoor (+20%) door de hoogste compostdosis. De introductie van NKB en composttoepassing noodzaakt op de korte termijn geen wijziging in de stikstofbemesting gezien de kleine veranderingen in globale stikstofbeschikbaarheid in de eerste jaren na de start van de toepassing van die bodemverbeterende maatregelen.

Biologisch beheerde veldproef aangaande bodemkwaliteit en nutriëntendynamiek 2012-2013

Met een tweejarige veldproef bodembeheer werden de effecten onderzocht van het type bodembewerking (niet-kerende bodembewerking (NKB) versus conventioneel ploegen), de vernietigingsstrategie voor groenbedekkers en het gebruik van organische bemestingsvormen op de stikstof- en fosforbeschikbaarheid en de gewasprestaties in een biologisch groenteteeltsysteem. Verschillende strategieën voor de vernietiging van een grasklaver groenbedekker werden beoordeeld in het eerste jaar. In het tweede jaar werd het effect van een maaimeststof (ingekuilde grasklaver) opgevolgd. De toepassing van boerderijcompost werd als bijkomende factor meegenomen. Met compost werden niet van het bedrijf afkomstige nutriënten aangebracht terwijl de nutriënten van de grasklaver maaimeststof intern circuleerden op het niveau van het bedrijf.

De vernietigingsstrategie was bepalend voor het niveau en de timing van de stikstofvrijstelling uit de resten grasklaver en voor de stikstofbenutting door het volggewas prei. De methode van bodembewerking had geen effect op de stikstofopname en de preiopbrengst. In vergelijking met een late vernietiging van de grasklaver in mei na herhaald mulchen resulteerde een vroege vernietiging van de grasklaver in maart in 30% meer minerale stikstof in de bouwvoor bij aanvang van de teelt van de prei (half juni). Deze hogere stikstofbeschikbaarheid leidde echter niet tot een betere gewasprestatie aangezien de behoefte aan stikstof van het preigewas en de stikstofbeschikbaarheid niet goed gesynchroniseerd waren. Bij late vernietiging van de grasklaver na herhaald mulchen werd de grootste hoeveelheid stikstof aangebracht via bovengrondse plantendelen, wat noch resulteerde in een hogere stikstofopname, in vergelijking met de vroege vernietiging, noch in een overmaat aan minerale stikstof. Late vernietiging van de grasklaver na verwijderen van een volgroeide snede verlaagde de biomassaopbrengst van de prei en de hoeveelheid minerale reststikstof in het bodemprofiel. Late vernietiging na herhaald mulchen hield qua risico op stikstofverliezen door uitspoeling het midden tussen beide andere strategieën en resulteerde in een goede opbrengst en wellicht in de hoogste opslag van stikstof in BOS.

In het tweede onderzoeksjaar verbeterde zowel de toepassing van maaimeststof als de toepassing van compost de ontwikkeling van het testgewas knolselder (*Apium graveolens, var. rapaceum*). Elk van deze bemestingsfactoren vertoonde een interactie met de factor bodembewerking voor hun effect op de stikstof- en fosforbeschikbaarheid. Hun bijdrage aan de knolopbrengst was echter niet gerelateerd aan de verhoogde stikstof- en fosforbeschikbaarheid, maar wellicht aan de aanvoer van kalium, en in het geval van compost aan zijn bijdrage aan de algemene bodemkwaliteit. NKB was niet effectief voor het opheffen van de bodemverdichting in het onderste deel van de bouwvoor die ontstond bij de oogst van de prei onder natte bodemomstandigheden. Die verdichting resulteerde in een 14% lagere knolopbrengst bij NKB. Zowel groenbemesting als composttoepassing onderhielden het niveau van BOS.

Algemene bevindingen

Zowel de perceelsopvolging als de veldproeven bodembeheer brachten nieuwe elementen aan het licht die het mogelijk maken de stikstofbemesting af te stemmen op specifieke bodemkwaliteitskenmerken of bepaalde bodembeheermaatregelen. Wanneer herhaalde composttoepassing en groenbemesting resulteren in een hoger BOS-gehalte en betere bodemkwaliteit kan dit zowel de beschikbaarheid van stikstof door mineralisatie van BOS als de stikstofbenutting door het gewas verhogen. Het positieve effect van bodemkwaliteit op de benutting van de voor de plant beschikbare stikstof zou algemeen onderkend moeten worden bij het opmaken van stikstofbemestingsadviezen. Bodemkwaliteit heeft een duidelijke invloed op het opbrengstpotentieel en de stikstofopname door het gewas. Het inschatten van dat opbrengstpotentieel dient gebaseerd te zijn op (i) bodemkwaliteitskenmerken (e.g., Ntot en HWC, zoals aangegeven door dit onderzoek), (ii) perceelshistoriek met betrekking tot opbrengsten en (iii) visuele bodembeoordeling. Ook andere aspecten die naar voren kwamen in deze studie dienen onderkend te worden bij de opmaak van stikstofbemestingsadviezen, met name de hogere netto stikstofmineralisatie in geval van vroege verbouwing en extra stikstofvrijstelling uit BOS door overmatige bemesting met minerale stikstof. Een gunstigere stratificatie van minerale stikstof in het bodemprofiel door herhaalde toepassing van NKB zal de stikstofbenutting wellicht ook verhogen wat de behoefte aan stikstofbemesting kan doen afnemen.

Door een onderscheid te maken tussen de eerste en de tweede helft van het groeiseizoen bij het berekenen van balansen voor plantbeschikbare stikstof, werd er vastgesteld dat de stikstofbeschikbaarheid een cyclisch patroon kent, i.e., netto stikstofmineralisatie in de eerste helft van het groeiseizoen (lente - vroege zomer) en netto stikstofimmobilisatie in de tweede helft (late zomer - herfst). Voor zover we weten is deze bevinding nieuw. Bij het inschatten van de stikstofbeschikbaarheid ter bepaling van een stikstofbemesting dient rekening gehouden te worden met dit cyclisch patroon doorheen het groeiseizoen. De gebruikelijke minerale stikstofbepalingen en mineralisatietests zijn geschikt voor het bepalen van de stikstofbeschikbaarheid vóór de vestiging van het gewas of in zijn jeugdstadium. Een ander type bodemtest dient echter ontwikkeld te worden om de voor de plant potentieel beschikbare stikstof te bepalen in de tweede helft van het groeiseizoen, nl. onder een goed gevestigd gewas.

Naast een beter inzicht te bieden in de stikstofdynamiek in relatie tot bodemkwaliteit en bodembeheermaatregelen, laat de uitkomst van deze studie toe om bodembeheerstrategieën te bepalen voor zowel gangbare als biologische groenteteeltsystemen met als doel de bodemkwaliteit te verbeteren en tegelijkertijd een goed evenwicht te vinden tussen de beschikbaarheid van nutriënten enerzijds en het fosfor- en BOS-gehalte in de bouwvoor anderzijds.

Acknowledgements

This PhD study started in May 2008 in a private-public cooperation between SYMBIOS, a consortium of horticultural cooperatives, and the Institute for Agricultural and Fisheries Research (ILVO). It focused on research questions that arose during the extension project FarmCOMPOST (2003-2007) that was initiated by SYMBIOS and financially supported by IWT.

Firstly, I want to thank vegetable growers Jan Van Overbeke, Rik Delhaye and Rudy Croket for sharing their practical experiences with me. They were pioneering with on farm-composting and soil improving practices. Thanks also for the opportunity I have got to cooperate with all vegetable growers linked to SYMBIOS who lent me their fields for a survey. They were always open for discussion on the results. Special thanks to Jan Deconinck whose field I could use for a multiyear soil management trial. Thanks to the whole ILVO management and the SYMBIOS board people Walter Geuens, Curd Vanmarcke (Vergro) and Paul Demyttenaere (REO auction).

I want to thank Paul Mäder (FiBL) for having been involved in the TILMAN-ORG project (2011-2014). By this project, I could deepen my study work on a certified organic trial field at ILVO. For decisions on agronomic practices, some good advice was welcome. Thanks therefore to Luc De Reycke (PCG), Robrecht Winnepeninckx (PCG), Lieven Delanote (Inagro) and Nico Vandevannet (Symorganic). Thanks to Stefaan Dondeyne (KUL) for the WRB soil classification. I am very grateful to all involved technicians from ILVO for the tremendous work which was done on the field and in the lab.

Many thanks to my promoters Prof. dr. ir. Stefaan De Neve and Dr. ir. Bart Vandecasteele, who followed and steered my study work, thoroughly and patiently. And thanks to the board of examiners, Prof. dr. ir. Filip Tack, Prof. dr. Geert Baert, Prof. dr. ir. Marie-Christine Van Labeke, Prof. dr. ir. Steven Sleutel, ir. Wijnand Sukkel (Wageningen Universiteit) and Dr. Francesco Montemurro (Consiglio per la Ricerca e Sperimentazione in Agricultura, Italia).

I may not forget my coauthors, those who are not mentioned above, David Buchan, Carl Koch (KOCH - EUROLAB), Bert Van Gils, Chris Koopmans (Louis Bolk Instituut) and Andreas Fliessbach (FiBL), thanking them all for their comments ameliorating my research output.

And last but not least, thanks a lot to my colleagues, my friends and particularly my family for their mental and logistic support.

List of Abbreviations

AMF	arbuscular mycorrhizal fungi
ANM	apparent net N mineralization
B:F	bacteria:fungi ratio
BD	soil dry bulk density
BNF	biological nitrogen fixation
BT	grass-clover biomass transfer
C*	compost application
Cmic	microbial biomass carbon
CT	conventional tillage
DM	dry matter
FAME	fatty acid methyl ester
FE N	fertilizer equivalent nitrogen
fertNmin	mineral N input by fertilization
fertNorg	organic N input by fertilization
fertNtot	total N input by fertilization
FYM	farmyard manure
GLM	general linear model
GM	grass-clover management strategy
HWC	hot water extractable carbon
KNS	Kulturbegleitende N_{min}-Sollwert System
MAP	Manure Action Plan
Ngav	gross N availability**
Nmin	soil mineral N amount
Nrec	fertilizer N recovery**
Nrel	N release from SOM**
NT	no-tillage
Ntot	soil total N content
PCA	principal component analysis
PLFA	phospholipid fatty acid
RT	reduced tillage
s*	sampling occasion
SOM	soil organic matter
TNA	total N availability
TOC	soil total organic C content
TS	grass-clover termination strategy

*with index dose, time

**incubation experiment

List of tables

List of figures

Table of contents

Chapter 1

Introduction and objectives

Conventional field vegetable cropping systems are highly intensive with regard to soil use and management for productivity reasons. However, application of agro-chemicals, narrow crop rotations (i.e., a high proportion of vegetables in the rotation) and frequent soil tillage increase the risk of soil deterioration. In the long term, a decrease in soil quality will jeopardize yield stability an may negatively affect product quality. Organic field vegetable cropping systems highly depend on natural mechanisms for plant nutrition and crop protection. Management practices are primarily directed at sustaining or improving soil fertility. Organic amendments are indispensible for this reason, however, extensive use of external organic inputs may cause nutrient imbalance. The care for soil quality should be a common feature of both organic and conventional cropping systems. The processes that govern N availability in soil are basically the same for both cultivation methods and optimization of the synchrony between N supply by the soil and N demand of the crop is a common aspiration for reasons of productivity and environmental quality. Decisions on fertilization should account for soil N supply and crop N demand in both systems.

The two main objectives of this research were (i) assessing the effects of specific soil management practices on soil quality, and (ii) understanding N dynamics in relation to soil quality and soil quality improving management practices. In this research, we hypothesize soil quality to be a central factor in crop productivity and environmental quality, taking into account that soil quality is the result of past soil management over a longer period. The research focused on N dynamics since N is a key element in crop productivity and at a same time, N losses (primarily by leaching) are the main environmental issue in intensive field vegetable production systems in Europe. A number of vegetable crops require a high N availability in order to guarantee maximum yield and product quality. N leaching losses are presumed to be primarily caused by a high fertilizer N input in combination with low fertilizer N recovery by the crop. The question remains how soil quality and soil quality improving management practices influence the N supply and N recovery in the plant-soil system. Do soil quality improving management practices enable an increase of the fertilizer N recovery by the crop and a reduction of the N losses. And how does N input by mineral and organic fertilizers interact with the C content and the P status of the soil?

In this introductory chapter, I firstly deal with soil characteristics and processes, impact of soil improving practices, and features and issues of field vegetable cropping systems. I end this chapter with the thesis outline, including main hypotheses and research questions.

1.1 Soil quality

Soil quality in agro-ecosystems is the result of both inherent soil properties (e.g., parent material, hydrology, slope) and management practices, e.g., tillage, fertilization and crop rotation. Soil quality covers physical, chemical and biological aspects and is in fact the result of the interaction of the processes related to these aspects.

Chemical soil fertility includes the content of inorganic nutrients, soil organic matter (SOM) content and constituents. Soil acidity (pH), base saturation, redox potential and electrical conductivity (EC) are chemical parameters indicative or decisive for nutrients availability. However, nutrients availability also largely depends on microbial activity (as described below). SOM is crucial for many soil functions. Total organic carbon content (TOC), as a proxy for SOM, is a keystone soil quality indicator inextricably linked to other chemical, physical, and biological soil quality parameters (Reeves, 1997). SOM consists of non-detectable plant residues, its decomposition products and humic substances to which they are gradually converted. SOM is converted by soil biota. Soil biota are also part of SOM. A variety of extraction methods are used to isolate different organic matter fractions which may be indicative for soil quality, e.g., hot water extractable carbon (HWC) (Haynes and Francis, 1993). Some extractable organic matter fractions (EOMs) are assumed to represent the biologically available SOM pool (Ros, 2012) and to be the result of recent soil management practices (Haynes, 2005).

Biological soil fertility concerns all soil biota and their functionality with regard to soil quality affecting processes (as described above and below). All soil biota are interrelated in the soil food web. The structure and complexity of the soil food web depends on many factors, e.g., organic matter resources, soil management, climatic conditions, …. Particularly, the presence of beneficial fungi is essential to obtain a diversified food web that guarantees nutrient retention and cycling (de Vries et al., 2011), a good soil structure (Ritz and Young, 2004) and pathogen suppression (Garbeva et al., 2006; Weller et al., 2002).

Physical soil fertility is related to soil structure that is decisive for water retention and transport, gas exchange, root ability to penetrate the soil, workability and traffic ability. Soil aggregates are the result of microbial activity and physical forces (drying, shrink-swell, freeze-thaw, root growth, soil fauna activity, …). Aggregate stability is a key parameter for physical soil fertility and is related to SOM content (Paul and Clark, 1996). Microbial activity depends on the input of organic matter and therefore, soil structure benefits from organic amendments. Soil structure is sustained and ameliorated by crops' root systems due to the stimulation of microbial activity in the rhizosphere by root exudates. The rhizosphere is the region under immediate influence of plant roots and in which there is a proliferation of microorganisms due to the plant roots (Paul and Clark, 1996). Root exudates are complex mixtures of carbon-containing compounds, e.g., sugars, amino acids and organic acids (Carvalhais et al., 2011). Two types of soil environment may be distinguished, i.e., (i) a litter containing non-rooted bulk soil where soil biota decompose SOM and convert organic amendments and crop residues into humic substances and (ii) a rhizosphere where microbiota live in symbiosis with the plant taking advantage of root turnover and exudates while potentially stimulating plant growth by modulation of nutrient availability and acquisition (Wang et al., 2008; Dakora and Phillips, 2002). Besides the dependency on metabolic processes in the rhizosphere, the availability of plant nutrients depends on exchangeable amounts of mineral elements on the clay-humus complex, the nutrient release due to decomposition of SOM and the nutrients amended with external organic or mineral inputs.

1.2 N dynamics

N is a key element in plant nutrition as it is an important part of some basic constituents of plant material, e.g., proteins, nucleic acids, and the cell wall components chitin and peptidoglycans (Paul and Clark, 1996). The N cycle illustrates how N moves between different forms in the plant-soil system, inclusive of the atmosphere (Figure 1.1). The Haber-Bosch process chemically fixes atmospheric N as ammonium (NH_4^+) for the production of synthetic N fertilizers. Fixation of atmospheric N by leguminous crops (e.g., *Medicago sativa* and *Trifolium* spp.) is mediated by *Rhizobium* bacteria species. This N cycle process is referred to as biological N fixation (BNF). The use of organic amendments (e.g., animal manure) also supplies N to te soil.

The major part of soil N is in organic forms, e.g., amino acids and amino sugars. Soil organic N is made available to plants as a result of decomposition of SOM by soil microbiota. NH_4^+ is a byproduct of this microbial decomposition. This N release process is called ammonification and referred to as soil N mineralization. The rate of N and C mineralization largely depends on the soil temperature, moisture content and the amount of oxygen (aeration).

NH_4^+ is either converted by microorganisms to nitrate (NO_3^-) to obtain energy (nitrification process) or fixed both by clays or SOM (abiotic N immobilization). Volatilization as NH_3 might occur in soils with high pH typically containing free carbonates (soil pH-KCl > 6.5). NO_3^- is readily soluble in water and thus subject to leaching (Paul and Clark, 1996). Leaching of nitrate occurs when rainfall exceeds the evapotranspiration, which is most likely in a bare soil or during crop youth stage, in combination with periods with high rainfall intensity. Gaseous losses can occur also after microbial conversion of NO_3^- to NO, N_2O and N_2. This process is called denitrification and is related to oxygen depletion as in poorly drained soils. During the oxidation of ammonia to nitrate (nitrification), these gaseous losses may occur as well (nitrifier denitrification).

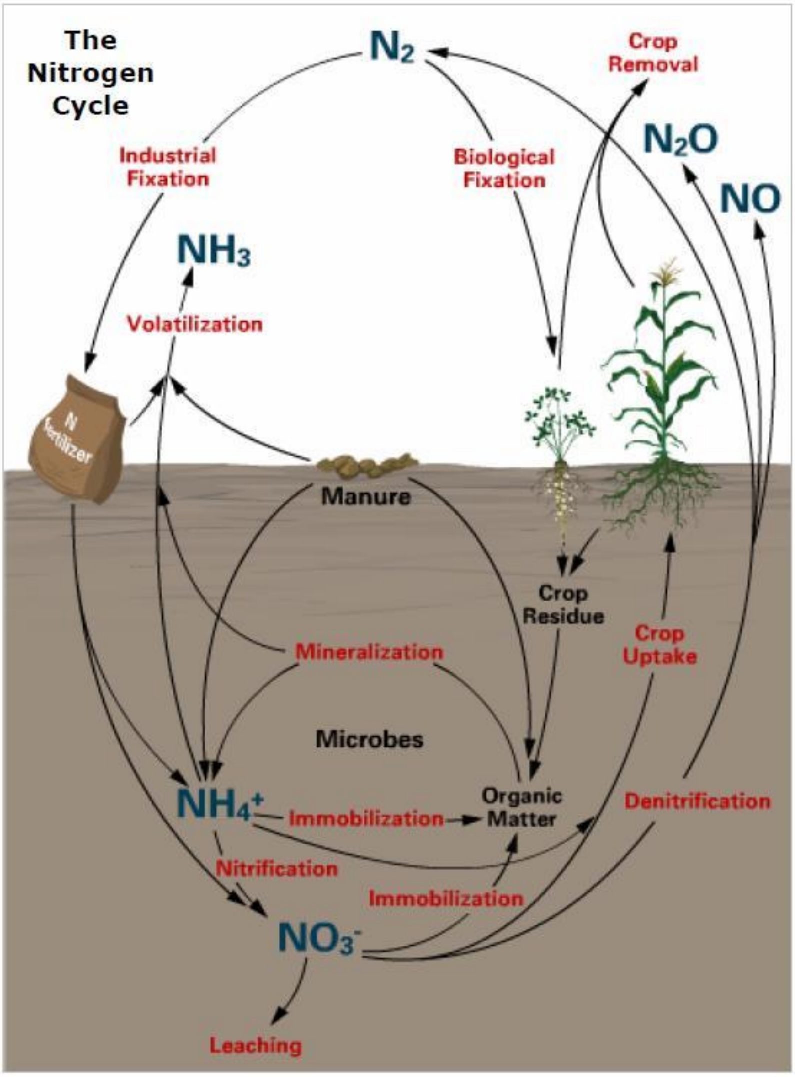

Figure 1.1 N cycle (Cornell University, Cooperative Extension, Agronomy Fact Sheet 2).

NH_4^+ and NO_3^- are the principal plant absorbable N forms. Mineral N forms are also consumed by bacteria and fungi and converted in organic forms (e.g., microbial protein), i.e., biotic N immobilization. Micro-organisms are competing with the plant for soil mineral N. However, a study of Bell et al. (2015) shows that plant N uptake rates inversely corresponded to microbial biomass N levels during periods of peak plant growth, indicating that plants are able to influence rhizosphere bacterial community for their own fitness. On the other hand, when biotic N immobilization occurs in the litter containing non-rooted bulk soil, temporary storage of N in microbial biomass prevents N from being either lost or fixed, and this N will be rendered available afterwards by mineralization.

1.3 Restoration of degraded soil by soil organic matter management

In Europe, soil degradation has been identified as a widespread problem (Holland, 2004; Zdruli et al., 2010). The European Commission recognized that soil degradation is accelerating across the EU, with negative effects on human health, ecosystems and climate change and on our economic prosperity and quality of life. To reverse this trend, the Commission launched the EU Soil thematic strategy in 2006 (Anonymous, 2006) which sets a common EU framework for action to preserve, protect and restore soil. The decline in SOM of many soils is seen as probably the major process of soil degradation (Diacono and Montemurro, 2010). Intensive field vegetable cropping systems are characterized by a high input of inorganic N, frequent soil tillage and short-lived crops in a narrow rotation. These practices may impair soil quality as they may result in SOM decline, soil structure deterioration and biodiversity losses. Degraded soils may be restored if farming practices are changed in favor of sustaining or even increasing the SOM (TOC) content and soil biological activity (Blank, 2008). Compost application and reduced tillage are both soil C saving practices. Compost application supplies stabilized organic matter (Diez and Kraus, 1997) while reduced tillage suppresses organic matter decomposition by minimizing soil inversion and soil structure disruption (Alluvione et al., 2013). Both soil management practices may also improve soil quality by favoring nutrient availability, soil structure and soil organisms. Besides compost application and reduced tillage, application of non-composted organic amendments, e.g., farmyard manure (FYM), and inclusion of cover crops may counteract soil degradation and recover soil quality by favoring SOM status and hence soil structure and soil biota (Alluvione et al., 2013; Pfotzer and Schuler, 1997; Six et al., 2000).

1.4 Soil quality improving management practices

Soil quality improving management practices mainly concern agronomic practices that favor SOM status by amending organic matter, preventing SOM losses or stabilizing SOM. My investigation dealt with reduced tillage, compost application and green manuring, all C saving practices that may affect N dynamics.

1.4.1 Reduced, non-inversion tillage versus ploughing

Moldboard ploughing is still the common tillage method in Flanders. It intends to incorporate crop residues and weeds by inverting the soil, and to prepare the seed or plant bed. Ploughing may also relieve soil compaction, e.g., caused by harvesting machines, rearranging the soil macrostructure (voids and aggregates > 0.5 mm) (Dexter et al., 1983). Frequent ploughing may create a plow pan which may impair soil water movement and root penetration to deeper layers. The availability of soil water can also be limited by the presence of a compacted layer not too far below the soil surface (Weatherly and Dane, 1979). Deep ploughing (> 25 cm tillage depth) may bring less fertile subsoil to the surface, i.e., soil with a lower SOM content and thus with lower aggregate stability and lower nutrient supplying capacity. This increases the risk for slaking and crusting, and subsequent soil erosion on sloping fields. Ploughing may destroy the soil structure by excessive loosening (total pore volume > 60%) leaving the soil very unstable. The latter reduces trafficability and enhances the risk of compaction. Tillage operations and field traffic show a strong compacting effect in formerly uncompacted soil (Langmaack et al., 2002). Soil tillage enhances SOM decomposition which lowers aggregate stability and hydraulic conductivity (Chan et al., 1993; Loch, 1994; Naidu et al., 1996).

In contrast to a plough-based system, not inverting tillage maintains crop residues and organic amendments at the soil surface resulting in an increased SOM content of the most superficial layers (D'Haene et al., 2009), resulting also in more stable aggregates (Cannell, 1985). Improved habitat and food resources availability for soil biota under reduced tillage favor a different range of organisms compared to a plough-based system in which crop residues are buried (Rasmussen and Collins, 1991). Emmerling (2001) investigated the response of earthworm communities to different soil tillage methods (ploughing, two-layer ploughing and non-inversion tillage down to 30 cm) and found that the abundance and the fresh biomass of the total community, the dominant species (*Aporrectodea caliginosa*) and juvenile earthworms were significantly enhanced by non-inversion tillage compared with ploughing and two-layer ploughing. Two-layer ploughing consists of shallow ploughing (15 cm) and deep loosening (up to 30 cm). Langmaack et al. (2002) found that soil structure rehabilitation after a single intentional compaction is due more to intrinsic soil processes and biological activity than due to tillage operations, especially ploughing. Restoration of degraded soil structure was faster under conservation tillage compared to conventional tillage.

1.4.2 (On-farm) composting and compost application

On-farm composting is an efficient method to recycle crop residues. Composting is the aerobic, or oxygen requiring, decomposition and stabilization of organic materials by microorganisms under controlled conditions (Rink, 1992). The microorganisms convert the fresh organic matter into a stable and humus-rich product (Bokhorst and ter Berg, 2001). More than 50% of the organic carbon applied to the soil with mature compost is recovered in the long term, i.e., effectively contributes to humus reproduction. This contribution is higher than from any other commonly used organic amendment (BGK e.V., 2005). Compost application affects many soil properties due to the incorporation into the soil of stabilized organic matter, macro- and micronutrients and beneficial microbiota (Zebarth et al., 1999; Tejada et al., 2001; Abawi and Widmer, 2000).

Regular addition of organic residues, particularly the composted ones, increased soil physical fertility, mainly by improving aggregate stability and decreasing soil bulk density (Diacono and Montemurro, 2010; Annabi et al., 2007). However, significant effects on soil physical properties can be only expected in long-term trials with repeated compost application (at least 7-10 years) with a special attention on the experimental design and the homogeneity of the location (Amlinger et al., 2007).

Annual compost applications of 30 m^3 ha^{-1} for 10 years resulted in a significant increase in soil organic carbon (21%) with vegetable, fruit and yard waste compost and with garden waste compost (Arthur et al., 2011). With mushroom compost, the third type of compost tested, soil organic carbon increased by 16%. Increased soil macroporosity and water content at saturation with a corresponding decrease in bulk density were observed for all three compost types (Arthur et al., 2011). A reduction in soil bulk density by recurrent compost application was also found by D’Hose et al. (2014). Compost application may improve plant available water content (Curtis and Claassen, 2009; Weber et al., 2007). Repeated application is expected to increase long term N availability (Chalhoub et al., 2013).

By favoring soil physical properties, compost application might benefit nutrient uptake and plant growth. D'Hose et al. (2012) reported a positive yield effect of recurrent farm compost application caused by both extra N supply and improved crop growth conditions. In a study with yearly recurrent application of leaf compost low in nutrients, Maynard and Hill (2000) found that year to year variability in onion (*Allium cepa*) yields was significantly lower in compost-amended plots (3% variation) compared to unamended control plots (52% variation) in response to variable rainfall from year to year. After three years, onion yield from the compost-amended treatments was significantly higher than that from the unamended plots.
Release of nutrients from compost increases nutrient availability and microbial activity (Duong et al., 2013). Bernard et al. (2012) observed an increased utilization of complex substrates and increased levels of gram-positive bacteria and fungi by compost amendment. D’Hose et al. (2014) found that repeated applications of farm compost increased microbial biomass and number of earthworms present. Many studies report disease suppressive effects of composts in open field crops, however, with net effects depending on compost maturity and the tested pathogen (Nortcliff and Amlinger, 2001).

1.4.3 Cover crops

Cover crops fulfill different services in the agro-ecosystem. By covering the soil, they protect it from being slaked and crusted and by their rooting activity, soil structure is developed and sustained. After termination, cover crops’ biomass activates soil biota and sustains SOM. Cover crops prevent residual soil mineral N from being lost by leaching, especially in intensive field vegetable cropping systems which are prone to N losses (Jackson et al., 1993). Cover crops also affect the P leaching risk: Vanden Nest et al. (2014) concluded that the incorporation of catch crop residues under typical soil and weather conditions and agricultural practices of NW Europe did not increase the potential P leaching losses. Enhancing the nutrient efficiency of the systems maximizes biomass production (Scopel et al., 2013). Cover crops may either control or stimulate soil-borne diseases. These effects necessitate to take into account the various interactions among inoculum level, soil characteristics, crop rotations, and technical management options for designing sustainable vegetable production systems (Collange et al., 2014). Invasive weed species may be suppressed by cover crops. Leguminous cover crop species import N in the system by BNF. Soil biota may be positively affected by inclusion of legumes in the rotation and animal manure application and negatively by mineral N fertilizers (Truu et al., 2008; Ge et al., 2008).

1.5 Soil N mineralization potential in relation to soil quality

N availability in vegetable cropping systems is often largely determined by soil N mineralization, which is related to soil quality status, particularly to SOM quantity and quality as affected by agronomic practices in the past (e.g., the use of cover crops). SOM is not a homogeneous pool, but consists of organic components with a wide range of turnover times (Woomer et al., 1994). Since specific EOM fractions are assumed to represent the biologically available SOM pool, chemical extraction methods have been developed to estimate the N supplying capacity of soil (Ros, 2012). However, a meta-analysis of the predictive value of EOM fractions by Ros et al. (2011) showed that most of them have less predictive power for soil N mineralization potential than total N. Moreover, a re-analysis of literature data showed evidence that relationships between EOM and soil N mineralization are due to the relationship between EOM and SOM (Ros, 2012). Estimation of soil N mineralization potential by standardized soil incubation tests neglects field conditions. In field conditions, several factors may limit the N mineralization (e.g., temperature, moisture content, O_2 availability, …) while these limitations are not taken into account in the incubation trials. Prediction of soil N mineralization should be based on a combination of soil tests and soil properties (Ros et al., 2011). An integrated approach to assess soil quality might be most successful in this respect. Additionally, N release from SOM is controlled by soil temperature and moisture content. In horticultural systems with irrigation facilities, fluctuations in soil moisture can be limited and this may lead to less fluctuation in the N mineralization rate, and may allow more accurate estimations. In rainfed systems, however, periodic drought stress for decomposer micro-organisms will tend to reduce N mineralization rates, but on the other hand rewetting may lead to a flush in N mineralization that cannot be predicted accurately with the current state of knowledge.

Soil N mineralization can be assessed (a posteriori) by establishing balances of plant available N. These balance calculations offer insight in the N flows in the plant-soil system but their outcome always represents the net result of N mineralization and N immobilization, or the apparent net N result if either N losses from the system or root/stubble N uptake, or both, are not considered (Feller and Fink, 2002).

1.6 Soil N mineralization potential in relation to soil management practices

Soil tillage practices may affect N turnover processes both spatially and temporally. In a study by D'Haene et al. (2008), a higher N mineralization rate in the 0–15 cm top soil under reduced tillage (compared to conventional tillage) was related to the strong stratification of SOM in the reduced tillage system. Koopmans and Bokhorst (2002) observed that reduced tillage decreased soil N mineralization at the beginning of the growing season.

Repeated compost application is expected to increase soil N mineralization potential due to accumulation of organic N (Leroy et al., 2007; Chalhoub et al., 2013). D'Hose et al. (2012) reported a positive yield effect of recurrent farm compost application, which could be attributed to extra N supply but also to improved growth conditions as crop yield increased even at the highest level of additional mineral fertilizer N supply. Application of not fully matured compost may cause temporary immobilization of soil mineral N due to readily available C sources being added to the soil (Amlinger et al., 2003) reducing soil N availability on the short term during decomposition of the readily available C sources.

The N supply by mineralization of cover crop residues, inclusive of the root system, can be substantial, particularly in case of leguminous cover crops or mixtures with a leguminous component. In a field study by Stute and Posner (1995), residues of leguminous cover crops were reported to release N in adequate amounts with regard to the uptake pattern of corn. Despite a delay in N uptake from a vetch green manure, sustained availability later in the growing season guaranteed optimum corn grain yield and N uptake (Kramer et al., 2002).

In their review paper, Kuzyakov et al. (2000) defined priming effects as strong short-term changes in SOM turnover caused by comparatively moderate treatments of the soil, e.g., fertilization, drying-rewetting, or mechanical disturbance. Priming effects might either have a negative or positive effect on soil N mineralization. A priming effect occurs when a limiting factor for microbial biomass is removed, e.g., when mineral N or an easily decomposable energy source is added. Green et al. (2006) discovered that urea application increases the biomass and activity of saprotrophic microorganisms resulting in enhanced litter decomposition. Investigating a long-term fertility experiment (50 years), Mulvaney et al. (2009) reported a net loss of TOC and a corresponding decline in total N at the highest level of synthetic N fertilizer application, compared to lower levels. Based on a decrease in total soil N in two long-term experiments (>23 years) Raun et al. (1998) found evidence of priming (increased net N mineralization) at low annual rates of fertilizer N (45-90 kg ha^{-1}).

Priming effects seem to be relevant for SOM content and N release predictions, but have a highly unpredictable nature.

1.7 N leaching losses from field vegetable cropping systems

As N is a key element in plant nutrition, plant available N is an important and valuable production factor. Low cost and high availability of N fertilizers was one of the key factors in increasing crop yields during the so-called Green Revolution. However, N use efficiency was not a major concern and this resulted in often dramatic N losses from the plant-soil system to the environment in many regions with intensive agriculture. In the livestock sector, excessive application of slurry, which has a high portion of mineral N and a readily decomposable organic N fraction, has lead to excessive N leaching. Excess residual mineral N in the soil profile at the end of the growing season poses a serious nitrate leaching risk. The European Nitrates Directive (91/676/EEC) aims at reducing environmental impacts of fertilizer and manure and at increasing N use efficiency (van Grinsven et al., 2012). Member states had to set up compulsory action programs for reducing N losses in order to comply with the 50 mg NO_3^- l^{-1} threshold value for nitrates in surface and groundwater. Nowadays, additional efforts are expected in vegetable production areas all over Europe. Intensive field vegetable production systems are particularly prone to N losses due to inherent low N efficiency related to superficial rooting of vegetables, large amounts of crop residues and excessive N fertilization which is used to boost crop productivity and quality (Armbruster et al., 2013). Knowledge-based N fertilizer recommendation can be a tool to reduce N leaching losses in order to fulfill both the crop requirements and the requirements of the Nitrates Directive (Rahn, 2013).

1.8 N fertilization limits and N fertilizer recommendation systems

In Flanders, successive Manure Action Plans (MAPs), in the frame of the European Nitrates Directive, have imposed crop and soil type dependent N fertilization limits in order to balance fertilizer N application and crop N requirement. Three vegetable crop groups were established reflecting a low, medium or high crop demand (MAP IV; Anonymous, 2011). The legislator largely relies on these fertilization limits to comply with the threshold for residual soil nitrate-N of 90 kg ha^{-1} in the 0-90 cm soil profile in the period between October 1st and November 15th.

Crop type dependent fertilization limits should be based on crop type related N demand and utilization as assessed in multiple fertilizer field experiments. Yield/crop N uptake response curves and associated residual soil mineral N amounts at harvest, derived from field experiments with various fertilizer application rates, allow to detect an optimum N fertilizer application rate, both from an agricultural and environmental point of view. By reanalyzing data from field experiments, D'Haene et al. (2014) scientifically substantiated fertilization rates and limits for cut grassland, silage maize, potatoes, sugar beets and winter wheat. Fink (2001) estimated the required residual soil mineral N for the vegetable kohlrabi (*Brassica oleracea* var. *gongylodes*) using the breakpoint of a linear response and plateau regression model. Vegetable crops that are harvested in their vegetative stage require a certain amount of residual soil mineral N to obtain optimum yield and quality. Conducting a 3-year field experiment, Miransari and Mackenzie (2012) developed a regression model relating corn grain and stover yield to residual soil mineral N in order to optimize corn production and minimize environmental impact by applying appropriate rates of N fertilization. However, application of crop type dependent N fertilization limits does not always allow to control residual soil mineral N. Therefore, various Member States have developed N fertilizer recommendation systems, which are either obligatory or highly recommended to prevent excess N fertilization and restrict N losses to the environment. In Flanders, specifically for vegetables, a system based on the German "Kulturbegleitende Nmin-Sollwert System (KNS)" recommendation system (Lorenz et al., 1989; Feller et al., 2011) has been made compulsory (Coopman et al., 2014).

Due to the large number of processes in which N is involved, most N fertilizer recommendation systems are based on a simplified approach of the N balance in the plant-soil system. These recommendation systems use measurements of soil mineral N amounts and take into account default N mineralization rates, N uptake curves and residual soil mineral N amounts. However, factors affecting soil N availability and crop N uptake are quite unpredictable, particularly in rainfed field vegetable cropping systems. Therefore, N fertilizer recommendation should rely on additional site- or soil-type related expert judgment, particularly with regard to soil N mineralization and yield/crop N uptake (Appel, 1994). With regard to their fields or a specific region, respectively growers or extension workers may have expert knowledge on yield potential and the corresponding need for N fertilizer application. The N-Expert software program, based on the KNS-system, allows for adapting N mineralization rate and yield level. Besides the prediction of N release from SOM, synchrony of N release from organic amendments with the N requirement of the crop is an additional challenge for extension workers and farmers. N release from organic amendments depends on the quality of the amendment (e.g., C/N), but also on soil temperature and moisture, as it is decisive for the N release from SOM. Agronomic practices affect soil microbial activity altering N dynamics by causing either negative or positive priming effects (Kuzyakov et al., 2000). Such interactions are neither fully understood nor implemented in N fertilizer recommendation systems. Intermediate soil Nmin measurements help to overcome the problem of unpredictability of N availability. Besides measurement of soil related parameters, e.g., mineral N amounts, measurement of crop related parameters that reflect the N status of the crop (e.g., chlorophyll content, plant sap nitrate-N content) can be a reliable tool to decide on top fertilizer N dressing. Often, several indicators have to be combined to have insight into the limiting factors for crop growth, and to allow for optimal decision making (Nicola et al., 2013). Computer simulation models (e.g., NDICEA) are hardly used for N fertilizer recommendation, however, are useful for designing fertilization strategies on crop rotation level.

1.9 Field vegetable cropping systems

1.9.1 Conventional field vegetable cropping systems

In the main vegetable cropping regions in Flanders, farms growing vegetables are either highly specialized farms producing mainly vegetables or are mixed farms growing vegetables besides fodder crops for cattle/pigs (e.g., corn, temporary grassland). Specialized vegetable growers might broaden their rotation by exchanging land with cattle farms. Conventional vegetable production is mostly characterized by frequent soil tillage and high inorganic N input from either synthetic fertilizers or slurries, or from both. However, soil quality improving management practices are applied as well. Recently, catch crops are quite commonly grown after cash crops. On mixed farms, temporary grassland in rotation with vegetables might improve soil quality. Farmyard manure and compost are appreciated for their contribution to soil quality, but not commonly used (Viaene et al., 2015). Some specialized vegetable farms use green waste compost or vegetable, fruit and garden waste compost.

1.9.2 Organic field vegetable cropping systems

Soil quality is a top priority in organic agriculture where soil is regarded as its central production factor. A diversified crop rotation is a standard practice in organic agriculture for reasons such as disease suppressiveness and N supply by the soil. Reduced, non-inversion tillage favors soil quality in a quite short-term perspective (Berner et al., 2008; Willekens et al., 2014a). However, it challenges organic producers with regard to weed control, incorporation of crop residues and animal manure, and N availability in spring (Peigne et al., 2007; Koopmans and Bokhorst, 2002). Inversion tillage practices are effectively controlling weed populations, and supporting the destruction and incorporation of green manures, crop residues, and animal manure. Consistent implementation of reduced tillage is particularly difficult in vegetable rotations. Alternating between tillage types, e.g., those which favor SOM build-up and others favoring the mineralization process and consequently N release from SOM might be a good strategy for organic horticulture to balance C content with sufficient N supply by the soil. However, P input should also be included in this balance.

P fertilization limitations in Flanders, due to excessively high soil P contents, also restrict C and N input with organic amendments, which jeopardizes soil quality and N provision. Balancing between fertilizer types is an important issue in organic field vegetable cropping systems in order to provide the crop with sufficient plant available N without overloading the soil with P. When P balances are extremely positive, soil P content might reach a point where high orthophosphate levels in the soil solution are prone to leaching. On the parcel level, leguminous cover crops can be part of the solution as they import N and C into the soil without importing additional P but only recycling the P already present in the soil. In addition, also at the farm level cover crops may be a solution for the balance between C, N and P in organic agriculture. As an alternative to using symbiotically fixed N by growing a cash crop after a leguminous cover crop, symbiotically fixed N can be used by applying the biomass of a leguminous or legume-containing cover crop, grown on a different field, to the cash crop in form of a cut-and-carry system (biomass transfer). In this way, nutrients can be efficiently recycled on-farm and N is provided without nutrients' input from off-farm amendments. The biomass can be conserved e.g., as grass-clover silage, which offers more flexibility for targeted N fertilization as studied by Sørensen and Thorup-Kristensen (2011) and Carter et al. (2014). For soils low in available P, green manure crops are suggested to mobilize P after destruction and mineralization of their biomass (Cavigelli and Thien, 2003). Ley pastures including leguminous species are often used for soil fertility building in organic cropping systems (Ball and Douglas, 2003).

Composting also aims at nutrient recycling. Farm compost is prepared with on-farm or off-farm feedstock materials, or both. Compost application sustains or increases SOM by the input of stabilized organic matter (D'Hose et al., 2012; Parkinson et al., 1999; Willekens et

al., 2014a). Stabilization of organic matter during the composting process implies mass reduction and consequently an increase in P concentration (Vandecasteele et al., 2014), which builds a risk for P-over-fertilization. However, by mixing feedstock materials rich in P with materials with a high C/P ratio, co-composting allows for producing amendments with a lower C/P ratio, i.e., a higher supply of stable C per unit of P (Vandecasteele et al., 2014).
Organic-input based systems succeed to retain N in the system as found in long-term cropping systems studies (Drinkwater et al., 1998; Jenkinson, 2001; Peters et al., 1997), whereas conventional management practices may lead to a reduction of soil fertility (Clark et al., 1998; Mulvaney et al., 2009). A lower potential risk of N leaching appeared from slower N mineralization in organic and low-input farming systems compared to conventional farming systems (Poudel et al., 2002).

1.10 Thesis outline and research questions

This study deals with the issues (i) soil degradation related to a decrease in SOM content in agricultural soil and (ii) N leaching losses from field vegetable cropping systems.
This study assesses the effectiveness of specific soil quality improving management practices on soil quality and crop performance. Key objective of this study was understanding N dynamics in relation to soil quality and soil quality improving management practices, i.e., reduced tillage, compost application and green manuring.
With respect to practical aspects, this study was expected to (i) generate new knowledge allowing for fine-tuning N fertilization to specific soil quality characteristics or certain soil management practices in order to optimize N utilization in the plant-soil system and minimize losses to the environment, and (ii) define soil management strategies for field vegetable production systems that allow to improve soil quality while improving good balance between nutrients availability.
To study these topics, situations with a gradient in soil quality were essential. The differences in soil quality required for this study were available from (i) existing variation in soil quality between farmers' fields that originated from differences in management history and (ii) by applying different soil management strategies in newly established multi-year field trials.
The main hypotheses of this study were (i) soil management affects soil quality (e.g., SOM, nutrients balance and availability, soil organisms, …), (ii) soil quality affects N dynamics in

the plant-soil system, (iii) soil management affects N dynamics (following from i and ii) and (iv) soil management, soil quality and N dynamics affect crop performance (Figure 1.2).

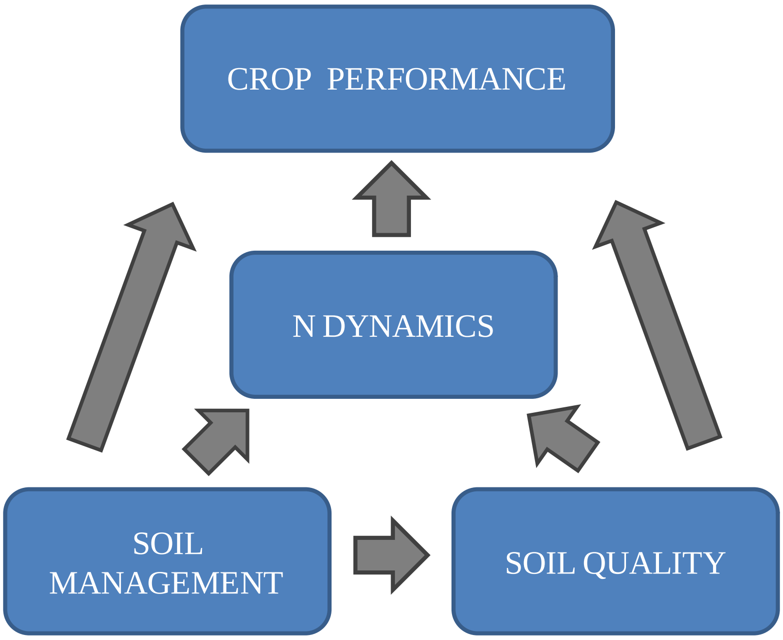

Figure 1.2 Studied hypothetical relationships

For this study, a field survey was performed, where farmers' practice was applied, besides designed multiyear soil management field experiments in both organic and conventional vegetable cropping systems.

Chapter 2 of this thesis deals with a one-year assessment of N dynamics under a leek crop on 28 horticultural fields where farmers' practice was applied. A three-year assessment of soil residual mineral N on 31 horticultural fields is presented in chapter 3. Chapters 4 and 5 deal with the outcome of a three-year soil management experiment (Vegtilco trial) in a conventional vegetable cropping system, more specifically focused on the effect of soil improving management practices on soil quality (chapter 4) and short-term changes in N dynamics due to soil management variants and shifts in soil quality (chapter 5). In chapter 6, the results of a two-year field experiment (Tilman-org trial) in an organic vegetable cropping system are presented. Nutrient availability and crop performance were evaluated in relation to the imposed soil management practices. Tested practices in this trial were: grass-clover management practices, reduced tillage and compost application. In chapter 7, the global findings of this study are presented and discussed, inclusive of some general conclusions and suggestions for future research.

Chapter 2

Nitrogen balances and soil quality in leek crop production and implications for Nmin-based fertilizer recommendation systems

After: Willekens, K., Vandecasteele, B., De Reycke L., Koch C., De Neve, S. (in preparation for submission to *Horticultural Science*). Nitrogen balances and soil quality in leek crop production and implications for Nmin-based fertilizer recommendation systems

2.1 Introduction

The eutrophication of surface and ground water from agricultural activities is a major concern for EU policy. To meet the objectives of the European Nitrates Directive for limitation of nutrient losses from the plant-soil system, national action programs must be established. Numerous studies and research projects illustrate that the problem of nitrate leaching still persists in many regions of Europe, especially in vegetable production systems (De Neve and Hofman, 1998; Vinten and Dunn, 2001; Thompson et al., 2007; Fonder et al., 2010; van Dijk and Smit, 2006; Benincasa et al., 2011). Various Member States have developed nitrogen (N) fertilizer recommendation systems, which are either obligatory or highly recommended to prevent excess N fertilization and restrict N losses to the environment. Meeting the crop N demand requires an appropriate fertilization strategy. Factors affecting crop growth and N availability are quite unpredictable, however, particularly in rainfed cultivation systems.

Crop N demand depends on crop growth and yield potential. Yield potential not only responds to nutrient availability but is also related to climatic conditions and site characteristics, particularly the soil structure, which influences hydrology and rooting ability (Groenevelt et al., 1984). The relationship between soil quality and yield potential should be taken into account in N fertilizer recommendation systems. Estimation of mineralization potential by single standardized soil tests does not sufficiently reflect the real situation. Prediction of N mineralization should be based on a combination of soil tests and soil properties (Ros et al., 2011). An integrated approach to assess soil quality might be most successful in this respect. Soil quality consists of physical, chemical and biological aspects and is affected by both inherent soil properties and management practices. Additionally, N release from soil organic matter (SOM) is controlled by soil temperature and moisture content. Soil water stocks may fluctuate widely due to changing weather circumstances.

In horticultural systems with controlled irrigation, fewer fluctuations in mineralization rate occur, likely resulting in more accurate estimations. In rainfed systems, periodic drought stress for decomposer micro-organisms will tend to reduce mineralization rates. A delayed or repeated assessment of soil mineral N stock measurements for fractionation of fertilizer N input might partly overcome the uncertainty with regard to the N supplying capacity of the soil.

Organic N input such as animal manure usually enhances the net N release, but the released amount is not easily predicted. Fertilizer application affects soil microbial activity and alters soil N dynamics by causing either negative or positive priming effects (Kuzyakov et al., 2000). A priming effect happens when a limiting factor for microbial biomass is removed, e.g., when mineral N or an easily decomposable energy source is added. Hamer et al. (2009) hypothesized that N deficiency favors the priming effect when mineral N is supplied. In their review paper, Kuzyakov et al. (2000) defined priming effects as strong short-term changes in SOM turnover caused by comparatively moderate treatments of the soil, e.g., fertilization, drying-rewetting, mechanical disturbance. Green et al. (2006) discovered that urea application increases the biomass and activity of saprotrophic microorganisms resulting in enhanced litter decomposition. Such interactions are neither fully understood nor implemented in N fertilizer recommendation systems.

N fertilizer recommendation systems thus have to consider a multitude of factors. However, because of the number and complexity of processes affecting N dynamics in the plant-soil system, existing recommendation systems are based on a simplified approach to the soil reality and therefore should rely on additional site- or soil-type related expert judgment. When using N fertilizer recommendation systems based on merely mineral N stocks in the rootable soil layer, a realistic crop N demand and yield potential and somehow the N supplying capacity of the soil of the particular field should be considered (Appel, 1994). In a comparison of fertilizer recommendation systems for cauliflower crops in Europe (Rahn et al., 2001), lack of accounting for the site-specific expected yield resulted in unrealistic recommendations. The first objective of this study was to investigate natural and anthropogenic factors that potentially affect N dynamics and leek (*Allium porrum*) crop growth (Figure 2.1) in 28 horticultural fields where common farming practices were applied. The second objective was to test the suitability of a Nmin-based fertilizer recommendation system while interpreting the observed relationships. It concerned conventional field vegetable cropping systems in which both synthetic N fertilizers and organic sources of N were applied and with no or limited irrigation facilities.

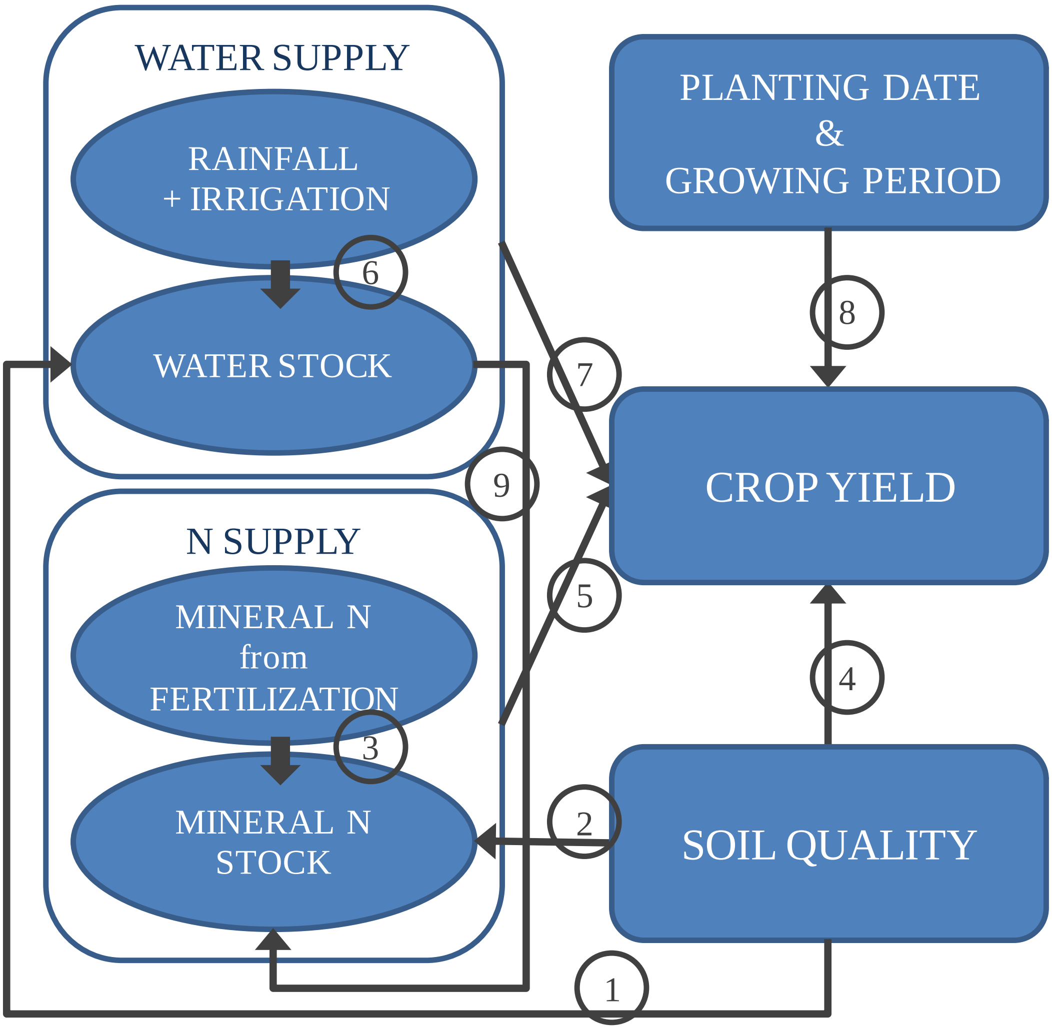

Figure 2.1 Natural and anthropogenic factors hypothetically affecting crop yield, soil mineral N and water stocks. Numbers refer to specific relations between factors which are further specified in the manuscript.

2.2 Materials and methods

2.2.1 Site selection, agronomic practices and soil and crop sampling

In 2009, a survey was carried out on 28 horticultural fields in northern Belgium, mainly located in the provinces of West and East Flanders, where vegetables are grown in rotation with arable crops such as corn (*Zea mays*), potatoes and cereals. Soils were WRB classified as Cambisols (10), Luvisols (9), Planosols (4), Podzols (2), Stagnosol (1), Retisol (1) and Anthrosol (1) (Dondeyne et al., 2014; IUSS Working Group WRB, 2015) (Figure 2.2). On all fields, the main crop was leek (*Allium porrum*). Fields were numbered from 1-31 omitting fields 24, 27 and 29 where no leek crop was grown in 2009.

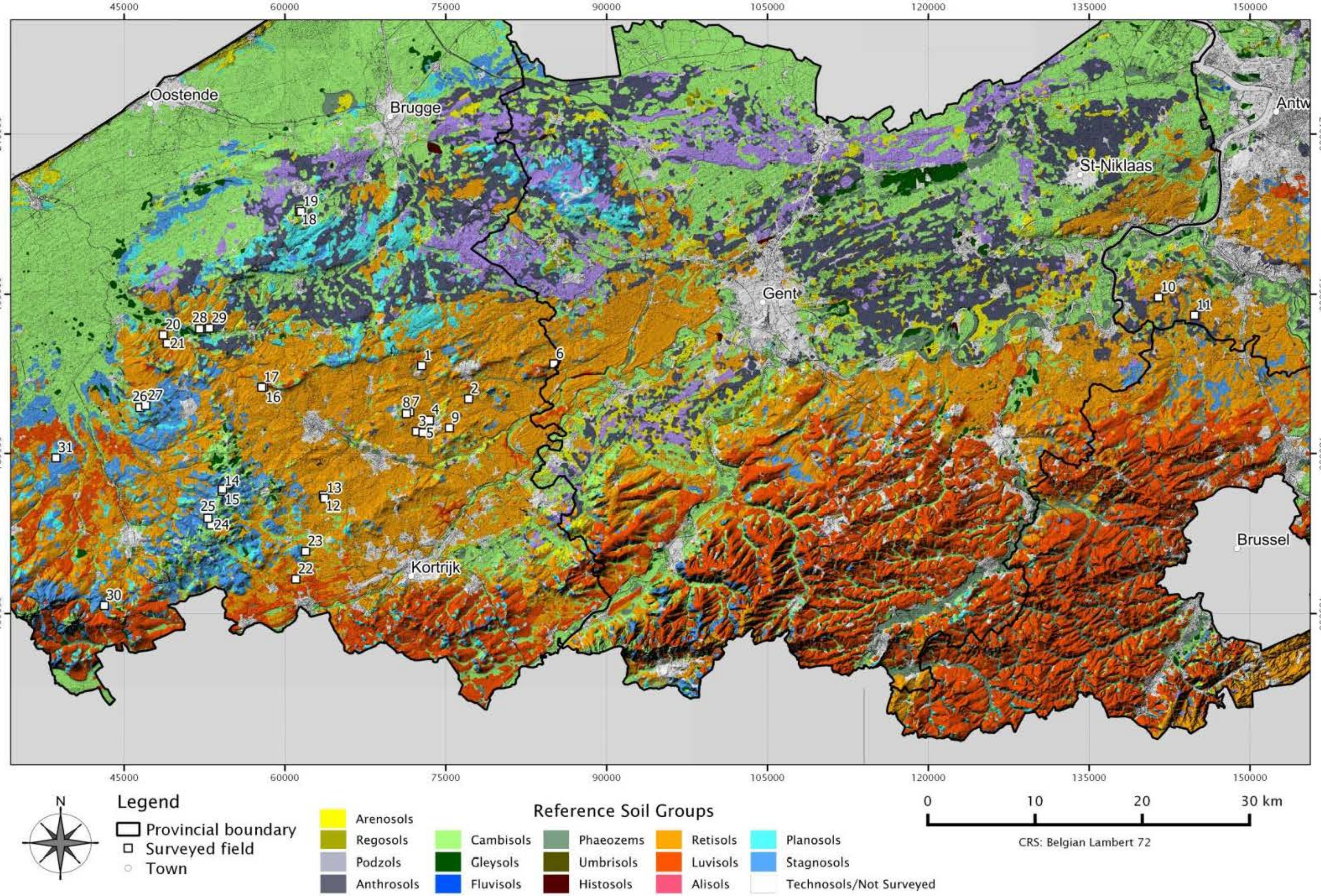

Figure 2.2 Location of the surveyed fields1-31 on the generalized WRB soil map (original scale 1:250 000) adapted from Dondeyne et al., 2014.

Leek crop earliness was parameterized either by using planting date expressed as ‘Julian days on which planting took place’ or by distinguishing two classes, i.e., early planting (19/05 - 25/06, n = 15) and late planting (30/06 - 20/07, n = 13). The crop parameter growing period represents the number of days from planting until yield determination in autumn. A representative subpart of each field (an area of approximately 50 x 50 m^2) was selected for soil and crop sampling. Main tillage was performed with a moldboard plow on the majority of the fields. Before planting leek, most of the fields received a combination of animal manure and mineral N fertilizers. Some fields received only mineral N fertilizer. Base mineral N dressing comprises the mineral N input by both organic and mineral fertilization. The mineral N input from animal manure was calculated using default total N concentrations from the Flemish Land Agency (VLM, 2009) and ‘mineral N : total N’ ratios from the Dutch Nutrient Management Institute (NMI, 2000). Seventeen fields received a top mineral dressing.

Soil was sampled for determination of the mineral N content in the 0-30, 30-60 and 60-90 cm soil layers at three sampling occasions, i.e., springtime (April - May) before fertilization and soil tillage (s1), summer period (mid July to mid August) 4-9 weeks after planting the crop (s2), autumn (October - November) at the time of yield determination (s3) (Figure 2.3). In each field, twelve auger borings were conducted according to a grid pattern (e.g., four borings along three parallel lines in the demarcated subpart of the field) and bulked into one composite sample per depth. In September – October, undisturbed soil cores (100 cm^3) were taken in triplicate under the leek crop at approximately 15 and 45 cm depth below the soil surface with an auger (Eijkelkamp Agrisearch Equipment) to determine dry soil bulk densities (BD; ISO 11272) of the 0-30 and 30-60 cm soil layers ($BD_{0\text{-}30\ cm}$ and $BD_{30\text{-}60\ cm}$), respectively. $BD_{60\text{-}90\ cm}$ was equated to $BD_{30\text{-}60\ cm}$. At s3, two times three meters of leek were harvested in two rows on each field. Whole plants, inclusive of the upper 2 cm of the root system, were harvested. After thoroughly washing the plants, fresh weight was determined.

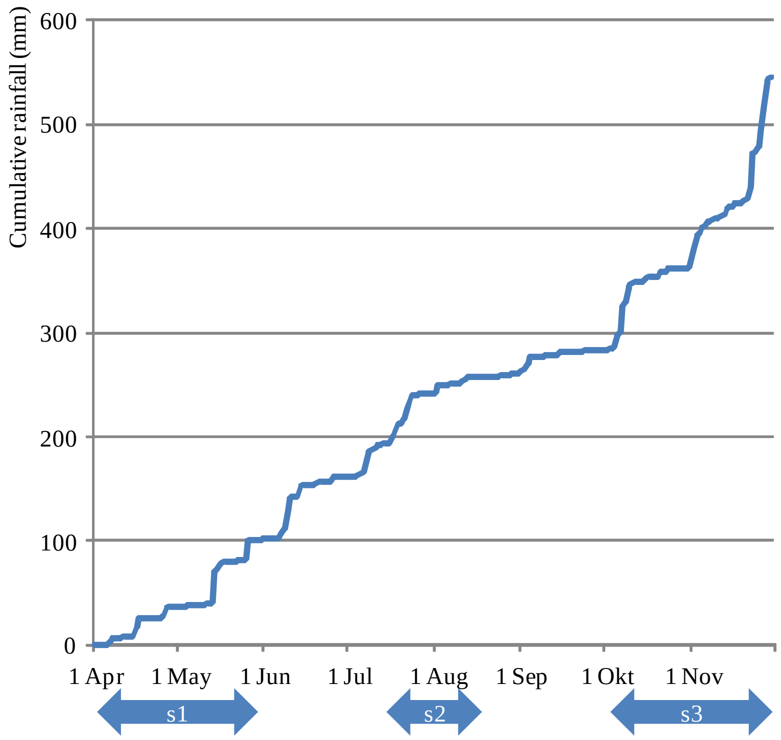

Figure 2.3 Cumulative rainfall data for 2009 (average of four regional weather stations: Beitem, Kruishoutem, Poperinge and Sint-Niklaas) and periods of the first, second and third sampling moments (s1, s2 and s3).

2.2.2 Recording of rainfall and sprinkler irrigation data and calculation of soil water stocks and water balance

For each field, rainfall data were acquired from the nearest weather station (four in total, spread over the study area). On average, rainfall was low in August and September (approximately 20 mm month^{-1}; Figure 2.3). Because this was less than half of the long term mean rainfall, some farmers applied irrigation. About half of the fields were sprinkler irrigated in the period s2-s3, with a maximum of 120 mm and 25th, 50th and 75th percentiles values of 0, 15 and 53 mm, respectively. The water input by rainfall and irrigation was calculated for both the period from planting until s3 and the s2-s3 period. Soil water stocks at s1, s2 and s3 in the 0-30 cm arable layer (water stock$_{0\text{-}30\ cm}$) and the 0-60 cm soil profile (water stock$_{0\text{-}60\ cm}$) were calculated based on gravimetric soil moisture content and BD data of the 0-30 and 30-60 cm soil layers and expressed as water height in mm. The water supply for the s2-s3 period was calculated as the sum of the water stock$_{0\text{-}60\ cm}$ at s2 plus the water input$_{s2\text{-}s3}$. A water balance for the s2-s3 period was obtained by subtracting the water stock$_{0\text{-}60\ cm}$ at s3 from the water supply$_{s2\text{-}s3}$. This water balance reflected the evapotranspiration in the s2-s3 period.

2.2.3 Assessment of N dynamics

Mineral N stocks in the 0-30 cm arable layer ($Nmin_{0\text{-}30\ cm}$) and the 0-90 cm soil profile ($Nmin_{0\text{-}90\ cm}$) at s1, s2 and s3 were calculated based on the soil mineral N content and BD values of the respective soil layers. Nitrate amounts at s3 in the 0-30 cm arable layer (residual NO_3^--$N_{0\text{-}30\ cm}$) and the 0-90 cm soil profile (residual NO_3^--$N_{0\text{-}90\ cm}$) were also considered.

The N uptake by the leek crop at s2 was not measured but was set equal to 40 kg N ha^{-1}, corresponding to the average N uptake by a 4- to 9-week-old crop according to the N uptake curve for autumn leek in the German "Kulturbegleitende N_{min}-Sollwert System (KNS)" recommendation system (Lorenz et al., 1989; Feller et al., 2011). Willekens et al. (2014b) found 39 kg N uptake ha^{-1} by a 7-week-old autumn leek crop for the plowed treatment of a soil management field trial. At s3, dry matter and N content of whole plant subsamples were determined for calculation of dry biomass and total N uptake at s3. Samples were oven dried in a ventilated oven at 70°C during at least 48h. N content was determined on ground dried plant material according to the Kjeldahl method (ISO 5983-2).

Balances of plant available N were calculated by subtracting the N supply from the N recovery (Table 2.1) resulting in the “apparent” net N mineralization (ANM) (Feller and Fink, 2002). Three balance periods were considered, i.e., s1-s3, s1-s2 and s2-s3. The N input through planting material was considered to be negligible. In the assumption that no N losses occur between the considered sampling occasions, ANM is the net N release from both SOM and organic matter applied by fertilization. The only substantial N loss in these rotations is nitrate leaching. Given that the period of this research (April – November 2009) was a growing season with no excess precipitation, as confirmed by the extremely dry August and September, the assumption of non-significant N losses is justified.

Table 2.1 Supply and recovery items of the considered balances of plant available N (profile: 0-90 cm soil profile); ANM: apparent net N mineralization; s1, s2 and s3: first, second and third sampling occasion.

	$ANM_{s1\text{-}s2}$	$ANM_{s2\text{-}s3}$	$ANM_{s1\text{-}s3}$
SUPPLY	profile mineral N at s1	profile mineral N at s2	profile mineral N at s1
	base mineral N dressing	top mineral N dressing	total mineral N dressing
RECOVERY	profile mineral N at s2	profile mineral N at s3	profile mineral N at s3
	young crop N uptake (= 40 kg ha^{-1})	crop N yield - 40 kg ha^{-1}	crop N yield

The applied top mineral N dressing was compared with an a posteriori recommendation by the KNS system. The KNS system and the related N-Expert software are designed for vegetable cropping systems in which water supply is non-limiting and N is supplied with mineral fertilizers. The system is based on Nmin measurements and uses a simple N balance approach. For autumn leek, it presumes a N uptake curve with a default total N uptake of 240 kg ha^{-1} corresponding to a fresh biomass of 89 Mg ha^{-1} (Feller, 2011). The system calculates target values for N supply by subtracting an intermediate N uptake from the total N uptake and adding a minimum residual $Nmin_{0\text{-}60\ cm}$ of 40 kg ha^{-1}. If a target value at a given growth stage exceeds the Nmin in the rootable layer determined at that time, the recommendation for top mineral N dressing is obtained by subtracting the mineral N stock from the target value. If the KNS target value exceeded $Nmin_{0\text{-}60\ cm}$ at s2, the resulting KNS-recommendation could be compared with the applied top mineral N dressing. The KNS-recommendation was evaluated from an agricultural and environmental point of view, respectively. Fresh biomass yield was assessed against the default KNS value and residual NO_3^--$N_{0\text{-}90\ cm}$ against a maximum of 90 kg ha^{-1} (Flemish Land Agency).

2.2.4 Assessment of soil quality and soil analyses

At s1, soil quality related characteristics of the 0-30 cm arable layer were determined: total organic carbon content (TOC), total nitrogen content (Ntot), pH-KCl, calcium to magnesium ratio (Ca:Mg), plant available Mn content (Mn_{sol}), exchangeable Fe content (Fe_{exch}) and the sand, silt and clay fraction. Hot water extractable carbon content (HWC) was measured on soil sampled at s2.

Mineral N content was extracted (1:5 w/v) in a 1 M KCl solution according to ISO 14256-2 and measured with a Foss Fiastar 5000 continuous flow analyzer. Soil moisture content was determined as the weight loss at 105 °C. TOC was measured on oven-dried (70 °C) soil samples by dry combustion at 1050 °C with a Skalar Primacs SLC TOC-analyzer according to ISO 10694. For soils with pH-KCl > 6.5, inorganic carbon was measured separately. None of the samples had inorganic carbon levels higher than the limit of quantification. Ntot was determined by dry combustion (Dumas principle) with a Thermo flash 4000 according to ISO 13878. pH was measured potentiometrically in a 1M KCl solution (1:5 v/v) according to ISO 10390. Ca:Mg was based on the exchangeable cations in the first percolate of the NH_4OAc extract from the cation exchange capacity (CEC) determination by the method described in Van Ranst et al. (1998). The exchangeable cations Ca and Mg were determined with a CCD simultaneous ICP-OES (VISTA MPX, Varian, Palo Alto, CA). Mn_{sol} was measured in a 1:10 (w/v) 0.01M $CaCl_2$ extract (NEN 5704). Fe_{exch} was determined by shaking 5 g air-dried soil in 100 ml ammonium lactate for 4 hours (Egnèr et al., 1960) and was measured using a CCD simultaneous ICP-OES (VISTA-PRO, Varian, Palo Alto, CA). The soil particle distribution (sand % 50 - 2000 µm, silt % 2 - 50 µm and clay % < 2 µm) was determined by the sieve-pipette method (ISO 11277). HWC was determined following a method of Haynes and Francis (1993). Soil samples (equivalent to 5 g oven dry weight) were weighed into 50 ml polypropylene centrifuge tubes and 25 ml of demineralized water was added. The tubes were capped and left for 16 h in a hot water bath at 70 °C. At the end of the extraction period these tubes were centrifuged and the supernatants were filtered over a Machery-Nagel mn640d filter. Total C in the extracts was determined by dry combustion at 1050 °C with a Skalar Primacs SLC TOC analyzer (Skalar, Breda, the Netherlands).

2.2.5 Data analysis

For each parameter, we checked normality of the data using the Kolmogorov-Smirnov test. For some parameters the data were subjected to a square root ($Nmin_{0\text{-}30\ cm}$ at s2 and s3, $Nmin_{0\text{-}90\ cm}$ at s2 and s3, residual NO_3^--$N_{0\text{-}30\ cm}$, residual NO_3^--$N_{0\text{-}90\ cm}$, N $recovery_{s1\text{-}s2}$, N $supply_{s2\text{-}s3}$ and Ca:Mg) or logarithmic transformation (N $recovery_{s2\text{-}s3}$, N $recovery_{s1\text{-}s3}$ and Mn_{sol}) in order to obtain normality. P-values for Pearson correlation coefficients and regression coefficients (multivariate linear regression analyses) were used to assess significant relations. For some dependent variables, a general linear model (GLM) approach, considering both planting date classes, or a stepwise linear regression technique was used. A principal component analysis (PCA) was performed with eight soil characteristics (TOC, HWC, pH-KCl, Ca:Mg, Mn_{sol}, Fe_{exch}, sand and clay) (non-standardized) of the 0-30 cm arable layer of the 28 fields in order to distinguish field groups according to soil quality status (soil quality groups). This classification was tested for its discriminative value with a canonical discriminant analysis (Fisher Method). Spotfire S+ 8.2 software was used.

2.3 Results

2.3.1 Soil water stocks

Water $stock_{0\text{-}30\ cm}$ at s1 was significantly correlated with TOC ($R = 0.53$, $p < 0.01$), Ntot ($R = 0.60$, $p < 0.001$) and clay content ($R = 0.56$, $p < 0.01$) (Fig 2.1., rel.1). Water $stock_{0\text{-}30\ cm}$

at s2 was significantly negatively correlated with sand ($R = -0.38$, $p < 0.05$) and positively with clay ($R = 0.59$, $p < 0.001$). Water stock$_{0\text{-}30\ cm}$ and stock$_{0\text{-}60\ cm}$ at s3 were significantly positively affected by water input$_{s2\text{-}s3}$ ($R = 0.63$, $p < 0.001$ and $R = 0.63$, $p < 0.001$, respectively) (Fig. 2.1, rel.6) and correlated with water supply$_{s2\text{-}s3}$ ($R = 0.69$, $p < 0.001$; $R = 0.70$, $p < 0.001$). Water stock$_{0\text{-}30\ cm}$ at s3 was significantly positively correlated with TOC ($R = 0.42$, $p < 0.05$) and Ntot ($R = 0.56$, $p < 0.01$) and significantly correlated with all textural classes, negatively with sand ($R = -0.61$, $p < 0.001$) and positively with silt and clay ($R = 0.52$, $p < 0.01$; $R = 0.73$, $p < 0.001$, respectively). Water stocks were related with C content and particle size distribution of the soil, and in the drier period (s2-s3) also with water input.

2.3.2 Grouping of fields reflecting differences in soil quality

The PCA biplot of the first two principal components resulted in a classification of the fields in four different soil quality groups (A ($n = 9$), B ($n = 5$), C ($n = 6$), D ($n = 8$)) (Figure 2.4). The first 2 principal components accounted for 70.3% of the total variance. The canonical discriminant analysis showed that the first two of three discriminant functions accounted for 99.3% of the total variance and significantly contributed to the discrimination of the four soil quality groups (significantly different means, Wilks Lambda, $\alpha = 5\%$). Variance-covariance matrices were equal for the different soil quality groups (implicit assumption; Box M test, $\alpha = 5\%$) and cross-validation showed an overall error of only 10.7%. Mean values of the soil parameters per soil quality group (A-D) are presented in Table 2.2. Despite the large range for TOC, between 0.94% (group A) and 1.55% (group C), no significant statistical differences appeared between soil quality groups. However, Ntot values, reflecting SOM as well, significantly differed between soil quality group A (0.09%) and soil quality group C (0.15%). Soils of soil quality group B were more waterlogged and less aerated than those of soil quality group A, as indicated by significantly higher mean Fe_{exch} and Mn_{sol} values for soil quality group B. At a normal pH level (pH-KCl > 5.2), a high Mn_{sol} indicates a disturbed oxygen supply, with higher pore water concentrations for Mn in anaerobic conditions (Du Laing et al., 2007). Poor drainage may also result in a higher Fe_{exch} content due to higher pore water concentrations (Du Laing et al., 2007). However, a higher Fe_{exch} content also coincides with a higher clay content. Compared to soil quality group A, soil texture was heavier for soil quality groups C and D, of which the average clay content was significantly higher and the average sand content significantly lower. Soil quality group B had an intermediate position, with a significantly higher sand content than soil quality group C. Soil quality group D had significantly higher pH-KCl and Ca:Mg values compared to all other soil quality groups. Soil quality group C had the highest average HWC value, significantly higher than that of soil quality group A.

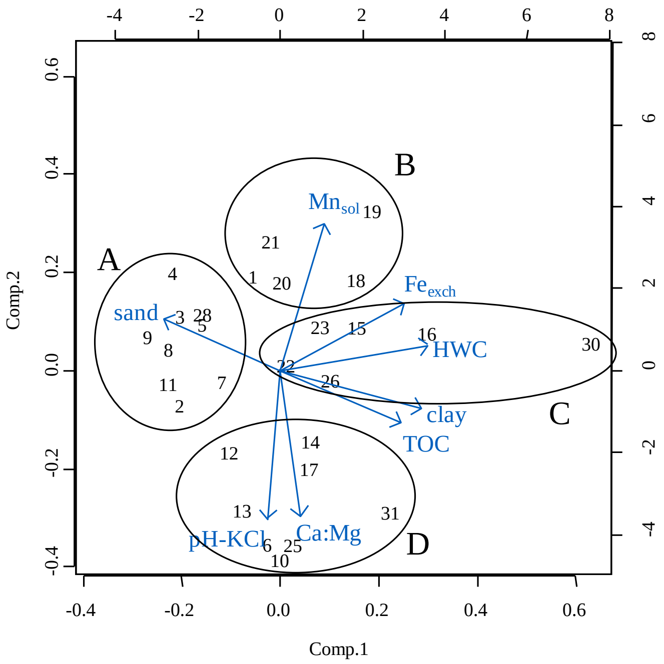

Figure 2.4 Biplot of the principal component analysis (PCA) with eight soil parameters for 28 fields (numbers inside the graph identify the fields; n = 28, field numbers 1-31, fields 24, 27 and 29 were omitted as no leek crop was grown in 2009) with identification of soil quality groups A, B, C and D.

Table 2.2 Average values of soil parameters for soil quality groups A-D, (SQGs) (significant differences between SQGs are indicated by different lowercase letters; 95% simultaneous confidence intervals using the Sidak method) (TOC: total organic carbon; HWC: hot water extractable carbon; Ntot: total nitrogen content).

SQG	n	TOC	HWC	pH-KCl	Ca:Mg	Mn_{sol}	Fe_{exch}	sand	clay	Ntot
		% w/w	mg kg^{-1} dry soil			mg kg^{-1} dry soil	mg kg^{-1} dry soil	% w/w	% w/w	% w/w
A	9	0.94 ^{a}	499 ^{a}	5.7 ^{a}	4.6 ^{a}	2.5 ^{a}	788 ^{a}	75.6 ^{c}	5.0 ^{a}	0.09 ^{a}
B	5	1.31 ^{a}	747 ^{ab}	5.4 ^{a}	3.4 ^{a}	15.0 ^{b}	1238 ^{bc}	69.8 ^{bc}	7.8 ^{ab}	0.12 ^{ab}
C	6	1.55 ^{a}	864 ^{b}	5.9 ^{a}	5.1 ^{a}	7.5 ^{b}	1283 ^{c}	49.6 ^{a}	10.5 ^{b}	0.15 ^{b}
D	8	1.47 ^{a}	606 ^{ab}	6.9 ^{b}	9.2 ^{b}	1.1 ^{a}	903 ^{ab}	58.2 ^{ab}	9.6 ^{b}	0.13 ^{ab}

2.3.3 Soil mineral N and residual nitrate

A large variation in $Nmin_{0\text{-}90\ cm}$ was found at each of the sampling occasions (Table 2.3) with values up to 900 kg N ha^{-1} at s2 and up to 450 kg N ha^{-1} at s3. At s1, significant positive correlations were found between $Nmin_{0\text{-}30\ cm}$ and Ntot ($R = 0.56$, $p < 0.01$) and between

$Nmin_{0\text{-}90\ cm}$ and Ntot (R = 0.58, $p < 0.01$) (Fig. 2.1, rel. 2) whereas at s2, $Nmin_{0\text{-}30\ cm}$ and $Nmin_{0\text{-}90\ cm}$ were significantly positively correlated with base mineral N dressing (resp. R = 0.70, $p < 0.001$; R = 0.72, $p < 0.001$) (Fig. 2.1, rel.3). A GLM for $Nmin_{0\text{-}90\ cm}$ at s2 including base mineral N dressing, Ntot (Fig. 2.1, rel. 2) and planting date class showed a significant effect of each factor ($p < 0.001$, $p < 0.01$ and $p < 0.01$, respectively) and a multiple R^2 of 0.66.

$$\sqrt{\ } Nmin_{0\text{-}90\ cm} \text{ at s2 (kg ha}^{-1}) = 6.39 + 0.056 * \text{base mineral N dressing (kg ha}^{-1}) + 47.9 * \text{Ntot (\%)} - 3.46 * y \quad (1)$$

y = 0 if ‘early planting’; y = 1 if ‘late planting’

Neither mineral N dressing nor N supply affected residual mineral N or NO_3^--N at s3. No correlation was found between residual mineral N or NO_3^--N at s3 and Ntot. At s1, significant positive correlations were found between $Nmin_{0\text{-}30\ cm}$ and water $stock_{0\text{-}30\ cm}$ (R = 0.56, $p < 0.01$) and between $Nmin_{0\text{-}90\ cm}$ and water $stock_{0\text{-}90\ cm}$ (R = 0.56, $p < 0.01$) (Fig. 2.1, rel. 9). At s2, a significant positive correlation was found between $Nmin_{0\text{-}90\ cm}$ and water $stock_{0\text{-}30\ cm}$ (R = 0.40, $p < 0.05$) and at s3, no correlations were found between water and mineral N stocks. At none of the sampling occasions, $Nmin_{0\text{-}30\ cm}$ and $Nmin_{0\text{-}90\ cm}$ differed between soil quality groups A-D reflecting soil quality.

Table 2.3 Mineral N stock in the 0-90 cm soil profile ($Nmin_{0\text{-}90\ cm}$), N supply, N recovery and apparent net N mineralization (ANM) (kg ha^{-1}); means, standard deviations, coefficients of variation and quartile values for the different sampling occasions and balance periods in 2009 (s1 April - May; s2 mid July - mid August; s3 October - November).

	$Nmin_{0\text{-}90\ cm}$ kg ha^{-1}			N supply kg ha^{-1}			N recovery kg ha^{-1}			ANM kg ha^{-1}		
	s1	s2	s3	s1-s2	s2-s3	s1-s3	s1-s2	s2-s3	s1-s3	s1-s2	s2-s3	s1-s3
mean	81	370	176	225	414	270	410	328	368	184	-86	99
stdev	36	202	85	74	181	72	202	86	86	160	182	95
cv%	45	55	49	33	44	27	49	26	23	87	213	97
min	26	125	60	102	125	105	165	209	249	-11	-579	-57
1st quart	52	214	131	173	279	225	254	272	312	64	-181	29
median	76	298	152	230	348	280	338	310	350	137	-64	74
3th quart	101	526	234	269	529	311	566	374	414	290	36	143
max	176	901	449	401	901	404	941	567	607	586	316	366

2.3.4 Fresh biomass, dry biomass and total N uptake

All crop yield parameters (fresh biomass, dry biomass and total N uptake) were significantly negatively correlated with planting date (R = -0.49, $p < 0.01$; R = -0.78, $p < 0.001$; R = -0.51,

$p < 0.001$, respectively) (Fig. 2.1, rel. 8). Dry biomass and total N uptake were significantly positively correlated with growing period ($R = 0.44$, $p < 0.05$; $R = 0.48$, $p < 0.05$, respectively) (Fig. 2.1, rel. 8). Fresh biomass, dry biomass and total N uptake were significantly positively correlated with water stock$_{0\text{-}30\ cm}$ at s1 ($R = 0.55$, $p < 0.01$; $R = 0.58$, $p < 0.01$; $R = 0.63$, $p < 0.001$, respectively) (Fig. 2.1, rel. 7) and with water input$_{pl\text{-}s3}$ ($R = 0.52$, $p < 0.01$; $R = 0.38$, $p < 0.05$; $R = 0.47$, $p < 0.05$, respectively) (Fig. 2.1, rel. 7). Water stock at s3, which was significantly positively correlated with water input$_{pl\text{-}s3}$ (results not shown) (Fig. 2.1, rel. 6), and water stock at s2 did not affect crop yield parameters (Fig. 2.1, rel. 7). Fresh biomass tended to be correlated with the water balance$_{s2\text{-}s3}$ ($p < 0.1$).
Dry biomass and total N uptake were significantly positively correlated with Ntot ($R = 0.39$, $p < 0.05$; $R = 0.38$, $p < 0.05$, respectively) (Fig. 2.1, rel. 4). Total N uptake was also positively correlated with HWC ($R = 0.38$, $p < 0.05$). Fresh and dry biomass and total N uptake did not differ between soil quality groups A-D. Total N uptake was not only affected by Ntot but also by N supply, as revealed by the positive correlations with N supply$_{s1\text{-}s3}$ ($R = 0.42$, $p < 0.05$) and N supply$_{s2\text{-}s3}$ ($R = 0.38$, $p < 0.05$) (Fig. 2.1, rel. 5). Fresh and dry biomass tended to be correlated with N supply$_{s1\text{-}s3}$ and Nsupply$_{s2\text{-}s3}$, respectively. Fresh biomass was negatively correlated with residual NO_3^--$N_{0\text{-}90cm}$ ($R = -0.41$, $p < 0.05$). By stepwise multivariate linear regression, additional factors were detected significantly affecting fresh and dry biomass and total N uptake (Table 2.4).

Table 2.4 Multivariate linear regression models for crop yield parameters (2 per parameter) obtained by stepwise linear regression including TOC, Ntot, HWC, water input$_{pl\text{-}s3}$, water input$_{s2\text{-}s3}$, water supply$_{s2\text{-}s3}$, total mineral N dressing, N supply$_{s2\text{-}s3}$, planting date and growing period; intercept and regression coefficients (rc) and related p-values.

		fresh biomass				dry biomass				total N uptake			
		(1)	p <	(2)	p <	(1)	p <	(2)	p <	(1)	p <	(2)	p <
	intercept	159.9	0.001	124.4	0.01	18.6	0.001	18.1	0.001	339.4	0.001	363.6	0.001
TOC	rc			10.4	0.1	0.74	0.05						
Ntot	rc							11.6	0.05	373.1	0.05	275.8	0.1
water input$_{s2\text{-}s3}$	rc	0.21	0.01			0.010	0.05	0.008	0.1			0.37	0.05
water supply$_{s2\text{-}s3}$	rc			0.12	0.05								
total mineral N dressing	rc									0.24	0.05		
planting date	rc	-0.73	0.001	-0.60	0.01	-0.088	0.001	-0.085	0.001	-1.35	0.01	-1.58	0.001
	R^2	0.44		0.45		0.73		0.76		0.48		0.50	

The soil quality parameter TOC emerged in the models for fresh biomass, whereas both TOC and Ntot appeared in models for dry biomass. Alternative equivalent models were found for total N uptake in which Ntot is replaced by HWC (results not shown). In one model for total N uptake, total mineral N dressing significantly affected total N uptake. R^2 values varied from 0.44 to 0.76.

2.3.5 N supply, N recovery and apparent net N mineralization (ANM)

Considering the N balance$_{s1\text{-}s2}$, N recovery was significantly positively correlated with N supply (R = 0.71, p < 0.001). A GLM for N recovery$_{s1\text{-}s2}$ including N supply$_{s1\text{-}s2}$ and planting date class showed a significant effect of each factor (p < 0.001 and p < 0.01, respectively) and a multiple R^2 of 0.61.

$$\sqrt{\text{N recovery}_{s1\text{-}s2}}\ (\text{kg ha}^{-1}) = 11.5 + 0.044 * \text{N supply}_{s1\text{-}s2}\ (\text{kg ha}^{-1}) - 3.4 * y \qquad (2)$$

y = 0 if ‘early planting’; y = 1 if ‘late planting’

According to this GLM, the amount of N recovered at s2 is 123 kg ha^{-1} higher in early planted fields than in late planted fields (Figure 2.5). Considering N balances for s2-s3 and s1-s3 periods, N recoveries were not related to their respective N supplies and were not affected by planting date class.

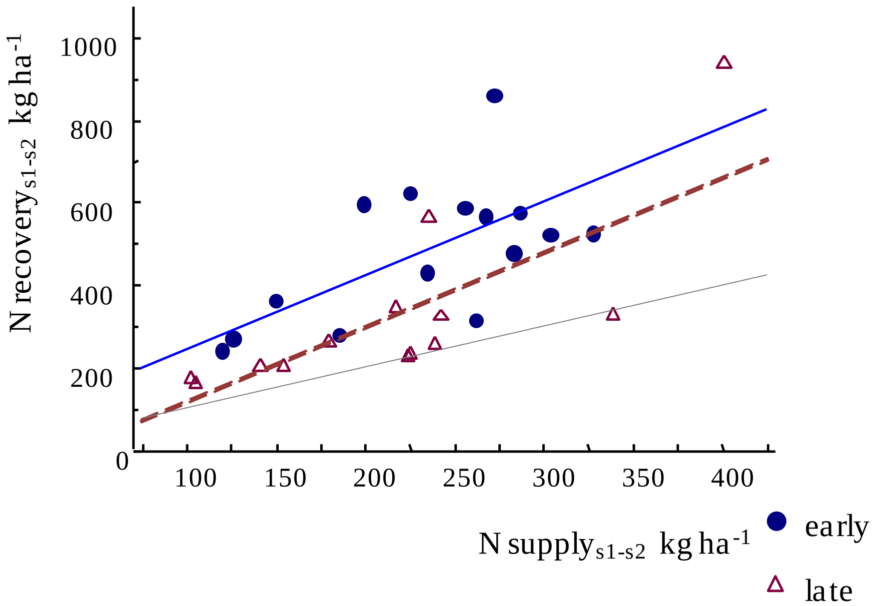

Figure 2.5 Linear regressions between N recovery$_{s1\text{-}s2}$ and N supply$_{s1\text{-}s2}$ for early (full line and dots) and late (dashed line and triangles) planted fields; recovery and supply items in table 2.1; thin grey line is the bisector in the graph; R^2 = 0.61.

ANM$_{s1\text{-}s3}$ varied from a few tens to a few hundred kg N ha^{-1} (Table 2.3). ANM$_{s2\text{-}s3}$ was mostly negative, which indicated an apparent net N immobilization in the second half of the growing season. ANM_{s1-s2} was significantly negatively correlated with ANM_{s2-s3} ($R = -0.85$, $p < 0.001$). All but two early planted fields showed ANM_{s1-s2} values larger than 100 kg N ha^{-1} followed by apparent net N immobilization in the summer period (negative ANM_{s2-s3}). This phenomenon of peaking apparent net N mineralization and subsequent apparent net N immobilization was observed to a lesser extent in late planted fields (Figure 2.6). ANM_{s1-s2} and ANM_{s2-s3} were significantly affected by planting date class. On average, ANM_{s1-s2} was 137 kg N ha^{-1} lower and ANM_{s2-s3} 117 kg N ha^{-1} higher for late than for early planted fields (Pooled-Variance Two-Sample One-Sided t-Tests, $p < 0.05$).

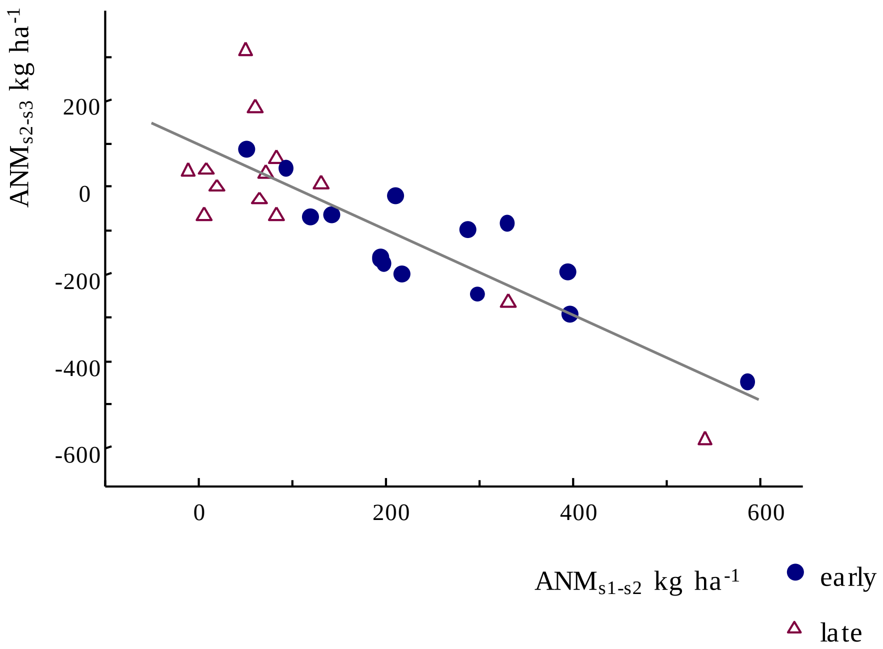

Figure 2.6 Linear regression between ANM_{s2-s3} and ANM_{s1-s2}, distinguishing between early (dots) and late (triangles) planted fields (ANM: apparent net N mineralization).

ANM_{s1-s2} was significantly positively correlated with N $supply_{s1-s2}$ ($R = 0.42$, $p < 0.05$) (Table 2.5); note the increasing vertical distance between observations and bisector (= ANM_{s1-s2}) with increasing N $supply_{s1-s2}$ (Figure 2.5). Considering the negative contribution of the N supply in the equation for ANM, a negative correlation between both parameters would be expected, as found for ANM_{s2-s3} ($R = -0.88$, $p < 0.001$) and ANM_{s1-s3} ($R = -0.50$, $p < 0.01$) and their respective N supplies. N $supply_{s1-s2}$ has two components: base mineral N dressing and $Nmin_{0\text{-}90\ cm}$ at s1 (Table 2.1). With regard to these two components, a significant positive correlation was only found between ANM_{s1-s2} and base mineral N dressing ($R = 0.48$, $p < 0.01$).

Table 2.5 Soil quality group, planting date class (e: early and l: late), planting date and number of growing days; mineral N stock in the 0-90 cm soil profile ($Nmin_{0\text{-}90\ cm}$) at s1, base mineral N dressing, supply of plant available N in the s1-s2 period (N $supply_{s1\text{-}s2}$) and apparent net N mineralization in the s1-s2 period ($ANM_{s1\text{-}s2}$); data of individual fields (n = 28, field numbers 1-31, fields 24, 27 and 29 were omitted as no leek crop was grown in 2009) plus means, standard deviations, coefficients of variation and quartile values.

NUMBER	SOIL QUALITY GROUP	PLANTING DATE CLASS	PLANTING DATE (CALENDAR DAYS)	NUMBER OF GROWING DAYS	$Nmin_{0\text{-}90\ cm}$ at s1 (kg ha^{-1})	BASE MINERAL N DRESSING (kg ha^{-1})	N $supply_{s1\text{-}s2}$ (kg ha^{-1})	$ANM_{s1\text{-}s2}$ (kg ha^{-1})
18	B	e	139	154	107	149	256	330
8	A	e	153	129	72	113	185	94
14	D	e	154	132	110	153	262	51
22	C	e	154	156	38	88	126	143
25	D	e	156	130	45	75	120	120
5	A	e	164	136	77	73	150	212
2	A	e	169	131	73	211	284	194
6	D	e	169	138	74	125	199	396
15	C	e	169	138	126	202	328	198
20	B	e	169	147	131	173	304	218
13	D	e	170	123	78	190	268	298
28	A	e	173	143	39	186	225	395
31	D	e	174	155	48	225	273	586
3	A	e	176	146	66	221	286	288
21	B	e	176	140	62	173	235	194
4	A	l	181	140	54	170	224	6
17	D	l	181	147	107	118	225	9
30	C	l	181	148	176	225	401	541
10	D	l	182	132	98	43	141	65
23	C	l	182	128	26	76	102	72
12	D	l	184	137	143	195	339	-11
16	C	l	184	144	99	118	217	131
19	B	l	185	136	94	149	242	83
9	A	l	187	135	95	141	236	331
7	A	l	188	134	92	88	180	83
11	A	l	191	123	45	194	239	20
26	C	l	197	125	62	92	154	51
1	B	l	201	121	27	78	105	60
		MEAN	175	137	81	144	225	184
		STDEV	14	10	36	54	74	160
		CV%	8	7	45	37	33	87
		MIN	139	121	26	43	102	-11
		1st QUART	169	131	52	91	173	64
		MEDIAN	176	137	76	149	230	137
		3th QUART	184	145	101	191	269	290
		MAX	201	156	176	225	401	586

None of the balance periods showed a significant correlation between ANM and Ntot. $ANM_{s1\text{-}s2}$ tended to be positively correlated with Ntot. A GLM for $ANM_{s1\text{-}s2}$ including Ntot and planting date class showed a significant effect of each factor ($p < 0.05$ and $p < 0.01$, respectively) and a multiple R^2 of 0.40.

$ANM_{s1\text{-}s2}$ (kg ha^{-1}) = 40 + 1824 * Ntot (%) – 157 * y (3)
y = 0 if 'early planting'; y = 1 if 'late planting'

N balance results did not differ between soil quality groups A-D, sorted according to soil quality.

2.3.6 N supply and N recovery data versus by KNS presumed N turnover in the plant-soil system

Thirteen fields showed a $Nmin_{0\text{-}60\ cm}$ at s2 higher than the KNS target value for N supply; consequently, the KNS recommendation for top mineral N dressing is zero (Table 2.6). All but two fields (9 & 30) were planted early and all but three fields (15, 18 & 28) showed a fresh biomass and total N uptake lower than the default values of KNS. Moreover, all but two fields (20 & 21) showed higher residual NO_3^--$N_{0\text{-}90\ cm}$ than the threshold of 90 kg ha^{-1}. Exceeding this threshold seemed not to be caused by top mineral N dressing (fields 6, 13 & 18) as the extent the threshold of 90 kg NO_3^--N ha^{-1} was surpassed was higher than the top mineral N dressing.

Fifteen fields show a $Nmin_{0\text{-}60\ cm}$ at s2 lower than the KNS target value for N supply. Seven of them (4, 7, 8, 11, 12, 22 & 25) received a top mineral N dressing similar to KNS recommendations. Fresh biomass and total N uptake were lower than the default values of KNS. On four of these seven fields, the threshold of 90 kg ha^{-1} for residual NO_3^--$N_{0\text{-}90\ cm}$ was exceeded (field 7, 8, 11 & 12). Two other fields (14 & 19) received a top mineral N dressing in an amount that exceeded the KNS recommendations. Only on field 14, fresh biomass and total N uptake exceeded the default values of KNS. Residual NO_3^--$N_{0\text{-}90\ cm}$ of both fields exceeded the threshold. However, if the KNS recommendation had been applied on field 19, residual NO_3^--$N_{0\text{-}90\ cm}$ would have been probably below the threshold. Six fields (1, 10, 16, 17, 23 & 26) got a top mineral N dressing that was (somewhat) lower than KNS recommendations. No field had fresh biomass and total N uptake that reached the default values of KNS. On four of the fields, residual NO_3^--$N_{0\text{-}90\ cm}$ was higher than the threshold (1, 16, 17 & 26) and on two (10 & 23) the threshold was not exceeded but probably would have been exceeded if the KNS recommendations had been applied.

For the fields on which the threshold for residual NO_3^--$N_{0\text{-}90\ cm}$ was not exceeded (4, 10, 20, 21, 22, 23 & 25) fresh biomass varied between the average of 72 Mg ha^{-1} and the default KNS value of 89 Mg ha^{-1} (Figure 2.7). The fields on which the threshold for residual NO_3^--$N_{0\text{-}90\ cm}$ was exceeded were four fields on which the default KNS value for fresh biomass was exceeded, four fields with a fresh biomass in between the average and the default KNS value and 13 fields with a fresh biomass lower than the average. The outlier at the left hand side is field 1 that was planted as latest, after the harvest of a cereal crop.

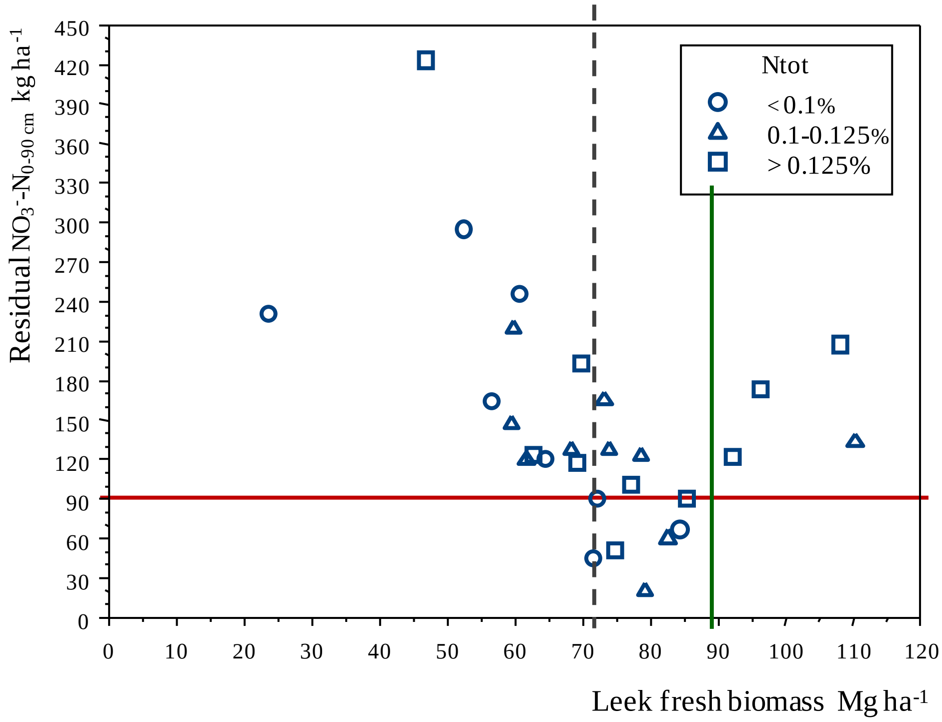

Figure 2.7 Relation between residual nitrate-N in the 0-90 cm soil profile and leek fresh biomass; individual fields classified for total nitrogen content in the 0-30 cm soil layer (Ntot); dashed vertical line in the graph at 72 Mg ha^{-1}: mean crop yield, full vertical line at 89 Mg ha^{-1}: crop yield presumed by KNS and horizontal line at 90 kg NO_3^--$N_{0\text{-}90\ cm}$ ha^{-1}: environmental threshold for residual nitrate-N in Flanders.

Table 2.6 Total nitrogen content in the 0-30 cm soil layer (Ntot), planting date class (e: early and l : late), base, top and total mineral N dressing, mineral N stock in the 0-60 cm soil profile ($Nmin_{0\text{-}60\ cm}$) at s2 and corresponding target values and N fertilizer recommendation according to the KNS-system (default values total N uptake and fresh biomass, 240 kg ha^{-1} and 89 Mg ha^{-1}, respectively), crop yield data (fresh biomass and total N uptake) and residual nitrate-N in the 0-90 cm soil profile (NO_3^--$N_{0\text{-}90\ cm}$ at s3); data of individual fields (n = 28, field numbers 1-31, fields 24, 27 and 29 were omitted as no leek crop was grown in 2009) plus means, standard deviations, coefficients of variation and quartile values.

FIELD				MINERAL N DRESSING			KNS-system				CROP		RESIDUAL
NUMBER	SOIL QUALITY GROUP	PLANTING DATE CLASS	TOTAL N CONTENT %	BASE kg ha^{-1}	TOP kg ha^{-1}	TOTAL kg ha^{-1}	Nmin 0-60 cm at s2 kg ha^{-1}	WEEKS planting - s2	TARGET VALUE	RECOMMENDATION	FRESH BIOMASS Mg ha^{-1}	N UPTAKE kg ha^{-1}	NO_3^--N 0-90 cm at s3 kg ha^{-1}
30	C	l	0.25	225	0	225	724	6	254	0	77	227	100
31	D	e	0.13	225	0	225	577	7	241	0	70	197	192
3	A	e	0.08	221	0	221	479	6	254	0	53	159	294
28	A	e	0.11	186	0	186	468	6	254	0	110	266	133
13	D	e	0.12	190	33	222	470	5	263	0	60	179	147
9	A	l	0.09	141	0	141	432	4	270	0	65	163	120
18	B	e	0.16	149	56	205	321	9	193	0	96	291	172
6	D	e	0.10	125	81	206	360	6	254	0	60	140	219
20	B	e	0.12	173	0	173	346	6	254	0	83	234	60
2	A	e	0.10	211	0	211	320	6	254	0	62	171	120
15	C	e	0.14	202	0	202	313	6	254	0	92	197	121
21	B	e	0.09	173	39	212	294	5	263	0	72	187	89
5	A	e	0.11	73	0	73	249	7	241	0	79	198	123
16	C	l	0.17	118	0	118	251	5	263	12	69	206	117
14	D	e	0.13	153	95	247	226	7	241	15	108	259	207
19	B	l	0.14	149	56	205	244	5	263	19	63	166	122
22	C	e	0.08	88	44	132	208	7	241	33	72	181	44
8	A	e	0.08	113	40	153	206	7	241	35	57	175	163
12	D	l	0.11	195	65	260	206	5	263	57	73	196	165
25	D	e	0.15	75	77	152	172	7	241	69	75	176	50
11	A	l	0.11	194	81	275	189	5	263	74	74	194	128
7	A	l	0.09	88	100	188	184	4	270	86	61	173	245
17	D	l	0.11	118	85	203	150	5	263	113	69	199	127
4	A	l	0.06	170	135	305	144	5	263	119	85	213	66
26	C	l	0.13	92	86	178	142	5	263	121	47	158	423
10	D	l	0.17	43	108	151	124	6	254	130	86	180	90
23	C	l	0.12	76	59	136	107	6	254	147	79	210	20
1	B	l	0.08	78	0	78	96	4	270	174	24	87	230
		MEAN	0.12	144	44	189	286		254	-32	72	192	146
		STDEV	0.04	54	42	54	152		15	155	18	40	84
		CV%	32	37	95	29	53		6	483	25	21	58
		MIN	0.06	43	0	73	96		193	-470	24	87	20
		1st QUART	0.09	91	0	152	181		251	-112	62	172	98
		MEDIAN	0.11	149	42	202	246		254	13	72	191	125
		3th QUART	0.13	191	81	221	350		263	77	80	207	177
		MAX	0.25	225	135	305	724		270	174	110	291	423

2.4 Discussion

2.4.1 Biomass yield and total N uptake as affected by water input, soil quality and N availability

Water input by rainfall and irrigation during the growing period clearly affected crop yield (Fig. 2.1, rel. 7)(Table 2.4). From the factors retained in the multivariate linear regression models, obtained by a stepwise linear regression technique, it was found that besides from water input or water supply, soil quality (parameterized by either TOC or Ntot, reflecting SOM) is important for crop yield (Fig. 2.1, rel. 4)(Table 2.4). From the three crop yield parameters, only total N uptake seemed to be related to mineral N input by fertilization and N supply (Fig. 2.1, rel. 5). No relationship between biomass production and N supply, a generally high residual NO_3^--$N_{0\text{-}90\ cm}$ and a negative correlation between fresh biomass and residual NO_3^--$N_{0\text{-}90\ cm}$ all indicate that N availability was a non-limiting factor for crop yield. At a higher SOM level, indicating a higher soil quality, crop yield was higher, resulting in a higher N utilization and lower residual NO_3^--$N_{0\text{-}90\ cm}$. A lower whole plant N content at a higher dry biomass ($R = -0.54$, $p < 0.01$) was indicative for a higher N use efficiency. These findings correspond with the outcome of a study of ten Berge et al. (2010) that assessed the importance of soil quality parameters in leek production relative to the importance of N applied as fertilizer. Soil properties (e.g., Ntot and SOM) promoted yield not only via a higher N supply, but also because better soil quality enhanced N use efficiency. Soils higher in SOM showed a higher yield level at a moderate residual NO_3^--$N_{0\text{-}90\ cm}$ (< 90 kg ha^{-1}) (Figure 2.7). On the other hand, a high residual NO_3^--$N_{0\text{-}90\ cm}$ at a relatively low yield level - coinciding with a low SOM content - indicated that a lower soil quality decreased N utilization and crop development. Top fresh biomass yields, higher than the KNS default value of 89 Mg ha^{-1} apparently coincided with excess residual NO_3^--$N_{0\text{-}90\ cm}$. Water $stock_{0\text{-}30\ cm}$ at s1 might serve as an indicator for water-holding capacity, as it was significantly positively correlated with organic matter and clay content (Fig. 2.1, rel. 1). The highly significant correlation between all crop yield parameters and water $stock_{0\text{-}30\ cm}$ at s1 might reflect the link between yield and soil organic matter content (Fig. 2.1, rel. 4). However, it might also prove the importance of a good water holding capacity (Fig. 2.1, rel. 7) particularly in a growing season with a dry summer period as was the case in this study. HWC was highly significantly positively correlated with Ntot and was closely related with crop productivity. Besides Ntot and TOC, HWC seemed to be an appropriate soil quality indicator, as proposed by Ghani et al. (2003) who found differences in HWC among different agricultural management practices. In contrast to individual soil quality parameters, soil quality classes (soil quality groups A-D in this research) established by a multi-parameter approach did not distinguish for N availability, biomass yield and total N uptake.

2.4.2 N availability in the soil profile as affected by soil quality and mineral N input by fertilization

In the first half of the growing season, soil quality (Fig 1, rel. 2) and mineral N input by fertilization (Fig 1, rel. 3) were clearly shown to affect soil mineral N stock. Ntot, as a proxy for SOM and strongly correlated with TOC, positively affected N availability in the soil profile at s1. Ntot also affected N availability in the soil profile at s2. Ntot can be considered as an indicator for the N mineralization potential in the first half of the growing season. N availability in the soil profile at s2 also reflected mineral N input by fertilization. Neither Ntot nor N supply items affected $Nmin_{0\text{-}90\ cm}$ and $NO_3^-\text{-}N_{0\text{-}90\ cm}$ at s3, however, both parameters affected total N uptake. N $recovery_{s2\text{-}s3}$ was not related to N $supply_{s2\text{-}s3}$. The absence of a relationship between N supply and N recovery for the N $balance_{s2\text{-}s3}$ and the N $balance_{s1\text{-}s3}$ can be attributed to an absence of a relationship between $Nmin_{0\text{-}90\ cm}$ stocks on the subsequent sampling occasions, either s1 or s2 versus s3, and an absence of impact of mineral N input by fertilization on the residual mineral N content. The dynamic and incidental nature of N turnover processes is responsible for the unpredictability of the level of the residual mineral N amount in the soil profile. The disappearance of a relationship between N supply and N recovery towards the end of the growing season obviously complicates the use of an Nmin-based recommendation system.

Base mineral N dressing affected $Nmin_{0\text{-}90\ cm}$ at s2 since the applied mineral N was only partially utilized by the crop at s2 (Fig 1, rel. 3). Base mineral N dressing also indirectly affected $Nmin_{0\text{-}90\ cm}$ at s2. The positive correlation between N $supply_{s1\text{-}s2}$ and $ANM_{s1\text{-}s2}$ ($R = 0.42$, $p < 0.05$) reflects a priming effect. N $supply_{s1\text{-}s2}$ consists of $Nmin_{0\text{-}90\ cm}$ at s1 and base mineral N dressing, but only the latter was significantly positively correlated with $ANM_{s1\text{-}s2}$ ($R = 0.48$, $p < 0.01$). High levels of base mineral N dressing thus positively affected the N mineralization rate and the resulting $Nmin_{0\text{-}90\ cm}$ at s2. Judging from a decrease in total soil N in two long-term experiments (>23 years) Raun et al. (1998) found evidence of priming (increased net N mineralization) at low annual rates of fertilizer N (45-90 kg ha^{-1}). Investigating another long-term fertility experiment (50 years), Mulvaney et al. (2009) reported a net loss of soil organic C and a corresponding decline in total soil N, which was more extensive at the highest rate of synthetic N fertilization compared to a medium rate or no fertilization.

2.4.3 Mineralization - immobilization pattern in relation to planting date

Late planting negatively affected yield, as it shortened the growing period (Fig 1., rel. 8) (Table 2.4). Besides this evident relationship, we found that planting date significantly affected soil N dynamics. Based on the partial balance results, a seasonal pattern for N dynamics appeared, with high apparent net N mineralization rates in the first half of the growing season and lower and even negative rates (i.e., apparent net N immobilization) in the second half of the growing season. Planting date affected this pattern. Early planting clearly coincided with a higher N availability in the soil profile at s2 (GLM 1) as it apparently favored net N release from SOM in the first half of the growing season (GLM 3). For early planted fields, high apparent net N mineralization rates in the first half of the growing season were observed to coincide with high apparent net N immobilization rates in the second half of the growing season. The higher soil N turnover for early vs. late planted fields seemed to have been a pure effect of timing since it could not be attributed to higher base mineral N dressings (larger priming effect), Ntot or moisture contents (higher mineralization potential). No significant differences for these parameters were found between late and early planted fields (Welch Modified Two-Sample t-Test). Early planting is associated with early tillage, fertilization or both, which probably increases N release. Besides by the level of the N availability in the soil profile at s2, $ANM_{s2\text{-}s3}$ or the amount of N immobilized in the second half of the growing season was significantly positively related with the microbial biomass in the arable layer ($p < 0.05$; results not shown). Apparent net N mineralization in the first half of the growing season followed by apparent net N immobilization in the second half of the growing season was also perceived under broccoli and leek in a multiyear field experiment on soil management (Willekens et al., 2014b). This phenomenon can be only perceived by establishing partial balances. Feller et al. (2011) found near-zero or slightly negative ANM values in the whole growing period in case of vegetable crops with a relatively short growing period and a high N demand. Apparent net N immobilization may also represent N losses. However, leaching losses did probably not occur as no rainfall excess occurred in the second half of the growing season due to the very limited rainfall in August - September. Microbiota immobilize mineral N but the N uptake in the root system was also partly responsible for the immobilization effect, as the latter was only included for a small part in the balance. Hermanson et al. (2000) mentioned that in these cases where the roots are not measured, the total plant N (shoots + roots) is typically underestimated by 5-15%. Considering a 10% underestimation and thus including the N amount of the whole root system in the balance calculation, ANM values increased somewhat, but none of the fields with a negative $ANM_{s2\text{-}s3}$ reached a positive value after applying this correction (results not shown).

A large variation in N turnover was observed between fields, including extremely large net mineralization and immobilization rates (Table 2.3). Such large C and N turnover rates may occur in conditions where soils contain large labile C pools. The majority of the fields were situated in West Flanders, a vegetable cropping region where, in addition to the restitution of easily decomposable crop residues, large amounts of animal slurry have been applied for decades. A high N turnover means a high microbial respiration activity and consequently high organic C losses. Using ^{14}C, ^{13}C and compound-specific analyses of soil carbon from long-term N fertilization plots, Neff et al. (2002) found that N additions significantly accelerate decomposition of light soil C fractions (with decadal turnover times).

2.4.4 Accuracy of Nmin-based fertilizer recommendation systems

High $Nmin_{0\text{-}60\ cm}$ values at s2, higher than the KNS target values for N supply, were primarily caused by the high net N mineralization rates on early planted fields. Early planted fields with $Nmin_{0\text{-}60\ cm}$ values at s2 lower than the KNS target values for N supply (8, 14, 22 & 25) received lower base mineral N dressings (< 160 kg ha^{-1}), thus reducing the possible priming effect.

Calculated KNS recommendations for top mineral N dressing doses were evaluated for 15 fields of which $Nmin_{0\text{-}60\ cm}$ at s2 was lower than the KNS target value for N supply. From this evaluation, we may assume that a KNS-recommended top mineral N dressing would have result in only 27% of the fields (4, 19, 22 & 25) in a residual NO_3^--$N_{0\text{-}90\ cm}$ content below the threshold.

A substantially lower yield level (< 80 Mg ha^{-1}) than the default KNS value occurred on 75% of the fields, which was clearly not related to a shortage of soil mineral N. A lower general soil quality and possibly a lower plant available water content at a lower SOM content, might have limited N utilization and consequently crop yield, resulting in an exceedance of the environmental threshold for residual NO_3^--$N_{0\text{-}90\ cm}$. On the other hand, at yield levels above the default KNS value, the threshold was exceeded as well. Assessment of the soil quality and related yield potential seems to be an important issue for N fertilizer recommendation. Field-specific and planting time related estimations of both yield levels and N mineralization rates should be implemented in any recommendation system. The N-Expert system (software version of the the KNS system) allows for adapting yield level and N mineralization rate.

2.5 Conclusions

Besides mineral fertilizer N, also native SOM mineralization was a decisive source of soil mineral N during the first half of the growing season. N availability in the first half of the growing season affected total N uptake, however, affected neither residual mineral N nor crop yield. N availability was a non-limiting factor for crop yield. Besides water supply, soil quality as reflected by SOM content positively affected crop growth in the second half of the season, resulting in a higher utilization of plant available N and a lower residual mineral N amount in the soil profile. Planting date - and thus probably the timing of fertilization and soil tillage - was a decisive factor for the mineralization-immobilization pattern during the growing season. Apparently, higher net N mineralization rates occurred in case of early planting. Excessive mineral N dressing at the start of the growing season caused extra N mineralization from SOM, i.e., a priming effect. Both phenomena require mitigation of the base mineral N dressing in order to prevent excess N availability. The multi-parameter approach for assessment of soil quality using basic soil characteristics did not distinguish for N dynamics in the studied fields. An Nmin-based fertilizer recommendation system should take into account crop biomass yield potential and count with variable daily net N mineralization rates.

Chapter 3

Factors affecting residual soil mineral nitrogen in intensively managed vegetable-arable rotations

After: Willekens, K., Vandecasteele, B., De Neve, S. (in preparation for submission to *Horticultural Science*). Factors affecting residual soil mineral nitrogen in intensively managed vegetable-arable rotations

3.1 Introduction

Excess residual mineral N in the soil profile at the end of the growing season in autumn poses a serious nitrate leaching risk. The European Nitrates Directive (91/676/EEC) aims at reducing environmental impacts of fertilizer and manure application and at increasing N use efficiency (van Grinsven et al., 2012). Member states had to set up compulsory action programs for reducing N losses from agricultural soils. In Flanders, successive Manure Action Plans have imposed crop and soil type dependent N fertilization limits in order to balance fertilizer N application and crop N requirement. The legislator largely relies on these fertilization limits to comply with the threshold for nitrate N residue of 90 kg ha^{-1} in the 0-90 cm soil profile in the period between October 1st and November 15th. Based on a large dataset of fertilizer experiments, D'Haene et al. (2014) looked for the tipping points in the relation between N fertilization rate and residual soil mineral N for grassland and the arable crops maize, potatoes, sugar beets and winter wheat, investigating the effectiveness of the current maximum allowed effective N fertilizer application rates in Flanders in terms of reducing residual soil mineral N. Miransari and Mackenzie (2012) established a model relating corn grain and stover yield to residual soil mineral N in order to optimize corn production and minimize environmental impact by applying appropriate rates of N fertilization. Fink (2001) estimated the required residual soil mineral N for the vegetable kohlrabi (*Brassica oleracea var. gongylodes*) using the breakpoint of a linear response and plateau regression model. However, besides N fertilization level, farmers and extension workers have to take into account other factors to minimize residual soil mineral N. Crop choice and related N fertilization level will affect soil N availability during the growing season, crop N uptake and residual soil mineral N. Soil N availability, inclusive of residual soil mineral N, will also be related to soil quality status, particularly to soil organic matter quantity and quality as affected by cultivation, rotation and fertilization in the past. In two multiyear experiments (1983-2009), both retainment of cereals' straw on the field and application of N fertilizer increased total and light fraction organic C and N content, which was more pronounced for N fertilization than for straw management (Malhi et al., 2011b). Application of N fertilizer also increased residual nitrate N and showed downward leaching of nitrate N in the soil profile (Malhi et al., 2011a).

During a three-year field survey we intended to assess the effect of crop related and soil quality defining factors on residual mineral N in the 0-30 cm arable layer (residual $Nmin_{0\text{-}30\ cm}$) and residual nitrate N in the 0-90 cm soil profile (nitrate N residue). The question was how much of the variance in residual soil mineral N can be explained by the investigated factors. Crop related factors were crop type and mineral N fertilization level. Soil quality defining factors were commonly used soil quality characteristics (Ntot, reflecting SOM status, soil acidity and texture) and short-term N availability indicators. A soil quality classification based on a set of 8 soil characteristics was tested as well for its effect on residual soil mineral N. We hypothesized that fields with a high SOM content bear a risk for excess residual soil mineral N. We also hypothesized that recurrent application of agronomic practices affecting SOM status by organic matter input alter N availability and consequently residual soil mineral N. Besides by application of animal manure (slurry and FYM) and compost, organic matter input is related to crop rotation, e.g., the use of cover crops and inclusion of cereals in the rotation. We looked at the factor crop type in connection with N fertilization level and assessed the effect of growing season on residual soil mineral N.

3.2 Materials and Methods

3.2.1 Site selection and soil sampling

This survey was carried out on 31 horticultural fields in Flanders (northern Belgium) mainly located in the provinces of West Flanders and East Flanders. It concerned the 28 horticultural fields of the survey in 2009 (Chapter 2) on which leek (*Allium porrum*) was grown in that year plus an additional three horticultural fields, WRB classified as Planosols (2) and Arenosol (1) (Dondeyne et al., 2014; IUSS Working Group WRB, 2015) (Figure 2.2). Most soils were relatively light textured (% clay < 20% and % silt < 60%) which is typical for vegetable production regions in Flanders. A representative subpart of each field (an area of approximately 50 x 50 m^2) was selected for soil sampling. The 0-30 cm arable layer was sampled before fertilization and tillage in spring 2009 for determination of soil quality related characteristics: total organic carbon content (TOC), microbial biomass C (Cmic), total nitrogen content (Ntot), pH-KCl, exchangeable calcium and magnesium contents, plant available Mn content (Mn_{sol}), exchangeable Fe content (Fe_{exch}) and the sand, silt and clay fractions. Soil of the 0-30, 30-60 and 60-90 cm soil layers was sampled in the period between October 1st and November 15th in three consecutive years (2009-2011) and analyzed for mineral N content. Each sample comprised the aggregate of 12 auger samples taken according to a grid (e.g., four borings along three lines). Residual $Nmin_{0\text{-}30\ cm}$ and nitrate N residue were calculated using measured dry bulk density of the 0-30 and 30-60 cm soil layers ($BD_{0\text{-}30\ cm}$ and $BD_{30\text{-}60\ cm}$) determined in the growing season 2009, whereas $BD_{60\text{-}90\ cm}$ was assumed to be equal to $BD_{30\text{-}60\ cm}$.

3.2.2 Factors potentially affecting residual soil mineral N

The data analysis pertained to 31 horticultural fields and two growing seasons (2010 and 2011), resulting in 62 observations. Residual soil mineral N was supposed to be affected by a range of crop related and soil quality defining factors and by soil condition due to weather conditions towards the end of the growing season (Figure 3.1).

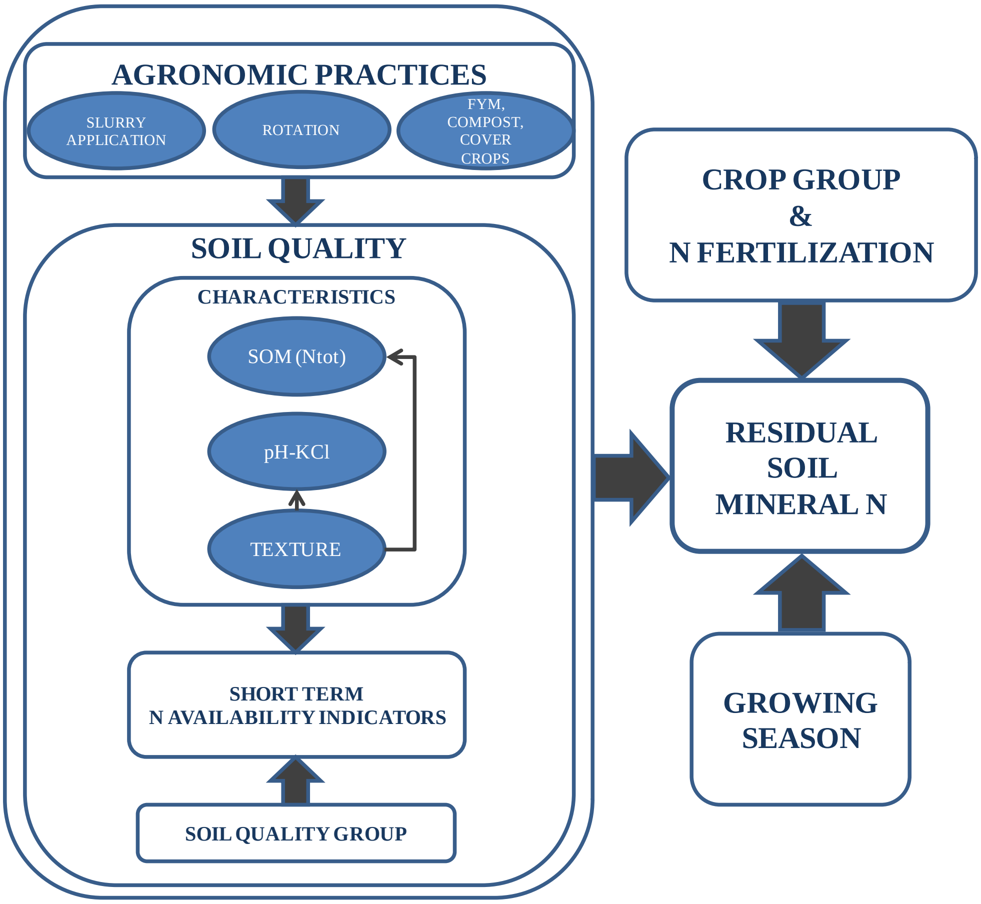

Figure 3.1 Crop related and soil quality defining factors, agronomic practices and growing season, hypothetically affecting residual soil mineral N, and presumed relationships between soil quality defining factors. Soil quality groups were established using eight soil characteristics.

Two crop related factors were assessed, crop group and N fertilization. Three crop groups were distinguished, i.e., vegetables (n = 29 fields, 2010: 15, 2011: 14), potatoes (n = 17, 2010: 7, 2011: 10) and cereals (n = 16, 2010: 9, 2011: 7). Cereal crops were predominantly maize, except two fields with wheat in 2011. Vegetable crops were predominantly leek (*Allium porrum*) and cabbages (e.g., headed cabbages) that clearly differ from maize and potatoes with regard to sowing or planting time (Figure 3.2). Both mineral and total N input by fertilization were considered, distinguishing three classes for mineral N input (fertNmin < 150 kg N ha^{-1} (n = 18), 150-200 kg N ha^{-1} (n = 21) and > 200 kg N ha^{-1} (n = 23)) and three classes for total N input (fertNtot < 220 kg N ha^{-1} (n = 21), 220-280 kg N ha^{-1} (n = 19) and > 280 kg N ha^{-1} (n = 22)). Most fields received a combination of animal manure and mineral N fertilizers and some crops received only mineral N fertilizers. The mineral N input from animal manure was calculated using default total N concentrations from the Flemish Land Agency (Anonymous, 2008) and 'mineral N / total N' ratios from the Nutrient Management Institute (Anonymous, 2000).

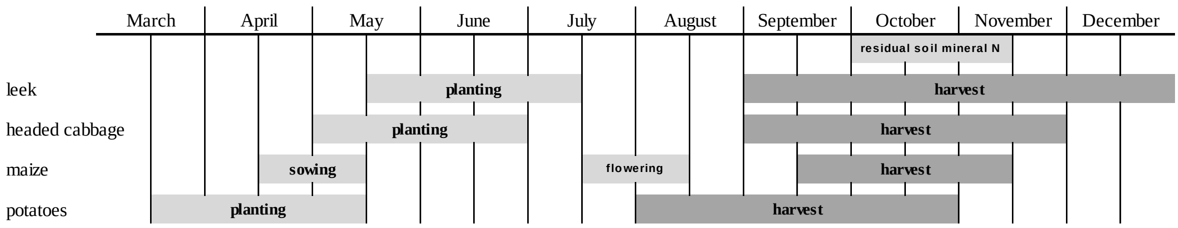

Figure 3.2 Planting and harvest period for the main crops, flowering period of maize and period in which residual soil mineral N was assessed.

Different types of soil quality defining factors were assessed for their effect on residual soil mineral N, being (i) soil quality characteristics, (ii) indicators for short term N availability derived from an aerobic incubation experiment, (iii) soil quality reflecting field group (soil quality group). Three soil quality characteristics were considered, i.e., (i) total N content (Ntot) reflecting soil organic matter (SOM) content, (ii) pH-KCl (soil acidity) and (iii) particle size distribution (soil texture). Three Ntot classes were distinguished (Ntot < 0.1 % (n = 9), 0.1-0.125 % (n = 11) and > 0.125 % (n = 11)) and three pH-KCl classes (pH-KCl < 5.6 (n = 12), 5.6-6.5 (n = 10) and > 6.5 (n =9)). Fields were classified for soil texture according to the Belgian texture triangle. Light textured soils, i.e., sand (S) and loamy sand (LS) were combined as S-LS (n = 14) whereas heavier textured soils, i.e., light sandy loam (lSL) and sandy loam (SL) were combined as lSL-SL (n = 17). Three indicators for short term N availability were derived from an aerobic incubation experiment (section 3.2.4),

(i) net N release from SOM (Nrel < 4.75 mg N kg^{-1} dry soil (n = 9) 4.75-6.25 (n = 12) > 6.25 (n = 10)), (ii) fertilizer N recovery (Nrec < 29.5 mg N kg^{-1} dry soil (n = 10) 29.5-32.5 (n = 11) > 32.5 (n = 10)) and (iii) the sum of both reflecting gross N availability after fertilizer N input (Ngav < 35 mg N kg^{-1} dry soil (n = 10) 35-38.5 (n = 11) > 38.5 (n = 10)). Four soil quality groups (A (n = 10), B (n = 5), C (n = 6) and D (n = 10)) were established based on the measurements of eight soil characteristics, i.e., TOC, Cmic, pH-KCl, calcium to magnesium ratio (Ca:Mg), Mn_{sol}, Fe_{exch}, % sand and % clay.

Also agronomic practices that potentially influence soil quality were assessed for their effect on residual soil mineral N. Following agronomic practices were considered (i) regular use of FYM, compost and cover crops (yes (n = 19) and no (n = 12)), (ii) frequent slurry application on farms with livestock (cattle and/or pigs) (yes (n = 18) and no (n = 13)) and (iii) rotation type. These parameters also distinguished for historical N input. The presence or absence of livestock on a farm was assumed to reflect the frequency of slurry application in the past on fields belonging to that farm. Based on the crops occurring in the 2006-2011 period, four different crop rotation types were distinguished: (i) rotations with only vegetables (n = 8), (ii) rotations with just vegetables and potatoes (n = 7) (iii) rotations containing vegetables, potatoes and cereal crops (n = 9) and (iv) rotations with an alternation of vegetables and cereals (n = 7).

Growing season, either 2010 (n = 31) or 2011 (n = 31) was also considered as a factor affecting residual soil mineral N. Besides that, the sensitivity of a field to exceed the nitrate N residue threshold - irrespective of growing season - was assessed by searching for a relation between the nitrate N residues of different growing seasons. Therefore, nitrate N residues of 2010 and 2011 were compared with the averaged nitrate N residues of both other growing seasons, 2009 and 2011, and 2009 and 2010, respectively.

3.2.3 Assessment of N fertilizer rates and nitrate N residues

The legislator in Flanders relies on crop and soil texture dependent N fertilization limits to comply with the nitrate N residue threshold of 90 kg ha^{-1} in the 0-90 cm soil profile. Permitted N fertilizer rates are either prescribed as total N or as fertilizer equivalent (FE) N amounts. The latter are shown in Table 3.1. Both systems include the animal manure limit of 170 kg N ha^{-1} $year^{-1}$. For vegetables, permitted N fertilizer rates were established according to crop N requirement. Three vegetable groups (I, II and III) were distinguished reflecting respectively a high, medium and low requirement (MAP IV; Anonymous, 2011).

Table 3.1 Maximum allowed fertilizer equivalent (FE) N application rate (kg (ha y)$^{-1}$) for the different crops and crop groups in the survey (Anonymous, 2011).

		Soil texture	Maximum allowed FE N	Maximum total N from animal manure
Vegetables	Group I	Sandy	225	170
		Non sandy	250	170
	Group II	Sandy	160	170
		Non sandy	180	170
	Group III	Sandy	115	170
		Non sandy	125	170
Potatoes		Sandy	190	170
		Non sandy	210	170
Maize		Sandy	135	170
		Non sandy	150	170
Winter wheat		Sandy	160	100
		Non sandy	175	100

Ninety % of the vegetables in the survey period 2010-2011 had a high or a medium N requirement (Group I, n = 21 and Group II, n = 5, respectively) and only 10% a low one (Group III, n = 3). Besides by fertNmin and fertNtot, the N fertilization level was quantified by FE N amount according to default N working coefficients of the different fertilizers (MAP IV), e.g., 60% of total N for slurry and 30% of total N for FYM. For each field in a particular growing season, the applied FE N amount was compared with the FE N limit and the nitrate N residue measurement with the nitrate N residue threshold. For the different crop groups and for both growing seasons, the degree of surpassing the FE N limit and the nitrate N residue threshold was expressed as the ratio 'applied FE N / FE N limit' and the ratio 'nitrate N residue / nitrate N residue threshold', respectively. These average ratios were calculated considering (i) all fields of a particular crop group or growing season and (ii) the fields of the respective crop group or growing season for which the limit or threshold was surpassed.

3.2.4 Soil analyses and incubation experiment

All soil analyses are fully described in Chapter 2, excepted the Cmic analysis. Cmic was determined by fumigation-extraction according to Voroney et al. (2008). The samples were fumigated for 24h followed by an extraction with 0.5 M K_2SO_4 (soil-to-extractant ratio of 1:2). The TOC in the extracts was determined by dry combustion at 1050 °C with a Skalar

Primacs SLC TOC-analyzer. A conversion factor k(EC) of 0.45 was used (Joergensen, 1996).

In a short-term aerobic incubation experiment, soils were incubated in PVC-tubes (Ø 4.63 cm, filling height 12 cm and bulk density 1.4 g cm^{-3}) in duplicate. NH_4NO_3 (p.a., 35% N) was first dissolved in water and added at a rate of 35.8 mg N kg^{-1} dry soil, equivalent to a dose of 60 kg N ha^{-1} (based on the ratio of the soil surface of a tube to 1 ha). Before filling the tubes, demineralized water was added together with the fertilizer solution to obtain a gravimetric moisture content of 16.8% (w/w) equivalent to 50% water-filled pore space. A blank treatment was included to determine N release from SOM during the incubation period. After thorough mixing, the tubes were filled and covered with a single layer of gas-permeable Parafilm® M Barrier Film (Pechiney Plastic Packaging) to minimize water loss. After 3 weeks incubation at 15°C and 70% relative humidity, entire tubes were destructively sampled and analyzed for mineral N content.

3.2.5 Data analysis

For each soil quality characteristic, we checked normality of the data using the Kolmogorov-Smirnov test. Ca:Mg data were subjected to a square root and Mn_{sol} to a logarithmic transformation in order to obtain normality. A principal component analysis (PCA) was performed with the soil characteristics TOC, Cmic, pH-KCl, Ca:Mg, Mn_{sol}, Fe_{exch}, % sand and % clay measured in the 0-30 cm layer. The biplot of the first two principle components was used to classify the fields in four different soil quality reflecting groups (A-D). This classification was tested for its discriminative value with the canonical discriminant analysis (Fisher Method).

Investigating factors affecting residual soil mineral N, the independent variables were categorized in classes. These classifications were used applying ANOVA. Residual $Nmin_{0\text{-}30\ cm}$ and nitrate N residue were either square root or logarithmically transformed in order to obtain models with normally distributed residues, checked by the Kolmogorov-Smirnov test. We started with performing two-way ANOVA with on one hand a crop related factor, either crop group or N fertilization, and on the other hand a soil quality defining factor, either the soil quality characteristic Ntot or soil quality group. In a model with significant effects of both factors, other factors were added one by one (3-way ANOVA). In two-way ANOVA models with only one significant factor, the non-significant one was omitted before adding other factors. Interrelated crop related or soil quality defining or affecting factors were not combined in the models. Relations between crop related or soil quality defining or affecting factors were assessed either by ANOVAs or by Pearson correlation coefficients. For factors combined in ANOVAs, we looked for possible interactions with regard to their effect on residual soil mineral N. Multiple comparison of the means was done by the Scheffé method. One-to-one relationships were assessed by Pearson correlation coefficients and p-values. ANOVAs were limited up to three factors.

3.3 Results

3.3.1 Grouping of fields reflecting differences in soil quality

Four soil quality groups were distinguished in the PCA biplot of the first two principal components (Figure 3.3) which accounted for 71.0 % of the total variance. The canonical discriminant analysis showed that the first two of in total three discriminant functions accounted for 98.6 % of the total variance and significantly contributed to the discrimination of the groups (significantly different means, Wilks Lambda, α = 5%). Variance-covariance matrices were equal for the different groups (implicit assumption; Box M test, α = 5%) and cross-validation showed an overall error of only 3.2%.

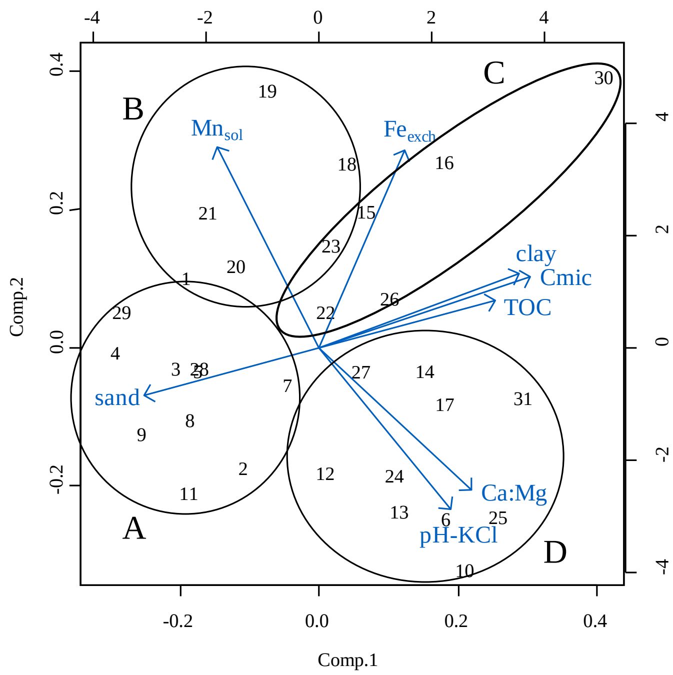

Figure 3.3 PCA biplot with eight soil parameters for 31 fields (numbers inside the graph identify the fields) with identification of soil quality groups A, B, C and D.

Average values of the soil parameters per soil quality group (A-D) are presented in table 3.2. Soils of group A were the most sandy and had the lowest Cmic values. Soils of group B were less aerated than those of group A, as indicated by significantly higher mean Fe_{exch} and Mn_{sol} values for group B. At a normal pH level (pH-KCl > 5.2), a high Mn_{sol} indicates a disturbed oxygen supply, with higher pore water concentrations for Mn in anaerobic conditions (Du Laing et al., 2007). Poor drainage may result in a higher Fe_{exch} content as well due to higher pore water concentrations (Du Laing et al., 2007). However, a higher Fe_{exch} content coincides with a higher clay content. Soils of group C and D had a significantly lower average sand and a significantly higher average clay and Cmic content than soils of group A. With regard to soil texture, group B had an intermediate position with a significantly higher sand content than group C. Group D had significantly higher pH-KCl and Ca:Mg values compared to all other groups.

Table 3.2 Average values of the soil parameters for soil quality groups (SQGs) A-D (significant differences between SQGs are indicated with different lowercase letters; ANOVA, Scheffe, $p < 0.05$) (TOC: total organic carbon, Cmic: microbial biomass carbon, Ntot: total nitrogen content).

SQG	n	TOC	Cmic	pH-KCl	Ca:Mg	Mnsol	Feexch	sand	clay	Ntot
		% w/w	mg kg^{-1} dry soil			mg kg^{-1} dry soil	mg kg^{-1} dry soil	% w/w	% w/w	% w/w
A	10	0.95 ^{a}	39 ^{a}	5.6 ^{a}	4.4 ^{a}	4.0 ^{ab}	790 ^{a}	76.7 ^{c}	4.8 ^{a}	0.09 ^{a}
B	5	1.31 ^{a}	54 ^{ab}	5.4 ^{a}	3.4 ^{a}	15.0 ^{c}	1238 ^{bc}	69.8 ^{bc}	7.8 ^{ab}	0.12 ^{ab}
C	6	1.55 ^{a}	84 ^{b}	5.9 ^{a}	5.1 ^{a}	7.5 ^{b}	1283 ^{c}	49.6 ^{a}	10.5 ^{b}	0.15 ^{b}
D	10	1.43 ^{a}	69 ^{b}	6.8 ^{b}	8.5 ^{b}	1.1 ^{a}	922 ^{ab}	59.1 ^{ab}	9.9 ^{b}	0.13 ^{ab}

3.3.2 Global assessment of N fertilizer rates and nitrate N residues on crop groups' level and per growing season

Considering growing seasons 2010 and 2011, fertNmin, FE N input and nitrate N residue significantly differed between crop groups (one-way ANOVA, $p < 0.05$, $p < 0.05$ and $p < 0.01$, respectively) with a higher input for vegetables than for cereals (Scheffe $p < 0.05$) and a lower nitrate N residue for cereals compared to potatoes and vegetables (Scheffe $p < 0.05$) (Figure 3.4). FertNtot and residual $Nmin_{0\text{-}30\ cm}$ did not differ between crop groups.

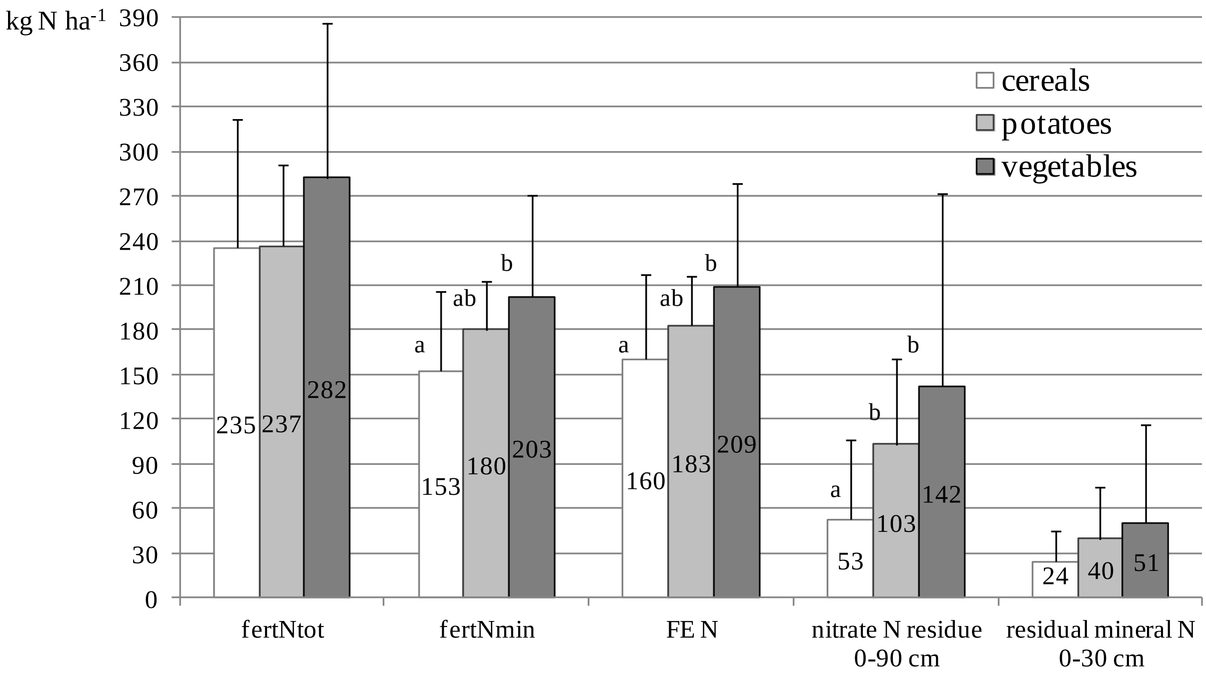

Figure 3.4 Total N, mineral N and fertilizer equivalent N input (fertNtot, fertNmin and FE N, respectively, nitrate N residue (0-90 cm) and residual mineral N in the arable layer (0-30 cm) averages per crop group considering growing seasons 2010 and 2011; significant differences between crop groups are indicated by different lowercase letters.

Ranking of crop groups for mineral and FE N input by fertilization clearly corresponded to ranking for nitrate N residue and residual $Nmin_{0\text{-}30\ cm}$. For each crop group, over growing seasons 2010 and 2011, the applied FE N nearly amounted the FE N limit, i.e., plus 7 % for cereals and minus 5 % for potatoes and minus 1 % for vegetables, whereas the nitrate N residue under cereals was 42% lower than the threshold, and the nitrate N residue under potatoes and vegetables was 14% and 58% higher than the threshold (Table 3.3). For growing seasons 2010 and 2011, on average over all crop groups, the applied FE N nearly amounted the FE N limit, i.e., plus 7 % in 2010 and minus 8 % in 2011. The average nitrate N residue of 2011 clearly surpassed the nitrate N residue threshold (+30%). On average over both growing seasons and all crop groups, applied FE N equalized the FE N limit whereas nitrate N residue surpassed the nitrate N residue threshold (+20%), and the percentage of fields surpassing the nitrate N residue threshold (42%) corresponded to the percentage surpassing the FE N limit (40%). In 2009, the growing season with only vegetables and mainly leek, the FE N limit was surpassed on one quarter of the fields whereas the nitrate N residue surpassed the threshold on three quarters of the fields.

Table 3.3 Degree of surpassing the FE N limit and the nitrate N residue threshold expressed as the ratio ‘applied FE N / FE N limit’ and the ratio ‘nitrate N residue / nitrate N residue threshold’ for the different crop groups and both growing seasons, an average for (i) all fields of a particular crop group or growing season and (ii) the fields of the respective crop group or growing season for which the limit or threshold was surpassed.

		# fields	applied FE N / FE N limit	# fields > limit	% fields > limit	applied FE N / FE N limit fields, '> limit'	nitrate N residue / nitrate N residue threshold	# fields > threshold	% fields > threshold	nitrate N residue / nitrate N residue threshold fields, '> threshold'
crop group - growing season	**veg 09**	31	0.84	8	26	1.14	1.65	24	77	1.94
	veg 10	15	1.03	6	40	1.43	1.54	8	53	2.52
	veg 11	14	0.95	3	21	1.42	1.62	8	57	2.48
	veg 10-11	29	0.99	9	31	1.42	1.58	16	55	2.50
	veg 09-11	60	0.91	17	28	1.29	1.62	40	67	2.17
	pot 10	7	1.08	5	71	1.14	1.06	3	43	1.37
	pot 11	10	0.86	1	10	1.12	1.20	4	40	2.09
	pot 10-11	17	0.95	6	35	1.14	1.14	7	41	1.78
	cer 10	9	1.14	7	78	1.20	0.41	1	11	1.27
	cer 11	7	0.97	3	43	1.47	0.80	2	29	1.90
	cer 10-11	16	1.07	10	63	1.28	0.58	3	19	1.69
growing season	**09**	31	0.84	8	26	1.14	1.65	24	77	1.94
	10	31	1.07	18	58	1.26	1.10	12	39	2.13
	11	31	0.92	7	23	1.40	1.30	14	45	2.29
	10-11	62	1.00	25	40	1.30	1.20	26	42	2.21
	09-11	93	0.95	33	35	1.26	1.35	50	54	2.08

3.3.3 Relationships between soil quality defining and affecting factors

Soil quality indicators reflecting short-term N availability did not differ between Ntot classes. Neither these N availability parameters nor Ntot differed between pH-KCl classes. However, pH-KCl was significantly lower for the low Ntot class compared to the medium Ntot class (one-way ANOVA, $p < 0.01$; Scheffé, $p < 0.01$). Ntot did not differ between textural classes despite a significant negative correlation between Ntot and % sand ($R = -0.44$, $p < 0.05$) and a significant positive correlation between Ntot and % clay ($R = 0.61$, $p < 0.001$). Both Nrec and Ngav were significantly higher (+7.5% and + 7.7% resp.) for the light textured soils (S-LS) compared to the heavier textured ones (lSL-SL) (one-way ANOVA, $p < 0.01$). pH-KCl significantly differed between textural classes (pH-KCl 5.7 and 6.3 for S-LS and lSL-SL, respectively, one-way ANOVA, $p < 0.001$). The presumed frequent use of slurry on fields of farms with livestock seemed to have negatively affected pH-KCl (ANOVA $p < 0.01$) with pH-KCl values of 5.7 and 6.4 on fields of farms with and without livestock, respectively. By contrast, regular use of FYM, compost and cover crops seemed to have positively affected pH-KCl (pH-KCl 6.2 for regular use and pH-KCl 5.7 for no use, ANOVA $p < 0.05$). Agronomic practices did not affect Ntot, however, an effect on N availability indicators was perceived. Nrel increased by the presumed frequent use of slurry on fields of farms with livestock (+19%) and tended to be higher for soil quality group A compared to soil quality group B (two-way ANOVA $p < 0.01$ and $p < 0.05$, respectively). Fields with vegetables and cereals in the rotation showed lower Nrec values (-15%) compared to fields with vegetables and potatoes (one-way ANOVA $p < 0.05$) and lower Ngav values (-15%) compared to fields with only vegetables in the rotation (one-way ANOVA $p < 0.05$). By a two-way ANOVA, it was found that Ngav was significantly higher (+15%) for soil quality group A compared to soil quality group C ($p < 0.05$) and significantly lower for fields with vegetables and cereals in the rotation compared to all other rotation classes ($p < 0.001$).

3.3.4 Residual $Nmin_{0\text{-}30\ cm}$ and nitrate N residue as affected by crop related and soil quality defining and affecting factors and by growing season

No interactions occurred between factors included in ANOVAs (Table 3.4) by which effects of crop related and soil quality defining and affecting factors, and of growing season on residual soil mineral N were assessed. Crop group significantly affected nitrate N residue but not residual $Nmin_{0\text{-}30cm}$. Nitrate N residue was significantly lower (-63%) under cereals compared to vegetables (ANOVAs 6-8). Residual soil mineral N was significantly positively affected by fertNmin. Residual $Nmin_{0\text{-}30\ cm}$ was significantly higher for fertNmin > 200 kg ha^{-1}, compared to fertNmin 150-200 kg N ha^{-1} (ANOVAs 2 & 3) or compared to both other classes (ANOVAs 3 & 4). Nitrate N residue tended to be higher for fertNmin > 200 kg ha^{-1}, compared to fertNmin 150-200 kg N ha^{-1} (ANOVA 5). Residual soil mineral N was not affected by fertNtot. Both Ntot and soil quality group affected residual $Nmin_{0\text{-}30\ cm}$ (ANOVAs 1 & 2 and 3 & 4, resp.) but did not affect nitrate N residue. The medium Ntot class showed the lowest residual $Nmin_{0\text{-}30\ cm}$, significantly lower (-60%) than residual $Nmin_{0\text{-}30\ cm}$ pertaining to the high Ntot class. Residual $Nmin_{0\text{-}30\ cm}$ was significantly lower (-70%) for soil quality group A compared to soil quality group C. Residual soil mineral N was affected by Nrel. Soils with a medium Nrel had the lowest residual soil mineral N. Residual $Nmin_{0\text{-}30\ cm}$ for soils with a medium Nrel was significantly lower than residual $Nmin_{0\text{-}30\ cm}$ of both other Nrel classes (ANOVA 2) and nitrate N residue was lower (-46%) for the medium Nrel class compared to the high Nrel class (ANOVA 6). A significant effect from Nrec appeared on nitrate N residue with a (tendency for) a lower nitrate N residue (-56%) for the medium Nrec class compared to the high Nrec class (ANOVAs 5 & 7).

Light textured soils (S-LS) showed a significantly lower residual $Nmin_{0\text{-}30\ cm}$ (-43%) compared to heavier textured ones (lSL-SL). Light textured soils showed a significantly lower nitrate N residue than heavier textured ones (-21%).

On average, a significantly lower nitrate N residue was found on fields of farms without livestock (50 kg nitrate N ha^{-1} less or -39%), compared to fields of farms with livestock (ANOVA 8). Residual $Nmin_{0\text{-}30\ cm}$ was significantly lower (-43%) in case of regular use of FYM, compost and cover crops (ANOVA 4).

Residual $Nmin_{0\text{-}30\ cm}$ was significantly lower (-49%) in 2010 compared to 2011 (ANOVA 3).

A GLM for nitrate N residue that includes the factors ‘average N residue of both other growing seasons’ and crop group, showed significant effects of both factors ($p < 0.05$ and $p < 0.01$, respectively).

Table 3.4 Residual soil mineral N in the 0-30 cm arable layer (residual $Nmin_{0\text{-}30\ cm}$) and residual nitrate N content in the 0-90 cm soil profile (nitrate N residue) for the different levels of crop related and soil quality defining factors and for variants of agronomic practices and both growing seasons. Significant differences between factorial classes are indicated by levels of p-values (multi-way ANOVA (A) and Scheffé test (S); * significance level $p < 0.05$, ** significance level $p < 0.01$) and by different lower case letters; [(1)] fertNmin <150 lower case letter a; FYM: farmyard manure.

	class	n	residual $Nmin_{0\text{-}30\ cm}$	1 sqrt	2 log	3 [(1)] sqrt	4 [(1)] sqrt	nitrate N residue	5 sqrt	6 sqrt	7 sqrt	8 sqrt
crop group	cer	16	24.4					52.5 a		A**	A*	A**
	pot	17	39.8					102.9 ab		S**	S*	S**
	veg	29	50.6					142.1 b				
fertNmin	<150	18	31.1 ab	A**	A**	A*	A**	83.2 ab	A*			
kg ha^{-1}	150-200	21	25.7 a	S**	S*	S*	S*	84.4 a	S			
	>200	23	62.3 b					149.7 b	p<0.1			
Ntot	<0.100	18	28.8 ab	A*	A*			78.0				
%	0.100-0.125	22	26.0 a	S*	S*			95.8				
	>0.125	22	65.6 b					145.4				
Nrel	<4.75	18	42.9 b		A*			126.6 ab		A*		
mg kg^{-1}	4.75-6.25	24	24.0 a		S*			72.3 a		S*		
dry soil	>6.25	20	59.2 b					134.9 b				
Nrec	<29.5	20	44.6					110.8 ab	A*		A*	
mg kg^{-1}	29.5-32.5	22	27.8					66.6 a	S*		S	
dry soil	>32.5	20	51.4					151.5 b			p<0.1	
texture	S-LS	28	29.0 a	A*				94.7 a				A*
	lSL-SL	34	50.6 b					119.4 b				
soil quality group	A	20	17.7 a					79.7				
	B	10	58.7 ab			A**	A**	163.4				
	C	12	58.4 b			S*	S**	120.1				
	D	20	44.6 ab					102.0				
livestock	no	26	29.5					79.2 a				A**
	yes	36	49.0					129.2 b				
FYM, compost & cover crops	no	24	55.6 b				A*	121.6				
	yes	38	31.5 a					99.8				
growing season	2010	31	27.7 a			A*		99.2				
	2011	31	54.0 b					117.3				
R^2				30.6	33.4	35.4	36.3		21.0	27.0	21.8	34.2

3.4 Discussion

3.4.1 Residual soil mineral N as affected by crop group and fertNmin

The nitrate N residue was related to the crop group factor with a significantly lower nitrate N residue for cereals compared to vegetables and potatoes (Figure 3.4). In contrast, residual mineral Nmin in the 0-30 cm arable layer did not significantly differ between crop groups nevertheless residual $Nmin_{0\text{-}30\ cm}$ under vegetables was on average twice that high than residual $Nmin_{0\text{-}30\ cm}$ under cereals. Mineral and FE N input were clearly related to crop group as well, with a significantly lower mineral and FE N input for cereals compared to vegetables (Figure 3.4). Regarding the cereals' crop group, the lowest nitrate N residue level coincided with the lowest level of mineral and FE N input by fertilization. The highest nitrate N residues were measured for vegetables, receiving the highest mineral and FE N input by fertilization. However, the nitrate N residue level might not only reflect the fertilization level but also the utilization of the fertilizer N input. Crop type is assumed to be decisive regarding the period during which N uptake takes place and the extent and depth to which this happens due to differences in rooting characteristics of the crops. Depletion of mineral N through N uptake by maize and potatoes halts quite early in the growing season, respectively at flowering and ripening stage (Figure 3.2). By contrast, most of the vegetables in our survey (leek and cabbages) are harvested in their vegetative stage quite late in the growing season. Leek requires a considerable residual mineral N amount in the root zone to obtain the desired yield and product quality. Due to a moderate N uptake in the first half of the growing season, excess mineral N in the arable layer from fertilization or mineralization might move downward the soil profile becoming less accessible for the leek root system later in the growing season. In a study on the effects of deep and shallow root systems on N dynamics by Thorup-Kristensen (2006), the observed rooting depth for leek was only 0.5 m whereas white cabbage rooted till a depth of 2.0 m. Headed cabbages (e.g., white cabbage) have a high N requirement and utilize quite well the mineral N stock in the soil profile due to a deep root system and therefore residual soil mineral N levels after application of the recommended rates of N fertilizer are low to moderate (20-75 kg N ha^{-1}) (Neeteson et al., 1999). However, application of the recommended rates to other field vegetables may result in rather large amounts of residual soil mineral N, especially after crops that are harvested before maturing. Shortages are avoided by top mineral N dressing for these vegetable crops. Compared to both other crop groups, the nitrate N residue under vegetables was not only higher but also a larger share of it was found in the lower part of the soil profile (results not shown).

As residual $Nmin_{0\text{-}30\ cm}$ was not related to the crop group factor, it was apparently not affected by differences between crop groups with regard to depletion of arable layer mineral N. Residual $Nmin_{0\text{-}30\ cm}$ was related to both the fertNmin and a number of soil quality defining factors affecting N availability in the arable layer (Table 3.4). A significant effect of the level of fertNmin on nitrate N residue was found as well, however, multiple comparison of the means did not show significant differences between the classes for fertNmin. A high level of fertNmin resulted in excess residual soil mineral N, but no difference in residual soil mineral N appeared between the low and medium level of fertNmin. In the range from low to optimum N fertilization rates, most crops show a rather constant residual soil mineral N at harvest (D'Haene et al., 2014). At rates above this optimum a steep increase in residual soil mineral N appears. In annual trials with increasing rates of fertilizer N, Linden et al. (2002) perceived that residual soil mineral N within 0-100 cm depth at the end of the N uptake period was only 5 kg N ha^{-1} larger after N fertilization at economically optimum rates than without N fertilization.

3.4.2 Nitrate N residue versus fertilization limits

For all crop groups, FE N input was fairly in accordance with the N fertilization limits. Nevertheless, nitrate N residue exceeded the threshold of 90 kg NO_3^--N ha^{-1} to a moderate extent for potatoes and to a large extent for vegetables, whereas it lied far below that threshold for the cereals' crop group (predominantly maize). The latter indicated that the average N fertilization rate for maize was quite optimal guaranteeing a good utilization of fertilizer N. The maximum allowed FE N input for silage maize in Flanders, i.e., 135 kg N ha^{-1} and 150 kg N ha^{-1} for sandy and non sandy soils, respectively (Table 3.1), corresponded with a nitrate N residue of about 55 to 61 kg N ha^{-1} according to an exponential regression of nitrate N residue in function of FE N input that was calculated by D'Haene et al. (2014) based on a large dataset from N fertilizer experiments. The cereals' crop group in our field survey showed an average nitrate N residue of 53 kg ha^{-1} at an average FE N input that slightly exceeded the FE N limit, which corresponded fairly well with the above-mentioned outcome of the more theoretical study by D'Haene et al. (2014). A segmented linear regression of the nitrate N residue (0-60 cm in that study) in function of FE N input in potatoes, calculated by D'Haene et al. (2014), showed a breakpoint at 199 kg ha^{-1} FE

N input, a value just in between the FE N limit for sandy (190 kg N ha^{-1}) and non sandy soils (210 kg N ha^{-1}). The nitrate N residue in the 0–60 cm layer at the breakpoint was about 70 kg N ha^{-1}. In our field survey the potatoes' crop group showed on average a 14% exceedance of the nitrate N residue (0-90 cm) at a FE N input that was 5% lower than the FE N limit indicating a risk of surpassing the nitrate N residue threshold while applying permitted FE N rates. For the vegetables' crop group the nitrate N residue threshold was largely surpassed at an average N fertilization level that corresponded with the FE N limit, which raises some questions about the N fertilization limits for vegetables. These limits are based on a presumed crop N uptake, necessary residual mineral N in the root zone (Hofman et al., 1981) and soil N supplying capacity. However, yield potential and related crop N uptake, and soil N supplying capacity depend on soil quality (Appel, 1994) and on weather circumstances affecting soil temperature and moisture content. Fertilization limits start from the assumption of an optimum crop performance at optimum soil conditions. Seeing the extent to which the threshold for nitrate N residue is surpassed at N fertilization levels that correspond with the limits, crop N uptake might be overestimated or soil N supplying capacity underestimated, or both. Another reason for surpassing the nitrate N residue threshold might be that the buffer included in the fertilization limits (to cope with exceptional losses guaranteeing sufficient crop yield level) is too high. A reason for an underestimation of soil N supplying capacity might be that additional N release from SOM by high mineral N dosage, i.e., a priming effect, is not accounted for. This positive priming effect was defined by Kuzyakov et al. (2000) as a strong short-term change in the turnover of SOM caused by a comparatively moderate treatment of the soil. Improving N availability under C-rich conditions allows increased microbial activity and growth (Wang and Bakken, 1997). This may again enhance predation, nutrient immobilization in microbial biomass, and co-metabolic decomposition of SOM. In the cropping systems in our survey, readily available C sources may originate from regular slurry application. In order to restrict residual soil mineral N from an environmental point of view, N fertilization should be tuned to a realistic crop N uptake and corresponding necessary level of residual mineral N in the root zone. N fertilization advice should also consider a realistic soil N supplying capacity. On the other hand, as illustrated above, crop type related development and N uptake curve and thereto related fertilization practices enhance the risk to surpass the nitrate N residue threshold in case of certain vegetables.

3.4.3 Residual soil mineral N as affected by soil quality and soil quality affecting agronomic practices

Average residual $Nmin_{0-30\ cm}$ values of both lower level Ntot classes and both lower level fertNmin classes were of the same order of magnitude, however, only residual $Nmin_{0-30\ cm}$ of both medium classes was significantly lower (ca -60%) than the residual $Nmin_{0-30\ cm}$ of the respective high classes. Excess $Nmin_{0-30\ cm}$ appeared both at a high fertNmin level and a high Ntot level and both factors acted additively as no interaction appeared for their effect on residual soil mineral N. Ntot might roughly indicate the potential N mineralization or soil N supplying capacity, however, Ntot was not related to the short-term net N release in the incubation experiment. It is more common to relate N mineralization to specific organic matter pools than to the overall organic matter content (Kader et al., 2010). Ntot did not significantly affect nitrate N residue, however, residual $Nmin_{0-30\ cm}$ was significantly higher for the high Ntot class (> 0.125 %) compared to the medium class (0.100-0.125 %) and consequently the risk of surpassing the nitrate N residue threshold increases at a high Ntot arable layer content. The short-term N availability indicators were related with residual soil mineral N. The highest level of N availability, either due to mineralization from SOM (Nrel) or with regard to the applied fertilizer N (Nrec) showed the highest level of residual soil mineral N, significantly higher compared to the medium level of N availability. In case of a low level of N availability due to mineralization of SOM, i.e., a presumed low soil fertility, an equally high residual $Nmin_{0-30\ cm}$ was found compared to the high level of N availability from SOM. A possible explanation might be that at a lower level of soil fertility the residual mineral N amount was higher due to a low N utilization by the main crop.

Regular soil quality improving practices as the use of FYM, compost and cover crops apparently reduced the risk of surpassing the nitrate N residue threshold as it was associated with a significantly lower residual $Nmin_{0-30\ cm}$. Fresh or composted organic matter supply probably favoured N immobilization by enhanced microbial activity due to the addition of C sources (Chaves et al., 2006; Yevdokimov et al., 2012). Input of organic matter with a high C/N ratio or stabilized C is a keystone for improving soil fertility but does not result necessarily in a higher level of residual soil mineral N.

The significantly higher nitrate N residues on fields of farms with livestock confirmed our assumption that a history of frequent application of relatively high doses of slurry result in a high N release from SOM. Yague and Quilez (2013) found that annual application of pig slurry to sprinkler-irrigated maize at agronomic rates can provide significant amounts of N to subsequent crops. It is important to consider residual N effects in fertilizer planning to avoid N losses from the system. Certain fields seemed to bear an inherent risk for high nitrate N residues, which was illustrated by (i) the relation between the nitrate N residue level on a field in a certain year (2010 or 2011) and the average level on that field with regard to both other years and (ii) the higher nitrate N residue level on fields of farms with livestock.

Soil pH and calcium carbonate contents are often hypothesized to be important factors controlling organic matter turnover in agricultural soils. In our survey, pH-KCl did not affect residual soil mineral N and was not related with short-term N availability indicators. A significantly higher pH-KCl for soil quality group D compared to all other soil quality groups coincided neither with a higher Nrel nor with a higher residual $Nmin_{0\text{-}30\ cm}$. No difference in N mineralization was found in a liming experiment with a sandy loam soil by Bertrand et al. (2007) in which marl ($CaCO_3$ 78%) was added at three rates, i.e., 0, 18 and 50 t ha^{-1} resulting in a soil pH-H_2O of respectively 5.1, 6.3 and 7.6.

Short-term N availability obtained from the incubation experiment seemed to be higher for light textured soils compared to heavier textured soils, whereas residual soil mineral N was lower for the light textured soils. The latter can be explained by a higher susceptibility for leaching losses during the growing season on light textured soils. A significantly higher residual $Nmin_{0\text{-}30\ cm}$ for soil quality group C compared to soil quality group A might also be explained by less nitrate N moving downward the soil profile due to a significantly heavier texture in case of soil quality group C. By contrast, short term N availability as derived from the incubation experiment was higher for soil quality group A compared to soil quality group C. The lower N availability in fields with rotations containing cereals as observed in the incubation experiment was not reflected by differences for residual soil mineral N between rotation types in the field.

3.4.4 Growing season and the level of explained variance or residual soil mineral N

In general, residual $Nmin_{0\text{-}30\ cm}$ was higher in 2011 compared to 2010, probably because of a higher N release from SOM and less leaching due to drier weather in autumn 2011 compared to autumn 2010. In the period between October 1st and November 15th, the cumulative rainfall amount was 147 mm in 2010 and 61 mm in 2011.

The explained variance by the models for residual soil mineral N is low. The variance may be additionally explained by a high spatial and/ or temporal variability, on short distances and in a short period of time, with regard to N availability and processes affecting

N availability in agricultural soils (Strong et al., 1998; Kuzyakov et al., 2000). Differences in water availability between fields might be explicative for a part of the variance in residual soil mineral N. Deprivation of water may reduce or limit crop N uptake and yield, resulting in higher residual soil mineral N. Wang et al. (2005) found that supplemental irrigation at elongation or grain-filling stage significantly decreased residual soil nitrate-N. Cultivars of certain crop species may differ with regard to utilization of available soil N. Wiesler and Horst (1992) observed differences between maize cultivars in N uptake reflected in a corresponding soil nitrate depletion. At harvest, nitrate N residue (0-90 cm) ranged from 34-63 kg N ha^{-1} in 1987 and 32-71 kg N ha^{-1} in 1988.

3.5 Conclusions

This survey revealed that only a small part of the variation in residual soil mineral N can be explained by the suggested crop related and soil quality defining factors, and by the growing season. A higher number of factors was involved in ANOVA models for residual mineral N in the arable layer compared to ANOVAs for nitrate N residue in the soil profile since the majority of the factors directly affect the arable layer with regard to soil circumstances and processes decisive for N availability. Crop group clearly affected the nitrate N residue, which was related with a crop type dependent N fertilization level and the fact that crop type is decisive for the period in which and the extent to which the plants utilize the N available in the soil profile. Only in the case of high fertNmin levels (> 200 kg N ha^{-1}), the nitrate N residue in the soil profile surpassed the nitrate N residue threshold. Nitrate N residue assessment seemed not to be a very reliable tool to evaluate farmers' fertilization practice of the current growing season, as it also reflects soil quality, soil management history and current weather conditions. Certain fields seemed to bear an inherent risk for high nitrate N residues, particularly the fields of farms with livestock.

Chapter 4

Soil quality is positively affected by reduced tillage and compost in an intensive vegetable cropping system

Adapted from:
Willekens, K., Vandecasteele, B., Buchan, D., De Neve, S., 2014. Soil quality is positively affected by reduced tillage and compost in an intensive vegetable cropping system. *Applied Soil Ecology* 82, 61-71.
Willekens, K., Vandecasteele, B., De Neve, S., 2014. Limited short-term effect of compost and reduced tillage on N dynamics in a vegetable cropping system. *Scientia Horticulturae* 178, 79-86.

4.1 Introduction

In Europe, soil degradation has only recently been identified as a widespread problem (Holland, 2004; Zdruli et al., 2010). Intensive vegetable cropping systems are characterized by a high input of inorganic N, frequent soil tillage and short-lived crops in a limited rotation. These practices are not favorable for soil quality as they may result in soil organic matter (SOM) decline, structure deterioration and biodiversity losses. Proper soil management by diversifying fertilization, reducing soil tillage and including cover crops in the rotation may counteract soil degradation and sustain soil quality. Degraded soils may be restored if farming practices are changed to favor increase in SOM and soil biological activity (Blank, 2008). SOM is crucial for many soil functions. Total organic carbon content (TOC), as a proxy for SOM, is a keystone soil quality indicator inextricably linked to other physical, chemical and biological soil quality parameters (Reeves, 1997). Particularly, the presence of beneficial fungi is essential to obtain a diversified food web that guarantees nutrient retention and cycling (de Vries et al., 2011), a good soil structure (Ritz and Young, 2004) and pathogen suppression (Garbeva et al., 2006).

Inclusion of cover crops in an intensive vegetable cropping system is in favor of efficient nutrient management, sustains crop productivity, enhances soil microbiota and controls soil-borne diseases (Collange et al., 2014). Cover crops prevent residual nitrogen (N) from being lost by leaching in intensive vegetable cropping systems which are prone to N losses (Jackson et al., 1993). Conservation agriculture maximizes biomass production by inclusion of cover crops and minimizes soil tillage (Scopel et al., 2013). Soil biota may be positively affected by inclusion of legumes in the rotation and animal manure application and negatively by mineral N fertilizers (Truu et al., 2008; Ge et al., 2008). Soil tillage enhances SOM decomposition which lowers aggregate stability and hydraulic conductivity (Chan et al., 1993; Loch, 1994; Naidu et al., 1996). Not inverting the soil by reduced tillage maintains crop residues and organic amendments near the soil surface resulting in an increased organic matter content (D'Haene et al., 2009) and larger aggregate stability (Cannell, 1985) in the surface layer. Improved habitat and food resources for soil biota under reduced tillage favor a different range of organisms compared to a plough-based system in which crop residues are buried (Rasmussen and Collins, 1991). Besides inclusion of cover crops and a reduced tillage practice, compost application may protect and recover soil quality by favoring soil organic matter status and hence soil biota and soil structure (Alluvione et al., 2013; Pfotzer and Schüler, 1997; Six et al., 2000). Compost application affects many soil properties due to the incorporation of stabilized organic matter, macro- and micronutrients and beneficial microbiota (Zebarth et al., 1999, Tejada et al., 2001, Abawi and Widmer, 2000). Repeated application is expected to increase long term N availability (Chalhoub et al., 2013) and to favor soil physical properties and hence nutrient uptake and plant growth. D’Hose et al. (2012) reported a positive yield effect of recurrent farm compost application caused by both extra N supply and improved crop growth conditions. Compost application increases nutrient availability and microbial populations and activity (Bernard et al., 2012; Duong et al., 2013).

Few studies have explored the combined effect of compost amendment and reduced tillage practice on soil quality, particularly in intensive vegetable cropping systems. In a study of Alluvione et al. (2013) at two Italian sites with contrasting pedoclimate, minimum tillage was compared to conventional mouldboard ploughing, however, included compost treatments were only conventionally tilled and it concerned a maize-based cropping system. Jackson et al. (2004) performed a study in an intensive vegetable production system in a coastal Mediterranean climate, however, they combined compost application with growing a rye cover crop. The aim of our study was to assess if the agronomic practices compost amendment and reduced tillage, applied either individually or in combination, would affect soil quality in the short term (3 years) in an intensive vegetable cropping system. We hypothesized that both practices additively affect soil quality. Besides that, we hypothesized that attained differences in soil quality result in differences in crop yield.

4.2 Materials and methods

4.2.1 Experimental setup and crop monitoring

This two-factorial experiment (Vegtilco trial) ran from September 2008 until February 2012, a period that covered three full growing seasons. The field was located 50° 57' 1.91" N, 3° 15' 7.79" E, 25 m asl. (Meulebeke, Belgium). It concerned a sandy loam soil (63% sand, 30% silt and 7% clay) with a 40 cm Ap horizon, classified as Endogleyic Stagnosol (hypereutric, loamic) according to WRB-2007 (Dondeyne et al., 2014; IUSS Working Group WRB, 2015).

The soil was tilled either conventionally (CT) by mouldboard ploughing or according to reduced non-inversion tillage (RT) with a chisel plough (Actisol). Soil tillage depth was approximately 30 cm for both soil tillage practices. Farm compost was prepared at the Institute of Agricultural and Fisheries Research (ILVO) in a windrow composting system. Composts prepared in 2008 and 2009 were obtained from two compost trials described by Steel et al. (2012). Feedstock composition in 2008 was 75% (v/v) ground poplar bark and 25% (v/v) straw of clover, supplemented with urea, cane molasses and wasted maize silage. The feedstock mixture in 2009 consisted of 7% (v/v) crop residues of leek, 27% (v/v) straw of grass, 16% (v/v) wasted maize silage and 50% (v/v) ground poplar bark. In 2010, the compost was prepared from grass clippings and straw, wood chips, tree bark and old compost, in proper proportions. Aerobic conditions and optimum moisture content levels were maintained using a Sandberger compost turner. This resulted in well ripened compost (high NO_3^--N : NH_4^+-N ratio) with a high organic matter content (Table 4.1). Dry matter content strongly varied due to outdoor storage. Farm compost was applied each autumn, starting in 2008, at three different rates, namely 0, 15 and 45 Mg ha^{-1} (henceforth named C_0, C_{15} and C_{45}). The average yearly N and P_2O_5 input by compost in the C_{15} treatment was 104 and 41 kg ha^{-1}, respectively. The mineral N input from compost was a very small fraction of the total N input (< 2%). Combining two tillage methods and three compost doses resulted in six different soil management regimes which were replicated four times and arranged according to a split-plot design with tillage as the main plot factor and farm compost application as the subplot factor (Figure 4.1). Individual subplots were 6 by 18 m. Winter cover crops were included in the rotation for reasons of good agricultural practice.

In September 2008, compost was applied on a cereal stubble, and then winter rye (*Secale cereale*) was sown as a cover crop. Before the end of March, the rye was terminated by spraying glyphosate (N-phosphonomethyl-glycine). On the entire experiment, a single dose of 25 Mg fresh farmyard manure (FYM) ha^{-1} was applied in 2009 on March 23. The FYM had a high C/N ratio (> 20) due to a high straw content. Both manure's low total N content (3.5 kg N Mg^{-1}) and the high ratio between its NH_4^+-N content and total N content (0.3) might have been related to a high ratio between urine and faeces. The mineral and organic N input by FYM application were 26 and 60 kg ha^{-1}, respectively (Table 4.2).

Table 4.1 Composition of the farm compost applied in the years 2008-2010; means and standard deviations (between parantheses) (n = 4); DM: dry matter; OM: organic matter; EC: electrical conductivity.

		2008		2009		2010	
DM	%	23.1	(0.5)	38.3	(0.5)	65.6	(5.6)
OM	% on DM	69.7	(2.3)	43.4	(4.3)	51.4	(2.0)
EC	µS cm^{-1}	901	(58)	615	(39)	1308	(174)
pH-$H_2$0	-	9.4	(0.6)	8.2	(0.1)	8.4	(0.2)
NH_4^+-N	mg l^{-1}	7.5	(3.3)	< 5,0		< 5,0	
NO_3^--N	mg l^{-1}	93.5	(5.8)	24.0	(2.1)	46.5	(29.0)
N	% on DM	2.04	(0.05)	1.24	(0.08)	1.73	(0.02)
P	g kg^{-1} DM	3.34	(0.52)	1.51	(0.13)	3.24	(0.22)
K	g kg^{-1} DM	16.64	(0.59)	7.38	(0.57)	10.70	(1.09)
Ca	g kg^{-1} DM	44.28	(4.07)	20.87	(1.31)	17.59	(1.40)
Mg	g kg^{-1} DM	4.34	(0.32)	1.76	(0.19)	2.25	(0.41)
Na	g kg^{-1} DM	0.75	(0.03)	0.58	(0.03)	0.39	(0.07)
C/N	-	19.0	(1.1)	19.6	(2.1)	16.5	(0.8)

Right after application, FYM was superficially incorporated. A base K dressing was applied before main tillage in spring. Mineral N fertilizer (potassium nitrate, 15.5% N) was used for an additional base mineral N dressing of 60 kg N ha^{-1} (besides the mineral N input by FYM) immediately before planting broccoli (*Brassica oleracea, var. Italica Group*) on two dates (replicate 1 and 2 on 14/05/2009 and replicate 3 and 4 on 20/05/2009) with a distance of 45 cm between plants in the row and 65 cm interrow distance. Based on mineral N availability in the 0-60 cm soil layer (15/06), 100 kg N ha^{-1} was applied as top mineral N dressing (calcium ammonium nitrate, 33% N) halfway through the cultivation period (19/06), i.e., one month after planting. At harvesting stage, during a one-week period at the end of July (22-29/07), buds of 40 plants per subplot were cut and weighed to determine marketable yield. In order to determine whole plant biomass yield, crop residues were also harvested and weighed separately. Marketable yield and whole plant biomass yield were calculated based on plant distances.

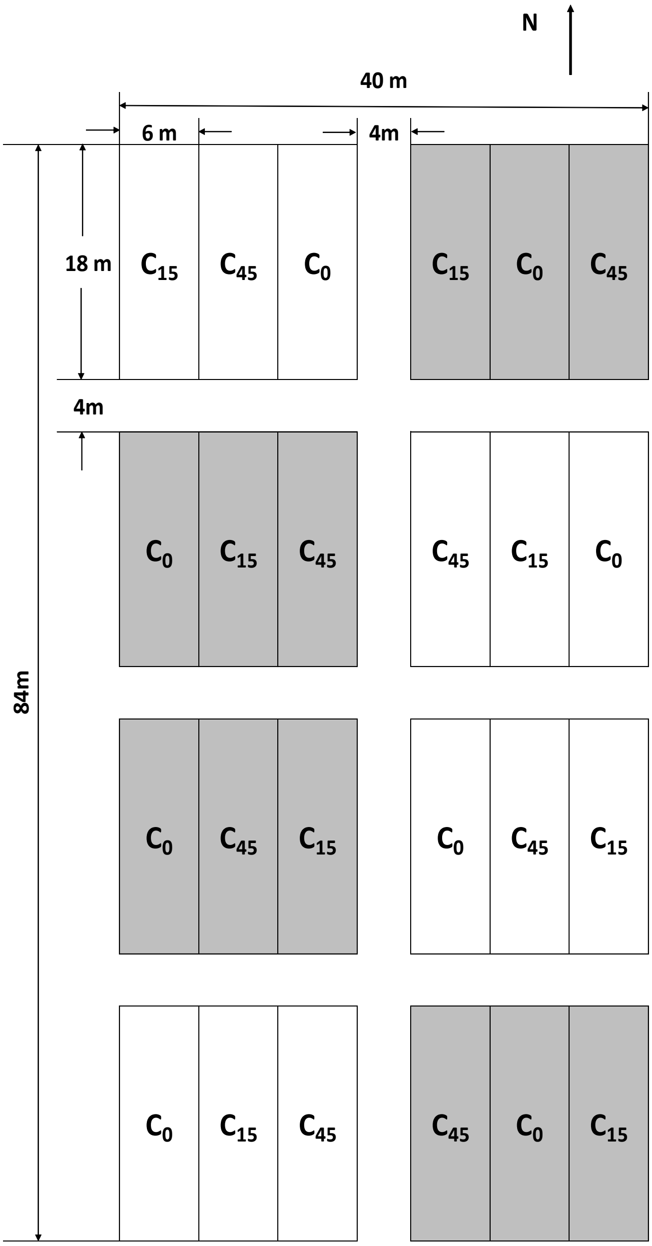

Figure 4.1 Split-plot design and dimensions of field experiment; shaded area: reduced (non-inversion) tillage, non-shaded area: conventional tillage by ploughing; C_0, C_{15}, C_{45}: 0, 15 and 45 Mg farm compost ha^{-1}.

Broccoli was followed by white mustard (*Sinapis alba*) as a cover crop, sown in early September immediately following the incorporation of compost on the compost-amended plots. In 2010, carrots (*Daucus carota*) were sown on April 21 on ridges with a spacing of 60 cm. On June 3, a top mineral N dressing of 50 kg ha^{-1} (calcium ammonium nitrate, 33% N) was applied. Carrots received top K and Mg fertilization as well (Table 4.2). In the second half of September, two times two meters of carrots were harvested per treatment and root yield was determined. Compost was applied in mid-October, but was not incorporated due to very wet soil conditions. In the third year of the experiment (2011), white mustard was sown at the end of March as a cover crop preceding the main crop, and was mulched in the middle of May. Leek (*Allium porrum*, cultivar Harston) was planted on July 4 in rows 65 cm apart. Mineral N fertilizer (calcium ammonium nitrate, 27% N) was used as base mineral N dressing of 70 kg N ha^{-1} immediately before planting leek (Table 4.2). Seven weeks after planting, mineral N availability in the 0-60 cm soil layer was determined to decide on the amount of top mineral N dressing, i.e., 30 kg N ha^{-1} applied eight weeks after planting. At the end of the growing season 2011, in the first half of November, whole plant biomass yield was determined by harvesting three times two meters of leek per treatment in three different rows. Marketable yield determination was postponed until spring 2012, i.e., the usual harvest time for winter leek. Each time, whole plants including the upper part of the root system were harvested. Fresh weight was recorded after thoroughly washing the plants.

Table 4.2 Nutrient input via compost treatments and other fertilization for the different crops; FYM: farmyard manure; fertNmin: mineral N input by fertilization; fertNorg: organic N input by fertilization; C_{15}, C_{45}: 15 and 45 Mg farm compost ha^{-1}.

	kg ha^{-1}	C_{15}	C_{45}	FYM	fertilizer
2009	fertNmin	-	-	26	60 + 100
BROCCOLI	fertNorg	71	213	60	-
	P	13	40	50	-
	K	58	173	145	180
	Mg	15	45	25	-
	Ca	153	460	75	-
2010	fertNmin	-	-	-	50
CARROT	fertNorg	71	213	-	-
	P	9	26	-	-
	K	42	127	-	185
	Mg	10	30	-	18
	Ca	120	359	-	-
2011	fertNmin			-	70 + 30
LEEK	fertNorg	170	511	-	-
	P	32	95	-	-
	K	106	318	-	-
	Mg	22	66	-	6 + 3
	Ca	173	520	-	11 + 5

4.2.2 Assessment of soil quality

The following soil properties were measured to characterize general soil quality at the start and at the end of the experiment: dry soil bulk density (BD), TOC, hot water extractable carbon content (HWC), hot water extractable phosphorous content (HWP), pH-KCl and plant available nutrients. At end of September 2008, the first sampling took place per main plot in the cereal stubble in order to determine initial TOC, HWC, BD and pH-KCl of the 0-10, 10-30 and 30-60 cm soil layers. Final BD, TOC, HWC and pH-KCl of the 0-10, 10-30 and 30-60 cm soil layers and plant available nutrients (P, Ca, Mg, K, Na and Fe) of the 0-10 and 10-30 cm soil layers were determined per subplot under the standing leek crop in the middle of August 2011. Additionally, we assessed the structure of the microbial community of the 0-10 and 10-30 cm soil layers by analysis of the composition of the phospholipid fatty acids (PLFAs) in soil. The 0-10 cm layer was considered as it was the tillage depth under RT.

4.2.3 Soil analyses

TOC content was measured on oven-dried (70 °C) soil samples by dry combustion at 1050 °C with a Skalar Primacs SLC TOC-analyzer according to ISO 10694. For soils with pH-KCl > 6.5, inorganic carbon was measured separately; none of the samples had inorganic carbon levels higher than the limit of quantification.

pH was measured potentiometrically in a 1M KCl solution (1:5 v/v) according to ISO 10390.

Plant available nutrients (P, Ca, Mg, K, Na and Fe) were determined by shaking 5 g air-dried soil in 100 ml ammonium lactate for 4 hours (Egnèr et al., 1960) and were measured using a CCD simultaneous ICP-OES (VISTA-PRO, Varian, Palo Alto, CA).

The soil particle size distribution (sand % 50 - 2000 µm, loam % 2 - 50 µm and clay % < 2 µm) was determined by the sieve-pipette method (ISO 11277).

HWC and HWP were extracted following a method of Haynes and Francis (1993). Soil samples (equivalent to 5 g oven dry weight) were weighed into 50 ml polypropylene centrifuge tubes and 25 ml of demineralized water was added. The tubes were capped and left for 16 h in a hot-water bath at 70 °C. At the end of the extraction period these tubes were centrifuged and the supernatants were filtered over a Machery-Nagel mn640d filter. For the samples taken at the start of the experiment, total C in the extracts was determined by dry combustion at 1050 °C with a Skalar Primacs SLC TOC-analyzer. For the samples taken at the end of the three-year period, total C and P in the extracts was measured using a CCD simultaneous ICP-OES (VISTA-PRO, Varian, Palo Alto, CA). Limit for quantification of C in the ectracts was 0.15% corresponding with 150 mg HWC kg^{-1} dry soil.

Undisturbed soil cores (100 cm^3) were taken with an auger (Eijkelkamp Agrisearch Equipment) for determination of BD at approximately 5 cm, 20 cm and 45 cm below the soil surface (ISO 11272) for the 0-10 cm, 10-30 and 30-60 cm layer, respectively.

PLFAs were extracted from freeze-dried soil using a modified Bligh and Dyer (1959) technique and determined using a procedure modified from Balser (2001), all fully described in Moeskops et al. (2010). Only fatty acid methyl esters (FAMEs) present in proportions more than 1% of the total (n = 48) were retained for further analysis and summed to give 'total PLFA' (n = 35) (Buchan et al., 2012). For gram-positive bacteria, the sum of i14:0, i15:0, a15:0, i16:0, a16:0, i17:0 and a17:0 was used. The fatty acids cy17:0, cy17:0new, cy19:0 and cy19:0new were considered to be typical for gram-negative bacteria. The sum of 10Me16:0, 10Me17:0 and 10Me18:0 was regarded as a reliable indicator for the actinomycetes. The fatty acid 18:2ω6c was used as signature fatty acid for fungi. Two alternative signature fatty acids for fungi were considered as well, i.e., 18:1ω9 and 18:3ω3. The fatty acid 16:1ω5c was used as signature for arbuscular mycorrhizal fungi (AMF). Bacteria:fungi (B:F) ratios were calculated by dividing the sum of markers for Gram-positive, Gram-negative bacteria, 15:0 and 17:0 by the fungal marker 18:2ω6c.

4.2.4 Data processing and statistical data analysis

TOC contents and BD values from both sampling times of the different soil layers (0-10, 10-30 and 30-60 cm) were used to calculate initial and final carbon stocks in the 0-60 cm soil layer (C $stock_{0\text{-}60cm}$). To compare the initial C stock with the final one, the same amount of inorganic soil must be considered (Gerzabek et al., 1997), and we assumed that no losses of inorganic soil occurred during the experiment. Changes in BD of the 0-10, 10-30 and 30-60 cm soil layers in the considered period required us to adapt final soil profile depth in order to consider the same amount of inorganic soil as in the 0-60 cm soil layer at the first sampling in 2008. Calculation of the amount of inorganic soil in the soil profile was based on BD values of the different soil layers. For C $stock_{0\text{-}60cm}$ and the parameters BD, TOC, HWC and pH-KCl, initial values - determined per main plot - were subtracted from final values in each subplot. These differences are further denoted as Δ.

Statistics were done by Spotfire S+ 8.2 software. Soil layer was considered as a third factor in a three-factorial split-plot ANOVA (Gomez and Gomez, 1984). When significant interaction effects were found between factors, data analysis was continued either per variant of one or both of the interacting factors or by comparing all six combinations of both factors. Normality of residues was checked using the Kolmogorov-Smirnov test. The Scheffe method was applied for multiple comparisons of the means. Paired t-test or exact Wilcoxon signed-rank tests were used to compare initial versus final parameter values. Significance levels are expressed presenting p-values < 0.05, < 0.01 and < 0.001. In case of $p < 0.1$, this was interpreted as a tendency for differences between variants of a certain factor. In a canonical discriminant analysis (CDA), six below mentioned soil characteristics were used to distinguish soil management regimes, i.e., combinations of tillage method and compost application (CT-C_0, CT-C_{15}, CT-C_{45}, RT-C_0, RT-C_{15} and RT-C_{45}). TOC and pH-KCl were selected as the two most commonly used parameters indicative for soil quality. Secondly, plant available Fe and Ca:Mg were selected as their readings may be indicative for the soil physical status and finally, marker PLFAs for fungi 18:2ω6 and actinomycetes that represent microbiota of which a soil in minor condition may show a shortage.

4.3 Results

4.3.1 Initial soil conditions

No significant differences were found between replicates for initial BD and TOC values. Average BD values were comparable for both the 0-10 and 10-30 cm soil layers (1.56 and 1.55 g cm^{-3}, respectively), and significantly lower than $BD_{30\text{-}60cm}$ (1.68 g cm^{-3}; $p < 0.001$). The average TOC content of both upper soil layers did not differ significantly (0-10 cm: 0.97% and 10-30 cm: 0.96%), however, both TOC contents were significantly different ($p < 0.001$) from the TOC content in the subsoil layer (0.55%). The average initial C $stock_{0\text{-}60\ cm}$ was 72.7 Mg ha^{-1}. At the start of the experiment, the HWC content was 921 mg kg^{-1} and the pH-KCl value 6.3 on average over all replicates and soil layers, and no significant differences between the soil layers were detected. However, significant differences between some replicates were found for pH-KCl and HWC values (results not shown).

4.3.2 Final soil quality assessment

4.3.2.1 Dry soil bulk density

Neither the tillage nor the compost factor affected BD. BD values differed between all soil layers ($p < 0.01$) and ΔBD values differed between the 0-10 cm and both underlying soil layers ($p < 0.05$) (Table 4.3). BD decreased in the 0-10 cm and 10-30 cm soil layers ($p < 0.001$ and $p < 0.05$, respectively) but increased in the 30-60 cm soil layer ($p < 0.05$).

Table 4.3 Average parameter values and standard deviations (between parentheses) of final soil status per soil layer with regard to total organic carbon content (TOC), hot water extractable carbon content (HWC), hot water extractable phosphorous content (HWP), pH-KCl, dry soil bulk density (BD), respective changes in a three-year period ΔTOC and ΔBD, plant available K, Mg and Fe content and Ca to Mg ratio (Ca:Mg); significant differences between soil layers are indicated with different lowercase letters and p-values (2-way ANOVA: compost x layer or 3-way split-split-plot ANOVA tillage x compost x layer); soil layers 0-10 cm, 10-30 cm and 30-60 cm; CT: conventional tillage (ploughing), RT: reduced (non-inversion) tillage.

		0-10 cm	10-30 cm	30-60 cm	ANOVA	Scheffe
TOC	CT	0.88 [b] (0.06)	0.90 [b] (0.08)	0.61 [a] (0.05)	0.001	0.001
%	RT	1.05 [c] (0.13)	0.93 [b] (0.09)	0.61 [a] (0.12)	0.001	0.001
ΔTOC	CT	-0.07 [a] (0.07)	-0.04 [a] (0.09)	0.10 [b] (0.09)	0.001	0.01
%	RT	0.07 [b] (0.11)	-0.05 [a] (0.05)	0.02 [ab] (0.09)	0.01	0.01
HWC	CT	580 [b] (73)	605 [b] (75)	428 [a] (39)	0.001	0.001
mg kg^{-1}	RT	689 [b] (112)	626 [b] (125)	491 [a] (118)	0.001	0.001
HWP	CT	36.8 [c] (3.9)	32.9 [b] (4.4)	23.7 [a] (3.5)	0.001	0.001
mg kg^{-1}	RT	40.2 [b] (6.4)	30.2 [a] (4.3)	26.4 [a] (4.1)	0.001	0.001
pH-KCl*		5.8 [a] (0.3)	6.0 [b] (0.3)	6.0 [b] (0.3)	0.001	0.001
BD*	g cm^{-3}	1.40 [a] (0.12)	1.50 [b] (0.13)	1.71 [c] (0.08)	0.001	0.01
ΔBD*	g cm^{-3}	-0.17 [a] (0.14)	-0.06 [b] (0.14)	0.03 [b] (0.09)	0.001	0.05
K	CT	24.9 [a] (5.2)	29.5 [b] (7.7)		0.05	
mg per 100 g	RT	32.2 (5.8)	30.7 (6.1)			
Mg	CT	12.3 [a] (1.0)	14.8 [b] (1.6)		0.05	
mg per 100 g	RT	16.1 [b] (2.4)	14.9 [a] (1.9)		0.05	
Fe	CT	99.4 (2.2)	100.2 (1.9)			
mg per 100 g	RT	94.7 [a] (4.5)	99.2 [b] (4.3)		0.001	
Ca:Mg	CT	6.3 [b] (0.5)	5.5 [a] (0.4)		0.001	
	RT	4.9 [a] (0.6)	5.7 [b] (0.5)		0.001	

*Anova tillage x compost x layer

4.3.2.2 TOC content

A significant interaction between the tillage and layer factor was found for TOC and ΔTOC ($p < 0.001$). $TOC_{0\text{-}10cm}$ was significantly higher for C_{45} than for C_0 ($p < 0.01$) (Table 4.4). A tendency for higher $TOC_{10\text{-}30cm}$ with increasing compost doses was observed. $\Delta TOC_{0\text{-}10cm}$ was significantly different between C_0 and C_{45} ($p < 0.01$). No change in $TOC_{10\text{-}30cm}$ was observed for C_{45}, but there was a significant decline in TOC in the 0-10 and 10-30 cm soil layers on C_0 plots ($p < 0.05$ and $p < 0.001$). A significant increase in TOC in the 30-60 cm soil layer was observed in compost amended plots ($p < 0.01$).

Tillage method did not significantly affect TOC in the different soil layers. Only for the 0-10 cm soil layer, TOC tended to be higher under RT compared to CT (Table 4.3). RT did not reduce $TOC_{10\text{-}30cm}$ compared to CT. Under RT, $TOC_{0\text{-}10cm}$ was significantly higher than $TOC_{10\text{-}30cm}$ ($p < 0.001$) whereas in the case of CT, the TOC of both upper layers did not differ significantly. As effects of the tillage factor seemed to be absent for chemical soil parameters (excepted a tendency for a higher $TOC_{0\text{-}10\ cm}$ under RT compared to CT), parameter values for both tillage practices were not explicitely presented in a table.

Table 4.4 Average parameter values and standard deviations (between parentheses) of final soil status per compost variant with regard to total organic carbon content (TOC), hot water extractable carbon content (HWC), pH-KCl, change in TOC in a three-year period (ΔTOC), plant available Ca, K and Fe content and sum of base cations (∑Ca,Mg,K,Na); significant differences between compost doses are indicated with different lowercase letters and p-values (2-way split-plot ANOVA: tillage x compost or 2-way ANOVA compost x layer); C_0, C_{15}, C_{45}: 0, 15 and 45 Mg farm compost ha^{-1}; soil layers 0-10 cm, 10-30 cm and 30-60 cm; CT: conventional tillage (ploughing), RT: reduced (non-inversion) tillage.

		C_0	C_{15}	C_{45}	ANOVA	Scheffe
TOC	0-10 cm	0.90 ^{a} (0.11)	0.95 ^{ab} (0.11)	1.04 ^{b} (0.13)	0.001	0.01
%	10-30 cm	0.87 (0.08)	0.91 (0.10)	0.95 (0.05)	0.1	
	30-60 cm	0.59 (0.07)	0.62 (0.13)	0.62 (0.07)		
ΔTOC	0-10 cm	-0.07 ^{a} (0.09)	-0.01 ^{ab} (0.09)	0.08 ^{b} (0.12)	0.001	0.01
%	10-30 cm	-0.08 (0.04)	-0.04 (0.09)	0.00 (0.05)	0.1	
	30-60 cm	0.03 (0.11)	0.07 (0.08)	0.07 (0.11)		
pH-KCl	0-10 cm	5.5 ^{a} (0.2)	5.9 ^{b} (0.4)	5.9 ^{b} (0.1)	0.01	0.01
	10-30 cm	5.8 ^{a} (0.3)	6.0 ^{ab} (0.3)	6.1 ^{b} (0.1)	0.05	0.05
	30-60 cm	5.9 (0.2)	6.1 (0.3)	6.1 (0.2)	0.05	0.1
HWC*	CT	497 ^{a} (77)	541 ^{ab} (111)	575 ^{b} (105)	0.01	0.01
mg kg^{-1}	RT	568 ^{a} (137)	581 ^{ab} (124)	657 ^{b} (159)	0.05	0.05
Ca	0-10 cm	118 ^{a} (18)	134 ^{b} (27)	137 ^{b} (19)	0.001	0.05
mg per 100 g	10-30 cm	133 (20)	139 (21)	140 (17)		
K	0-10 cm	24.4 ^{a} (4.3)	28.5 ^{ab} (5.9)	32.7 ^{b} (7.0)	0.01	0.01
mg per 100 g	10-30 cm	26.0 ^{a} (3.5)	29.6 ^{ab} (6.2)	34.7 ^{b} (7.6)	0.05	0.05
∑Ca,Mg,K,Na	0-10 cm	7.6 ^{a} (1.1)	8.7 ^{b} (1.5)	9.0 ^{b} (1.3)	0.001	0.01
cmol+ kg^{-1}	10-30 cm	8.6 (1.2)	8.9 (1.2)	9.2 (1.1)		
Fe	0-10 cm	98.9 ^{b} (3.7)	96.9 ^{ab} (4.6)	95.4 ^{a} (4.1)	0.05	0.05
mg per 100 g	10-30 cm	101.3 ^{b} (3.8)	99.9 ^{ab} (3.0)	97.9 ^{a} (2.5)	0.05	0.05

*Anova compost x layer

4.3.2.3 C stocks

Since neither tillage nor compost application affected BD, average BD values per soil layer were combined with TOC contents of the different layers per subplot to calculate final C $stocks_{0\text{-}60cm}$ per subplot. In this calculation, the depth considered for the 30-60 cm subsoil layer was extended by 1.04 cm in order to compensate for the lower bulk density in the upper layers (i.e., it was calculated considering equal amounts of soil at both sampling moments). C $stock_{0\text{-}60\ cm}$ and ΔC $stock_{0\text{-}60\ cm}$ were significantly affected by compost application (ANOVA $p < 0.05$; $C_{45} > C_0$, Scheffe $p < 0.05$). ΔC $stock_{0\text{-}60\ cm}$ for C_0, C_{15} and C_{45} were respectively -2.9, +1.1 and +3.5 Mg ha^{-1} or -4.0, +1.5 and +4.8% compared to the initial C stock of 72.7 Mg ha^{-1}. Comparing the increase of the C $stock_{0\text{-}60cm}$ by C_{15} or C_{45} with the decrease on C_0 plots, the organic carbon recovered from C_{15} and C_{45} applications was 71% and 39% of the respective organic C inputs (i.e., 5.5 Mg ha^{-1} in C_{15} and 16.6 Mg ha^{-1} in C_{45}). No tillage effect on C $stocks_{0\text{-}60cm}$ was observed. Yearly, 1.33 % of the C $stock_{0\text{-}60cm}$ was lost on C_0 plots.

4.3.2.4 HWC and HWP

A significant interaction between the tillage and layer factor was found for HWC ($p < 0.05$) and a significant interaction between the tillage and compost factor was found for $HWC_{0\text{-}10cm}$ ($p < 0.05$). On average over all soil layers, HWC for C_{45} was significantly higher than HWC for C_0 (CT plots: $p < 0.01$ and RT plots: $p < 0.05$) (Table 4.4). A significantly lower HWC was found in the 30-60 cm layer compared to both upper layers ($p < 0.001$) (Table 4.3). A general decline in HWC was observed in the three-year period. ΔHWC was on average -352 mg kg^{-1} considering data of all three soil layers. ΔHWC was significantly positively affected by compost application (ANOVA, $p < 0.01$, Scheffe $p < 0.05$). The HWC decline was significantly higher for C_0 (-389 mg kg^{-1}) than for C_{45} (-305 mg kg^{-1}).

A significant interaction between the layer and tillage factor was found for HWP ($p < 0.01$) (Table 4.3). The distribution of HWP over the soil profile differed between both tillage types. $HWP_{10\text{-}30\ cm}$ was significantly higher under CT compared to RT ($p < 0.01$). Compost application did not affect HWP.

4.3.2.5 pH-KCl

pH-$KCl_{0\text{-}10cm}$ was significantly higher on compost amended plots than on non-amended ones ($p < 0.01$) (Table 4.4). Averaged over all soil layers, pH-KCl was significantly higher (ANOVA, $p < 0.01$; Scheffe $p < 0.01$) for C_{15} (6.0) and C_{45} (6.0) than for C_0 (5.7). pH-KCl was significantly lower in the top layer compared to both deeper layers ($p < 0.001$) (Table 4.3). No significant effect from the soil tillage factor on pH-KCl was found. A general decrease in pH-KCl was observed in the three-year period. On average over all soil layers, the decrease in pH-KCl was significantly larger (ANOVA, $p < 0.01$. Scheffe $p < 0.01$) for C_0 (-0.5) than for C_{15} (-0.3) and C_{45} (-0.3). ΔpH-KCl did not differ between soil tillage methods.

4.3.2.6 Plant available nutrients

Neither tillage practice, nor compost application affected plant available P content in the arable layer (final value 63.1 mg 10^{-2} g^{-1}). A significant interaction between the layer and tillage factor was found for plant available K, Mg and Fe. In both the 0-10 and 10-30 cm soil layers, C_{45} had a significantly higher plant available K content than C_0 ($p < 0.01$ and $p < 0.05$, resp.) (Table 4.4). $K_{0\text{-}10cm}$ tended to be higher in the case of RT compared to CT (Table 4.3). $K_{10\text{-}30cm}$ did not differ between tillage types. Under CT, $K_{0\text{-}10cm}$ was significantly lower than $K_{10\text{-}30cm}$ ($p < 0.05$). A significant interaction occurred between tillage and compost factors affecting $Mg_{0\text{-}10cm}$. For C_{15} and C_{45} plots, $Mg_{0\text{-}10cm}$ was respectively 32% and 43% higher under RT compared to CT ($p < 0.001$ and $p < 0.01$, respectively, results not shown). For RT plots, $Mg_{0\text{-}10cm}$ was significantly higher for C_{15} and C_{45} than for C_0 (ANOVA, $p < 0.01$. Scheffe $p < 0.05$) (results not shown). Under RT, $Mg_{0\text{-}10cm}$ was significantly higher than $Mg_{10\text{-}30cm}$ ($p < 0.05$) whereas under CT, the opposite occurred ($p < 0.05$) (Table 4.3). Compost application lowered plant available Fe content in the 0-10 and 10-30 cm soil layers ($p < 0.05$) (Table 4.4). $Fe_{0\text{-}10cm}$ was significantly higher on CT plots than on RT plots ($p < 0.05$). Under RT, $Fe_{0\text{-}10\ cm}$ was significantly lower than $Fe_{10\text{-}30cm}$ ($p < 0.001$) (Table 4.3). With regard to plant available Ca and the sum of plant available base cations (∑Ca,Mg,K,Na), significant interactions between the layer and compost factor were found. Compost application positively affected $Ca_{0\text{-}10cm}$ and $\sum Ca,Mg,K,Na_{0\text{-}10cm}$ ($p < 0.05$ and $p < 0.01$, respectively) (Table 4.4). No significant effect from the tillage factor on the plant available Ca and ∑Ca,Mg,K,Na was found.

4.3.2.7 Soil microbial community

The microbial community structure in the top 0-10 cm soil layer was significantly affected by the tillage and compost factors. Interactions occurred between the layer factor and one or both of the other factors. Total microbial biomass and the amount of marker PLFAs for gram-positive bacteria, actinomycetes, fungi 18:1ω9 and AMF in the 0-10 cm soil layer were significantly higher for C_{45} than for C_0 and C_{15} ($p < 0.05$) and significantly higher for RT compared to CT ($p < 0.05$) (Table 4.5). Under RT, these functional groups were present in significantly higher amounts in the 0-10 cm than in 10-30 cm soil layer ($p < 0.001$). The concentrations of the fungal FAME markers 18:2ω6 and 18:3ω3 in the 0-10 cm soil layer were only significantly favored by RT ($p < 0.01$ and $p < 0.05$, resp.), compared to CT, and not by compost application (Table 4.5). Under RT, fungi 18:2ω6 and 18:3ω3 were significantly more present in the 0-10 cm than in the 10-30 cm soil layer ($p < 0.001$) and, under CT, fungi 18:2ω6 were significantly more present in the 10-30 cm than in the 0-10 cm soil layer ($p < 0.05$). A significantly higher B:F ratio in the 0-10 cm soil layer was found for CT compared to RT ($p < 0.01$) (Table 4.5). On RT plots, the B:F ratio was significantly lower in the 0-10 cm than in the 10-30 cm soil layer ($p < 0.001$) and the opposite was observed on CT plots ($p < 0.01$). Gram-negative bacteria in the 0-10 cm soil layer were only affected by compost application with a significantly higher amount for C_{45} compared to C_0 and C_{15} ($p < 0.01$), but not by tillage. Under RT, the concentrations of FAME markers for gram-negative bacteria were significantly higher in the 0-10 cm than in the 10-30 cm soil layer ($p < 0.01$).

Table 4.5 Final soil status with regard to soil biota in the 0-10 cm and 10-30 cm soil layers (total microbial biomass (Total), gram-positive (G+) and gram-negative (G-) bacteria, actinomycetes, fungal PLFA markers 18:1ω9, 18:2ω6 and 18:3ω3, arbuscular mycorrhizal fungi (AMF) and bacteria to fungi ratio (B:F 18:2ω6)), average values and standard deviations (between parentheses); significant differences between tillage methods or compost doses are indicated by different lowercase letters and p-values (2-way split-plot ANOVA tillage x compost); CT: conventional tillage (ploughing), RT: reduced (non-inversion) tillage; C_0, C_{15}, C_{45}: 0, 15 and 45 Mg farm compost ha^{-1}.

		CT		RT		ANOVA	C_0		C_{15}		C_{45}		ANOVA	Scheffe
Total	0-10 cm	14.11 a	(2.31)	20.29 b	(3.31)	0.05	15.51 a	(3.72)	16.47 a	(4.02)	19.63 b	(4.20)	0.001	0.05
nmol g^{-1}	10-30 cm	15.26	(2.63)	14.03	(3.21)		14.15	(2.49)	15.06	(3.90)	14.73	(2.53)		
G+ bacteria	0-10 cm	2.60 a	(0.51)	3.51 b	(0.70)	0.05	2.69 a	(0.67)	2.92 a	(0.56)	3.56 b	(0.81)	0.01	0.05
nmol g^{-1}	10-30 cm	2.80	(0.57)	2.50	(0.65)		2.58	(0.63)	2.70	(0.74)	2.66	(0.56)		
G- bacteria	0-10 cm	1.59	(0.31)	2.01	(0.42)		1.65 a	(0.40)	1.70 a	(0.40)	2.05 b	(0.40)	0.01	0.01
nmol g^{-1}	10-30 cm	1.72	(0.36)	1.66	(0.42)		1.67	(0.33)	1.71	(0.51)	1.69	(0.34)		
Actinomycetes	0-10 cm	1.12 a	(0.19)	1.54 b	(0.26)	0.05	1.21 a	(0.28)	1.25 a	(0.27)	1.54 b	(0.30)	0.001	0.05
nmol g^{-1}	10-30 cm	1.25	(0.23)	1.15	(0.26)		1.18	(0.22)	1.21	(0.30)	1.20	(0.24)		
Fungi 18:2ω6	0-10 cm	0.34 a	(0.07)	0.77 b	(0.14)	0.01	0.54	(0.27)	0.53	(0.25)	0.61	(0.25)		
nmol g^{-1}	10-30 cm	0.43	(0.09)	0.35	(0.08)		0.36	(0.07)	0.41	(0.11)	0.39	(0.09)		
Fungi 18:1ω9	0-10 cm	0.74 a	(0.15)	1.30 b	(0.22)	0.05	0.92 a	(0.34)	0.97 a	(0.35)	1.17 b	(0.30)	0.001	0.05
nmol g^{-1}	10-30 cm	0.84	(0.17)	0.78	(0.22)		0.77	(0.14)	0.88	(0.28)	0.79	(0.13)		
Fungi 18:3ω3	0-10 cm	0.05 a	(0.02)	0.19 b	(0.05)	0.05	0.12	(0.09)	0.11	(0.07)	0.13	(0.08)		
nmol g^{-1}	10-30 cm	0.07	(0.02)	0.04	(0.02)	0.1	0.06	(0.03)	0.06	(0.03)	0.05	(0.02)		
AMF	0-10 cm	0.66 a	(0.17)	1.11 b	(0.33)	0.05	0.72 a	(0.25)	0.84 a	(0.36)	1.10 b	(0.34)	0.001	0.05
nmol g^{-1}	10-30 cm	0.75	(0.17)	0.67	(0.25)		0.63	(0.18)	0.74	(0.28)	0.75	(0.16)		
B:F 18:2ω6	0-10 cm	13.13 b	(1.42)	7.60 a	(1.22)	0.01	9.89	(3.37)	10.68	(3.63)	10.52	(2.60)		
nmol g^{-1}	10-30 cm	11.22	(1.62)	12.56	(2.29)		12.58	(2.52)	11.30	(2.19)	11.80	(1.33)		

4.3.2.8 Overall final soil condition

Soil management regimes, i.e., combinations of specific tillage and compost treatments, clearly differed in soil condition using six soil characteristics (TOC, pH-KCl, plant available Fe, Ca:Mg, fungi 18:2ω6 and actinomycetes) in a CDA analysis. With regard to the 0-10 cm soil layer, the first two (of a total of five) discriminant functions accounted for 97.3% of the total variance. Likelihood ratio tests showed that the first discriminant function significantly contributed to the discrimination of the soil management regimes ($p < 0.001$), whereas the second just tended to contribute to the discrimination. This is illustrated in the plane of the first two discriminant functions (Figure 4.2). The first discriminant function clearly separated the RT and CT treatment (canonical coefficient TOC 16.0, pH-KCl -3.5, plant available Fe 0.1, Ca:Mg -2.1, fungi 18:2ω6 6.2 and actinomycetes 0.8) whereas the second function seemed to discriminate according to the compost treatments (canonical coefficients TOC 4.9, pH-KCl -3.2 , plant available Fe 0.3, Ca:Mg -0.01, fungi 18:2ω6 10.0 and actinomycetes -7.1).

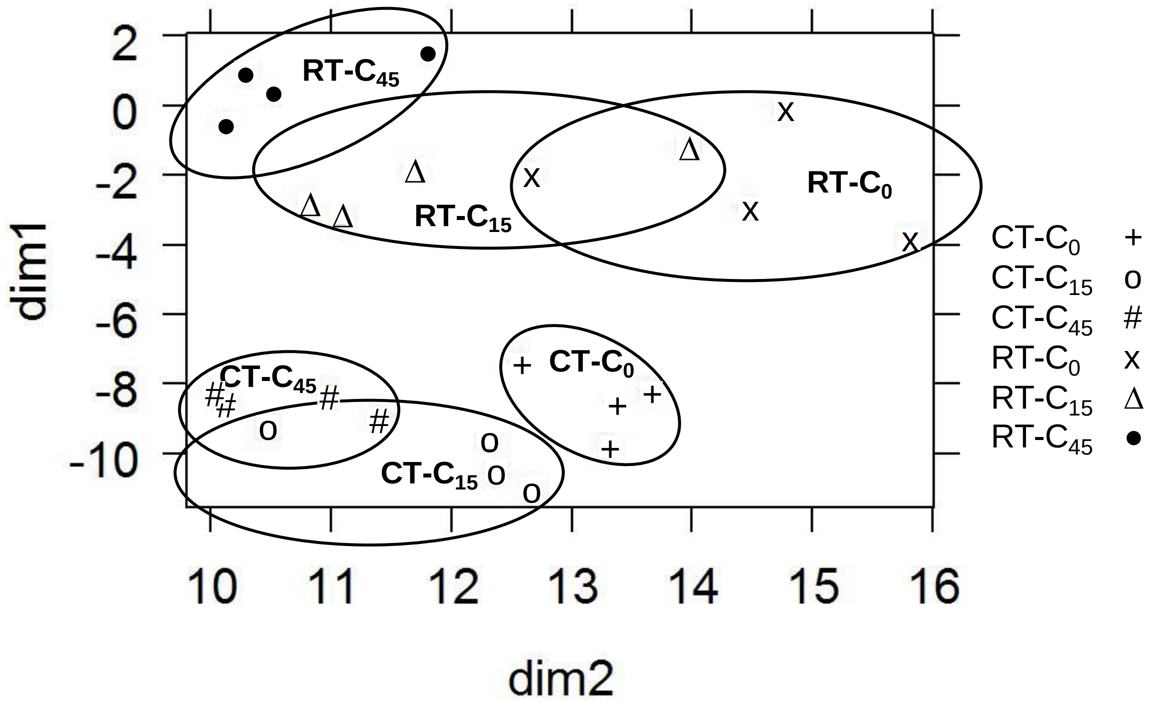

Figure 4.2 Plane of the first two discriminant functions from a canonical discriminant analysis in which six soil characteristics (TOC, pH-KCl, extractable Fe, Ca:Mg and marker PLFAs for fungi and actinomycetes) of the 0-10 cm soil layer were used to discriminate six soil management regimes, i.e., CT-C_0, CT-C_{15}, CT-C_{45}, RT-C_0, RT-C_{15} and RT-C_{45}; the first discriminant function accounted for 87.5% of the total variance, the second for 9.8%; CT: conventional tillage (ploughing), RT: reduced (non-inversion) tillage; C_0, C_{15}, C_{45}: 0, 15 and 45 Mg farm compost ha^{-1}.

With regard to the 10-30 cm soil layer, the first two (of a total five) discriminant functions accounted for 89.6% of the total variance. Likelihood ratio tests showed that only the first discriminant function significantly contributed to the discrimination of the soil management regimes ($p < 0.05$) (canonical coefficients TOC -35.4, pH-KCl 8.5 , plant available Fe -0.06, Ca:Mg 2.0, fungi 18:2ω6 -35.2 and actinomycetes 14.9). In the plane of the first two discriminant functions, only four of the six considered soil management regimes were clearly grouped, i.e., CT-C_0, CT-C_{15}, RT-C_{15} and RT-C_{45} (Figure 4.3).

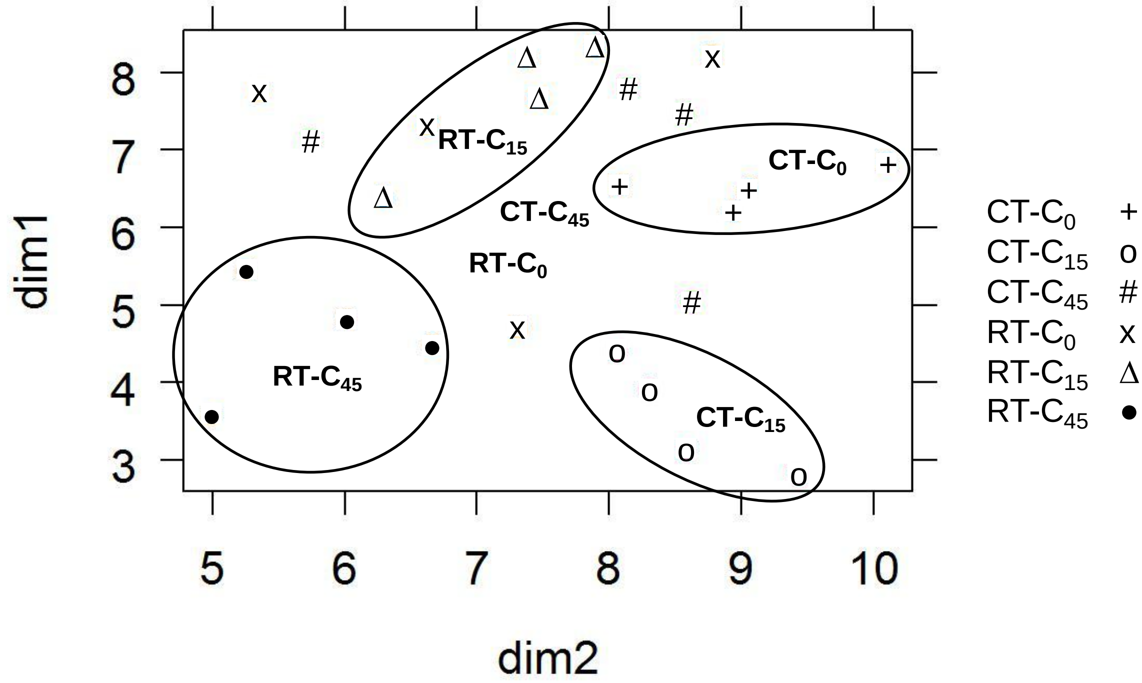

Figure 4.3 Plane of the first two discriminant functions from a canonical discriminant analysis in which six soil characteristics (TOC, pH-KCl, extractable Fe, Ca:Mg and marker PLFAs for fungi and actinomycetes) of the 10-30 cm soil layer were used to discriminate six soil management regimes, i.e., CT-C_0, CT-C_{15}, CT-C_{45}, RT-C_0, RT-C_{15} and RT-C_{45}; the first discriminant function accounted for 57.7% of the total variance, the second for 31.9%; CT: conventional tillage (ploughing), RT: reduced (non-inversion) tillage; C_0, C_{15}, C_{45}: 0, 15 and 45 Mg farm compost ha^{-1}.

4.3.3 Crop yields

No significant effect from compost application on total plant biomass was observed for any of the crops. For broccoli in 2009, RT resulted in a significantly higher amount of total plant biomass (RT: 60.8 Mg ha^{-1} and CT: 56.0 Mg ha^{-1}, $p < 0.05$). Under RT, marketable broccoli yield tended to be higher (24.2 Mg ha^{-1}) than under CT (23.0 Mg ha^{-1}) as a result of a tendency for a higher bud piece weight for RT (+35 g piece^{-1}). The total leek plant biomass in autumn 2011 tended to be higher on CT than on RT plots (CT: 77.9 Mg ha^{-1} and

RT: 70.5 Mg ha^{-1}). Leek marketable yield in the following spring did not differ between tillage treatments (average 44.7 Mg ha^{-1}). Carrots marketable yield was 111.8 Mg ha^{-1}, with no differences between treatments.

4.4 Discussion

4.4.1 BD

At the start of the experiment in autumn 2008, the arable layer was compacted, probably due to the harvest of the cereal pre-crop. Under the standing leek crop at the end of the experiment, the arable layer seemed to be decompacted. However, the subsoil 30-60 cm layer was apparently gradually more compacted by this intensive vegetable cultivation. The three-year period of RT versus CT and different doses of compost did not result in significant differences in BD. Dolan et al. (2006) also found no differences in BD for topsoil and subsoil 0-5, 20-25, 30-45 cm layers under short-term RT.

4.4.2 TOC, C stock and HWC

Organic C from compost was retained to a higher extent in the surface 0-10 cm layer under RT, compared to CT. The 18.5% $TOC_{0\text{-}10cm}$ increase under RT did not result in a $TOC_{10\text{-}30cm}$ decrease. Several authors mentioned higher top layer organic carbon contents due to stratification of organic matter with non-inversion tillage, compared to conventional tillage (e.g., Alvarez, 2005; D'Haene et al., 2009, Van Den Bossche et al., 2009), which is related to differences in incorporation depth of (external) organic matter and in soil disturbance.

C input by compost application (C_{15} and C_{45}) compensated for C losses due to mineralization of soil organic matter in the 0-60 cm soil layer. Apparent C recovery from compost over a depth of 60 cm was considerably higher for C_{15} (71%) than C_{45} (39%). Alluvione et al. (2013) reported 55.1% recovered C from added compost in a short-term experiment and considering 0-30 cm C stock changes. From a long-term experiment with recurrent application different urban waste compost and FYM as reference amendment, Chalhoub et al. (2013) reported 32-79% apparent N recovery in SOM. As aboveground biomass production of crops did not differ between compost doses, a similar root biomass can reasonably be assumed (Alluvione et al., 2009) and therefore, differences in C stocks and ΔTOC values were probably originating from compost C input. Cover crop biomass production was also assumed to be equal between compost treatments. Considering

C_{15} plots, negative ΔTOC values for both 0-10 and 10-30 cm soil layers together with a positive $\Delta TOC_{30\text{-}60cm}$ suggest that compost C was partially leached from the arable layer to the 30-60 cm subsoil layer, a phenomenon that possibly occurred on the non-amended plots as well. A study by Kindler et al. (2011) showed that C losses by leaching of dissolved organic carbon (DOC) were of an order of magnitude of 40 kg ha^{-1} yr^{-1} for croplands. The lower apparent C recovery at a higher level of compost application may be related to proportionally higher C losses due to leaching or removal by wind. Aeolian losses may have occurred, particularly in case of compost application in autumn 2010 as the compost stayed unincorporated over winter. In case of C_{45}, a proportionally higher amount might have been removed by wind, compared to C_{15}. Proportionally higher leaching losses were not likely to happen as $\Delta TOC_{30\text{-}60\ cm}$ values did not differ between compost variants. A proportionally higher soil respiration due to an accelerated SOM decomposition by C_{45} might have been another possible explanation for the lower apparent C recovery from $C_{45,}$ compared to C_{15}. However, the minor impact of compost application on N availability (chapter 5) does not support this explanation. Tits et al. (2014) studied the recurrent application of vegetable, fruit and garden waste compost at different doses (0, 15, 30 and 45 Mg ha^{-1}) and different application frequencies (yearly, 2- and 3-yearly) on N availability, crop performance and SOM content. Their TOC measurements, 14 years after the start of the experiment did not always reveal a clear linear response of TOC content either on dosage (at a certain application frequency) or on frequency (at a certain dosage). In a field experiment performed by Scotti et al. (2015), two different mixtures of compost and scraps from poplar pruning were amended at two different rates, i.e., 30 and 60 Mg ha^{-1} year^{-1} for two consecutive years, which apparently resulted in an effective long lasting increase of SOM. However, as the apparent C recovery seemed to be proportionally lower at the highest rate, the authors conclude that the smaller rate was the most viable option.

Considering CT plots, a positive $\Delta TOC_{30\text{-}60cm}$, significantly different from the negative ΔTOC values in both upper layers, suggests a downward movement of organic C compounds. A completely other ranking of ΔTOC values was observed under RT for which a positive $\Delta TOC_{0\text{-}10cm}$ was found, significantly different from the negative $\Delta TOC_{10\text{-}30cm}$, and an insignificant $\Delta TOC_{30\text{-}60cm}$. With this observation, it can be assumed that C leaching was reduced by RT, which is consistent with the lower risk of leaching losses of base cations under RT compared to CT (see below).

Over all treatments, a considerable decrease of HWC was observed. D'Hose et al. (2014) did not find an increase in HWC in the 0-15 cm soil layer on farm compost amended plots compared to the non-amended ones in a multiyear field experiment with recurrent compost application. The general decline of HWC may additionally indicate a C leaching loss, probably both on compost amended and non-amended plots. Ghani et al. (2003) proposed to use HWC as a soil quality indicator as it differentiates between agricultural management practices. Probably root exudates are an important component of the labile soil organic carbon fraction that HWC represents. As cereal crops develop a very large rooting system and produce large amounts of root exudates, a high HWC content could indeed be expected under the cereal stubble at the start of the experiment. This contrasts with the superficial and not well developed rooting system of the young leek crop, which may be part of the explanation for the lower value of final HWC.

4.4.3 pH-KCl

Compost application positively affected pH-KCl, irrespective of the dose. Compost is an alkaline material (pH-H_2O > 8) but the dose itself apparently played a minor role in pH buffering. Also a moderate yearly dose (C_{15}) counteracted acidification. In contrast, Lee (2012) found an increasing linear effect on soil pH by application of cattle manure compost at different rates.

D'Hose et al. (2014) found a significantly higher pH-KCl in the 0-15 cm soil layer on plots that received annually 50 m^3 farm compost ha^{-1}, compared to non-amended plots, i.e., a 0.6 pH increase in five years time. With regard to the 0-10 cm soil layer, the difference between C_{45} and C_0 plots was of the same order of magnitude (0.4 pH units) for an annual recurrent application in a time span of only three years. Incubation experiments by Steel et al. (2012) with several farm composts including composts applied in this field experiment also revealed a significant pH increase compared to the blank treatment irrespective of the feedstock materials used in the compost.

No effect from the tillage factor on soil pH was found. Rasmussen (1999) mentioned in a review paper that most experiments have shown that soil reaction (pH) was unaffected by tillage systems and depths. However, in a long-term tillage trial on loam soil in Norway, repeated measurement of soil acidity (pH-H_2O) showed values for the 0-5 and 5-20 cm soil layers which were 0.1-0.3 pH units lower with reduced tillage than with conventional autumn ploughing (Ekeberg and Riley, 1997). The lower pH in the 0-10 cm than in the underlying 10-30 cm soil layer may be related to a greater acidification at higher rates of net N mineralization and nitrification (Paul et al., 2001). The lower pH-$KCl_{0\text{-}10cm}$ layer may also be related to the acidifying effect of synthetic N fertilizers, which apparently manifests itself in the surface layers, according to different studies. At the end of a 5-year study period, Blevins et al. (1977) found that - irrespective the tillage method - N fertilization lowered the pH of the 0-5 and 5-15 cm upper layers of a silt loam at a rate of 0.02-0.03 units for every g m^{-2} $year^{-1}$ of N fertilizer and not in the 15-30 cm layer. From a ten-year study of tillage practices on a sandy loam, Aase and Pikul (1995) also found no effect from the tillage factor on soil acidity (pH-H_2O), but yearly application of N fertilizer (NH_4NO_3) decreased pH of the 0-8 cm top layer by about 0.06 units $year^{-1}$ whereas $pH_{8\text{-}15cm}$ was stable. In our field experiment, the pH decrease in the 0-10 cm soil layer on C_0 plots was four times higher, i.e., 0.25 units $year^{-1}$. Taking into account the above mentioned mineral N fertilizer related pH reduction determined by Blevins et al. (1977), a reduction in our three-year study period of about 0.08 units for every g m^{-2} $year^{-1}$ of mineral N fertilizer suggests that another factor than the use of acidifying mineral N fertilizers negatively affected the pH. Moreover, in contrast to the above mentioned studies, the pH decline in our experiment was also apparent in the 10-30 and 30-60 cm soil layers (0.18 and 0.11 units $year^{-1}$, respectively). Periodic lack of oxygen due to waterlogging is typical for the Stagnosol soil group. In addition, the carrot harvesting machine compacted the soil in autumn 2010. So, additional reasons for the steep pH decline might be periodic waterlogging and the bare and poorly aerated soil condition in the winter period 2010-2011 resulting in anaerobic decomposition of incorporated organic material resulting in acidification and leaching of base cations. Fertilizer application and general crop and soil management obviously resulted in an overall pH decrease which was, however, counteracted by compost application.

4.4.4 Plant available nutrients and HWP

Despite the high P input by compost application, especially in case of C_{45}, both plant available P and HWP were not affected by this practice probably due to the very high P status of the soil. K input by compost application enhanced plant available K contents in both 0-10 and 10-30 cm soil layers. K distribution in the soil profile was affected by the tillage method. Our findings are consistent with those cited by Rasmussen (1999) in a review study, i.e., a significant increase of available K in the top layer of shallow tilled soil compared with conventional ploughing, but not in the 10-20 cm layer. A higher

K concentration in the top 0-10 cm layer of the RT plots is apparently due to the shallow incorporation of organic fertilizers and crop residues, as suggested by Lal et al. (1990). The plow-till treatment in their experiment caused a higher exchangeable K content in the 10-20 cm layer. In our experiment, plant available K content in the 10-30 cm soil layer of CT plots did not surpass the content in the 10-30 cm soil layer on RT plots. Therefore, we may assume that, under CT, K moved downward the soil profile beyond the 0-30 cm arable layer by leaching. The significantly higher plant available K content in the 10-30 cm than in the 0-10 cm top layer on CT plots may also be an indication for an on-going leaching process. K might also be susceptible to leaching on RT plots, however, probably at a lower rate or with a certain delay compared to the presumed leaching on CT plots. Although plant available K content in the 0-10 cm soil layer of RT plots tended to be higher than that on CT plots, K did not really accumulate in the 0-10 cm top layer under RT since its concentration was equivalent to that of the 10-30 cm layer. Tillage effects on plant available Mg content were similar to the effects on plant available K content, i.e., a higher $Mg_{0\text{-}10cm}$ under RT compared to CT (on compost amended plots) and no difference between RT and CT for the underlying 10-30 cm soil layer. Only in the case of RT, compost application affected Mg content. These observations indicate that Mg moved downward by leaching beyond the 0-30 cm arable layer on CT plots, certainly to a greater extent than on RT plots. A decrease in soil content of the base cations K and Mg by leaching was confirmed by the general pH decrease, both of which were counteracted by compost application. $Ca_{0\text{-}10cm}$ increased by compost application and was not affected by the tillage factor. Steel et al. (2012) found that the increase of plant available K, Mg and Ca in compost-amended soil corresponded with the concentrations of these elements in the respective composts, which were affected by the elemental concentrations in the feedstock materials.

A significantly higher $Ca{:}Mg_{0\text{-}10cm}$ (+27%) and $Fe_{0\text{-}10cm}$ (+5%) under CT compared to RT may be indicative for subtle differences in soil structure and hydrology. A low $Ca{:}Mg_{0\text{-}10cm}$ on RT plots may have a negative effect on surface soil structure (Little et al., 1992). Yaduvanshi et al. (2010) found that waterlogging significantly increased plant available Fe in comparison to drained treatments. As $Fe_{0\text{-}10cm}$ was significantly higher under CT compared to RT (+5%), we may assume that the top soil under CT was more susceptible to waterlogging. Reduction of plant available Fe by compost application may be explained by the fact that incorporation of compost favors soil aeration limiting a redox potential decrease at high moisture levels.

4.4.5 Soil microbial community

Most microbial groups were significantly and consistently affected by both tillage and compost application. Effects were merely additive and restricted to the 0-10 cm soil layer. In our experiment, both gram-positive and gram-negative bacteria were positively affected by compost application. Bernard et al. (2012) found that compost amendments generally led to increased levels of gram-positive bacteria and fungi. Fungal FAME marker 18:1ω9 was positively affected by compost application in our field trial, but, contrary to the finding of Bernard et al. (2012), the fungal FAME marker 18:2ω6 was not affected. Our results with respect to the tillage factor are in agreement with other studies where abundances of both bacteria and fungi in surface soil (0-7.5 cm) were observed to be higher in NT compared to CT (Doran, 1980; Linn and Doran, 1984). However, in our study it concerned RT and with regard to the bacteria, only the gram-positive bacteria were observed to be higher. On the other hand, all fungal FAME markers were clearly favored by RT, which is consistent with the idea that reduced disturbance facilitates establishment and maintenance of extensive hyphal networks (Wardle, 1995). Beare et al. (1992) found that saprophytic fungi exerted greater control over surface litter decomposition in a NT agro-ecosystem than did bacteria and by contrast, bacteria were more important than fungi in affecting the decomposition rates of buried litter in a conventional tillage system. Fungal FAME markers in the 10-30 cm soil layer were not significantly affected by tillage practice, however, fungal FAME marker 18:2ω6 was significantly more present in the 10-30 cm soil layer compared to the 0-10 cm layer under CT, which possibly indicates that buried litter favored fungal activity as well. From a study at sites representing a wide range of climatic conditions, Frey et al. (1999) observed a significantly higher fungal abundance in NT surface soil (0-5 cm) compared to CT. Actinomycetes and AMF, an important soil quality indicator (Bending et al., 2004), were favored by a combination of reduced tillage and compost application in our experiment.

4.4.6 Overall final soil conditions

When we make a ranking of the six soil management regimes from a hypothetical low to high positive impact on soil quality, i.e., CT-C_0, CT-C_{15}, CT-C_{45}, RT-C_0, RT-C_{15}, RT-C_{45}, this ranking seems to be confirmed by the grouping of management regimes in the biplot of the first two discriminants from a CDA in the six 0-10 cm soil layer. The same impact on quality seems to be confirmed in the 10-30 cm layer, with the exception of the groups ranked in the middle, i.e., CT-C_{45} and RT-C_0.

4.4.7 Crop yield

Annual farm compost amendment did not affect crop yield in our three-year experiment. This is consistent with the results of another Belgian multiyear field trial that tested farm compost application and where only since the fourth year significant increases of dry matter yield were found (D'Hose et al., 2012). Although no short-term effect on crop yield was perceived, recurrent compost application clearly sustained soil quality and therefore might guarantee crop yield level on the longer term. Compost application sequesters carbon in the soil. The maintainance of SOM by compost application also supports soil N supplying capacity. The buffering of the pH and the nutrients input may additionally justify the investment in soil quality by compost application.

Differences in crop yields in our experiment were related to soil tillage but obviously not in a consistent way. Subtle differences in soil condition at youth growth stage affected further crop development and finally crop yield. The fact that a better soil quality, achieved in particular in the 0-10 cm top layer, did not clearly result in a higher production potential may have different reasons. Weather-related growth circumstances were quite favorable during the different growing periods and nutrient input by fertilization was a non-restrictive factor. However, Scandinavian experiments during the 1970s and 1980s have shown that the effect of ploughless tillage on yields has been relatively small (Rasmussen, 1999). In field experiments in southern Europe (Italy) at two locations, the same maize yields were obtained by adoption of minimum tillage compared to traditional ploughing (Alluvione et al., 2013). By combining data of 47 European studies in a meta-regression analysis, Van den Putte et al. (2010) found that the overall average yield reduction by conservation tillage techniques was ca. 4.5% and that deep reduced tillage - as we have practiced - did not result in significant crop yield reduction (except for grain maize). Vegetable crops having a superficial root system and a high yield potential (e.g., leek and carrots) might be extra sensitive for differences in soil structure. Our experiment shows that reduced tillage at a depth comparable to the normal ploughing depth is a viable option for intensive vegetable cropping systems, at least in the initial phase of conversion to a reduced tillage system.

4.5 Conclusions

Compost application and reduced tillage, and the combination of both practices counteracted soil degradation in the short term. Soil degradation was otherwise inevitable under this intensive vegetable cropping system in the three-year study period. Soil degradation was manifested as a decrease of SOM, acidification and leaching of base cations. Apparently, even leaching of organic matter compounds occurred in this trial field. Only the highest compost dose could maintain the initial level of TOC in the arable layer. Compost application buffered the pH irrespective of the compost dose and was a source of plant available Ca, Mg and K. Compost application did not increase yield level in the short term, however, might guarantee yield level on the longer term by sustaining soil quality. Compost application sequesters carbon in the soil.

Reduced tillage induced a favorable stratification for different soil quality indicators and lowered leaching. Differences in soil quality between tillage practices and compost doses were most striking in the top 0-10 cm soil layer. In the 0-10 cm layer, fungi were only favored by reduced tillage and not by compost application whereas gram-positive bacteria, actinomycetes and AMF benefitted from both soil improving practices. In the 10-30 cm layer, neither the tillage factor nor the compost factor significantly affected soil life.

Tillage practice hardly interacted with compost application with regard to its contribution to soil quality. Both practices additively favored soil life in the top 0-10 cm layer. Conversion to reduced, deep non-inversion tillage, sustained crop production in this intensive vegetable cropping system while maintaining soil organic carbon levels.

Chapter 5

Limited short-term effect of compost and reduced tillage on N dynamics in a vegetable cropping system

Adapted from:

Willekens, K., Vandecasteele, B., De Neve, S., 2013. Strong effect of compost and reduced tillage on C dynamics but not on N dynamics in a vegetable cropping system. In: D'Haene, K. et al. (eds.) Proceedings NUTRIHORT: Nutrient management, innovative techniques and nutrient legislation in intensive horticulture for an improved water quality, September 16-18, Ghent, Belgium, 162-169.

Willekens, K., Vandecasteele, B., De Neve, S., 2014. Limited short-term effect of compost and reduced tillage on N dynamics in a vegetable cropping system. *Scientia Horticulturae* 178, 79-86.

5.1 Introduction

Compost application and reduced tillage are both soil carbon (C) saving practices. Compost application supplies stable organic matter while reduced tillage suppresses organic matter decomposition by minimizing soil inversion and soil structure disruption (Alluvione et al., 2013). These soil management practices may also improve soil quality by favoring nutrient availability, soil structure and soil organisms. Bernard et al. (2012) observed an increased microbial population and activity after compost application. D'Hose et al. (2014) found that repeated applications of farm compost increased soil organic carbon content, hot-water extractable carbon content, number of earthworms present, microbial biomass and reduced soil bulk density. Release of nutrients from compost increases nutrient availability and microbial activity (Duong et al., 2013). Aggregates in the surface layer are more stable in case of no-till or reduced tillage soils, which is associated with an increased organic matter content (Cannell, 1985). In contrast to a plough-based system, in which residues are buried, a reduced tillage system increases the organic matter content in the top layer. This encourages growth of a different range of soil organisms compared with a plough-based system (Rasmussen and Collins, 1991).

Nitrogen (N) is a key element in plant nutrition. Excessive N use has led to environmental problems, which now calls for careful management of N application. Intensive field vegetable production systems are particularly prone to N losses due to inherent low

N efficiency related to superficial rooting, large amounts of crop residues and excessive N fertilization, which is used to boost crop productivity and quality (Armbruster et al., 2013). Knowledge-based N fertilizer recommendation can be a tool to reduce N losses in order to fulfill the requirements of the EU Nitrates Directive (Rahn, 2013). Recommendation of N fertilization should be based on properly estimated crop N demands and soil N mineralization potential (Appel, 1994) and should account for effects of soil management practices on N availability. Repeated compost application is expected to increase N availability due to an increase in N mineralization from the added organic N (Leroy et al., 2007; Chalhoub et al., 2013). On the other hand, application of not fully matured compost (high C/N) may cause temporary immobilization of N due to readily available C sources being added to soil (Amlinger et al., 2003). Addition of stabilized organic matter by regular compost application may improve the soil physical properties and hence plant growth and nutrient uptake. D'Hose et al. (2012) reported a positive yield effect of recurrent farm compost application, which could be attributed to extra N supply but also to improved general conditions for crop growth. In that trial, crop yield increased even at the highest level of fertilizer N supply (D'Hose et al., 2012). Soil tillage practices may change the N turnover processes in the soil both spatially and temporally. In a study by D'Haene et al. (2008), a higher mineralization rate in the 0-15 cm top soil under reduced tillage (compared to conventional tillage) was related to the strong stratification of soil organic matter (SOM) in the reduced tillage system.

Our research hypothesis was that soil quality sustaining practices, namely compost application and reduced tillage, would affect soil N mineralization potential, fertilizer N availability and crop N uptake in the short term. Related research questions were if the supposed change in N availability would occur to an extent that (i) N fertilization strategy should be adapted and (ii) the risk of N losses (by nitrate leaching) would considerably change. We set up a field trial in September 2008 with different combinations of compost application rates and soil tillage practices. During three growing seasons (2009-2011), N dynamics were assessed.

5.2 Materials and methods

5.2.1 Experimental setup and crop monitoring

Experimental setup and crop monitoring of the Vegtilco trial were fully described under Chapter 4, except following N dynamics' items. At broccoli harvesting in July, subsamples were composed from bud and crop residue parts, on which whole plant dry matter and N contents were determined in order to calculate dry matter production and total N uptake.

In the leek growing season, top mineral N dressing was introduced as a third factor and the trial design was extended from a split-plot to a split-split-plot design. Eight weeks after planting leek in 2011, i.e., one week after soil sampling for determination of the mineral N amount in the 0-60 cm soil layer, three N doses, i.e., zero, 30 and 60 kg N ha^{-1} were applied as top mineral N dressing (calcium ammonium nitrate, 27% N) on three randomized sub-subplots (Figure 5.1). Presented and discussed effects of tillage and compost application at the last sampling moment (s3) in 2011 just concern the outcome from the sub-subplots that received 30 kg top mineral N dressing ha^{-1}. At leek harvesting in November, a subsample of a few plants was taken to determine whole plant dry matter and N content and calculate dry matter production and total N uptake.

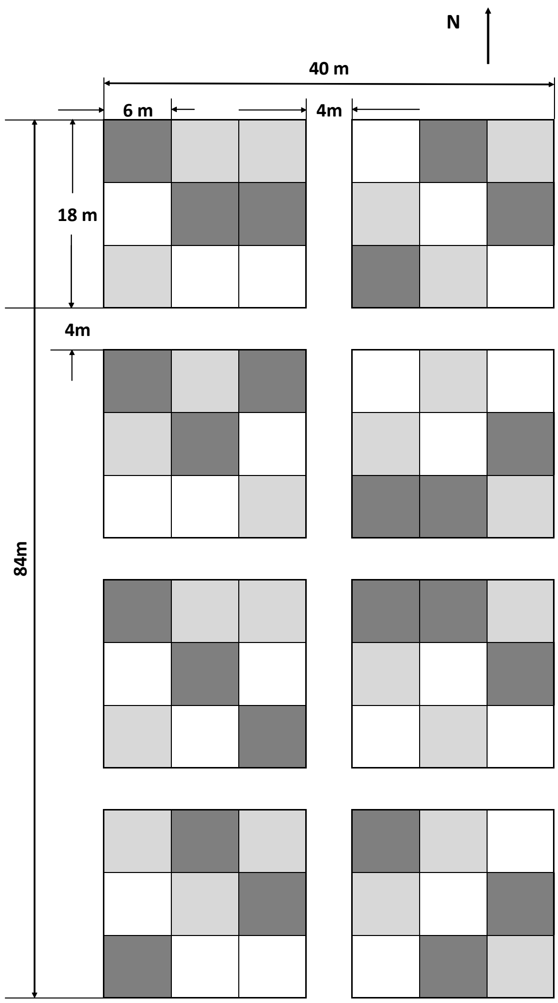

Figure 5.1 Sub-subplots in the field experiment with split-split-plot design; levels of top mineral N dressing (sub-subplot factor) in the leek growing season represented by blank, light-shaded and dark-shaded squares for zero, 30 and 60 kg N ha^{-1}, applied with calcium ammonium nitrate, 27% N (main and subplot factor presented in Figure 4.1).

5.2.2 Assessment of N dynamics

The amount of mineral N in both the 0-30 cm arable layer ($Nmin_{0\text{-}30cm}$) and the 0-90 cm soil profile ($Nmin_{0\text{-}90cm}$) was determined before the start (s1), during (s2) and at the end of the cultivation period (s3) (Table 5.1). The distribution of mineral N in the soil profile was assessed by the ratio between $Nmin_{0\text{-}30cm}$ and $Nmin_{0\text{-}90cm}$.

Table 5.1 Profile sampling data for the different growing seasons and respective crops; s1, s2 and s3: first, second and third sampling occasion.

	BROCCOLI 2009	CARROTS 2010	LEEK 2011
s1	3/19	4/14	6/14
s2	6/15	6/28	8/24
s3	7/29	9/27	11/8

With respect to the cultivation period of broccoli and leek, a balance of plant available N was calculated by subtracting N supply from N recovery and was expressed in kg ha^{-1} (Table 5.2). The output side of the balance is the sum of aboveground crop total N uptake and residual soil mineral N. The input side of the balance is the sum of the initial soil mineral N content and mineral N input. The balance represents the "apparent" net N mineralization (ANM) from SOM and added organic materials ("apparent" in that it may also include N losses if these occur during the growing season) (Feller and Fink, 2002). ANM was calculated for the different time periods between sampling events, namely s1-s2, s2-s3 and s1-s3. The intermediate entire plant biomass and N uptake of leek at s2 were determined by harvesting four times two meters of leek per treatment, divided between two rows. Based on the N uptake curve for a standard broccoli crop (Feller et al., 2011), the intermediate N uptake at s2 was assumed to be 20% for broccoli. The mineral N by compost application was less than 2% of the total N input by compost application (section 4.2.1, table 4.1). Mineral N input from compost and the N input from the broccoli and leek planting material were considered to be negligible.

Table 5.2 Supply and recovery items of the considered balances of plant available N; ANM: apparent net N mineralization; Nmin: soil mineral N content; s1, s2 and s3: first, second and third sampling occasion.

	$ANM_{s1\text{-}s2}$	$ANM_{s2\text{-}s3}$	$ANM_{s1\text{-}s3}$
SUPPLY	$Nmin_{0\text{-}90cm}$ at s1	$Nmin_{0\text{-}90cm}$ at s2	$Nmin_{0\text{-}90cm}$ at s1
	base mineral N dressing	top mineral N dressing	base + top mineral N dressing
RECOVERY	$Nmin_{0\text{-}90cm}$ at s2	$Nmin_{0\text{-}90cm}$ at s3	$Nmin_{0\text{-}90cm}$ at s3
	N $uptake_{s1\text{-}s2}$	N $uptake_{s2\text{-}s3}$	N $uptake_{s1\text{-}s3}$

The apparent N recovery from top mineral N dressing for leek, either 30 or 60 kg ha^{-1}, was determined by subtracting the N $uptake_{s2\text{-}s3}$ on the non-fertilized sub-subplots from the N $uptake_{s2\text{-}s3}$ on the fertilized sub-subplots and dividing this by the mineral N dose.

In 2011 at s2, soil samples were taken from the 0-10 and 10-30 cm layers in order to assess potential plant N availability. This was done by determining the net N mineralization using an incubation test. Soil of each subplot was placed in PVC tubes (Ø 4.63 cm, filling height 12 cm and bulk density 1.4 g cm^{-3}) in duplicate. Before filling the tubes, demineralized water was added to obtain a gravimetric moisture content of 16.8% (w/w) equivalent to 50% water-filled pore space. After thorough mixing, the tubes were filled and covered with a single layer of gas-permeable Parafilm® M Barrier Film (Pechiney Plastic Packaging) to minimize water loss. After three weeks' incubation at 15°C and 70% relative humidity, entire tubes were destructively sampled and analyzed.

Besides assessment of plant available N during the experiment, total N stocks in the 0-60 cm soil layer ($Ntot_{0\text{-}60cm}$) were determined at the start and at the end of the experiment in order to evaluate the effect of soil management (tillage type and compost application) on the evolution of N stored in SOM and to estimate the mean yearly net N release from SOM on C_0 subplots.

As rainfall might be important for interpretation of N dynamics, we used data from a nearby weather station for the different balance periods and calendar years (Table 5.3).

Table 5.3 Total amount of rainfall and average daily rainfall (mm) for the different growing seasons and respective time spans (days) between sampling occasions; s1, s2 and s3: first, second and third sampling occasion.

CROP	year	period	mm	days	mm day^{-1}
BROCCOLI	2009	s1-s2	286	88	3.3
		s2-s3	100	44	2.3
		s1-s3	386	132	2.9
		01/01-12/31	915	365	2.5
CARROTS	2010	s1-s2	73	75	1.0
		s2-s3	329	91	3.6
		s1-s3	402	166	2.4
		01/01-12/31	916	365	2.5
LEEK	2011	s1-s2	173	71	2.4
		s2-s3	166	76	2.2
		s1-s3	339	147	2.3
		01/01-12/31	699	365	1.9

5.2.3 Plant and soil analyses and soil mineral N and total N stock calculations

Soil mineral N content was extracted (1:5 w/v) in a 1 M KCl solution according to ISO 14256-2 and measured with a Foss Fiastar 5000 continuous flow analyzer. Soil moisture content was determined as weight loss at 105 °C. Total nitrogen (N_{tot}) content was determined by dry combustion (Dumas principle) with a Thermo flash 4000 according to ISO 13878.

To determine dry bulk density (BD) of the 0-10 cm, 10-30 and 30-60 cm layer, three undisturbed soil cores (100 cm^3) were taken with an auger (Eijkelkamp Agrisearch Equipment) at approximately 5 cm, 20 cm and 45 cm below the soil surface, respectively (ISO 11272). At the start of the experiment in September 2008, BD was determined per main plot under the cereal stubble whereas final BD was determined per subplot under the standing leek crop in August 2011.

The soil layers 0-30, 30-60 and 60-90 cm were sampled separately for analysis of the mineral N content. Sampling was done per subplot, except for broccoli at s2 where samples were taken separately for the two tillage practices across all four replicates. For the calculation of $Nmin_{0\text{-}30cm}$ and $Nmin_{0\text{-}90cm}$, average final BD values of the different soil layers were used. Average values could be taken, as BD was neither affected by soil tillage nor by compost application. BD values in 2009 and 2010 were presumed to be in line with final BD values under the leek crop in 2011. The BD was not determined for the 60-90 cm soil layer, and $BD_{60\text{-}90cm}$ was equated to the $BD_{30\text{-}60cm}$ value.

Initial $Ntot_{0\text{-}60cm}$ values per main plot and final $Ntot_{0\text{-}60cm}$ values per subplot were calculated using initial and final Ntot contents and BD values of the 0-10, 10-30 and 30-60 cm soil layers. To compare the initial $Ntot_{0\text{-}60cm}$ with the final $Ntot_{0\text{-}60cm}$, the same amount of soil must be considered. Differences in BD of the 0-10, 10-30 and 30-60 cm soil layers between both sampling times required an extension of the depth of the subsoil 30-60 cm layer by 1.04 cm for the calculation of the final Ntot $stock_{0\text{-}60cm}$. The difference between the initial and the final $Ntot_{0\text{-}60cm}$ is denoted as $\Delta Ntot_{0\text{-}60cm}$.
To determine broccoli and leek dry matter content, crop subsamples of whole plants were dried in a ventilated oven at 70°C during at least 48h. The N content was determined on ground dried plant material according to the Kjeldahl method (ISO 5983-2) for broccoli and the Dumas method (ISO 16634-1) for leek.

5.2.4 Statistical methods

Split-plot ANOVA (Gomez and Gomez, 1984) with soil tillage as main plot factor and compost application as subplot factor was applied. When top mineral dressing was included in the leek growing season, split-split-plot ANOVA was applied with top mineral dressing as sub-subplot factor. Split-split-plot ANOVA was also conducted with soil layer as sub-subplot factor. At the first sampling occasion in 2009 (19/03), compost application (once in autumn 2008) was the only factor because main tillage (either conventional or reduced) had not yet been performed. If significant interaction effects were found between factors, data analysis was continued either per variant of one or both of the interacting factors. Normality of parameter data was checked using the Kolmogorov-Smirnov test. The Scheffe method was applied for multiple comparison of the means.

5.3 Results

5.3.1 Mineral N stock in the 0-30 cm arable layer

Only in 2010, significant effects were found from the tillage and compost factor on the N availability in the 0-30 cm arable layer (Table 5.4). $Nmin_{0\text{-}30cm}$ at s1 was significantly higher for C_{45} compared to C_0 ($p < 0.01$). $Nmin_{0\text{-}30cm}$ at s1 in year 2 was not affected by the difference in tillage practice in year 1. $Nmin_{0\text{-}30cm}$ at s2 was significantly higher in case of CT compared to RT ($p < 0.001$) and significantly higher for C_{45} compared to C_0 ($p < 0.05$). At s3, no significant effect from the tillage and compost factor on $Nmin_{0\text{-}30cm}$ was observed.

At s3 in 2010, compost application significantly affected the moisture content in the 0-30 cm soil layer, which was significantly higher for C_{45} (17.0% on fresh soil) compared to C_0 (15.8%) ($p < 0.01$) with an intermediate value for C_{15} (16.2%).

Table 5.4 Mineral N content (Nmin) in the 0-30 cm soil layer for the different growing seasons 2009-2011, mean values and standard deviations (between brackets); significant differences between tillage methods or compost doses are indicated by different lowercase letters and p-values (2-way split-plot ANOVA tillage x compost); CT: conventional tillage (ploughing), RT: reduced (non-inversion) tillage; C_0, C_{15}, C_{45}: 0, 15 and 45 Mg farm compost ha^{-1}; s1, s2 and s3: first, second and third sampling occasion; at s1 in 2009, the tillage factor was not yet introduced; at s2 in 2009, samples were only taken separately for the two tillage practices across the 4 replicates.

$Nmin_{0\text{-}30cm}$	kg ha^{-1}	CT	RT	ANOVA	C_0	C_{15}	C_{45}	ANOVA	Scheffe
2009	s1	-	-		17	18	19		
BROCCOLI		-	-		(3)	(10)	(10)		
	s2	101	95		-	-	-		
		-	-		-	-	-		
	s3	23	19		23	19	20		
		(13)	(5)		(12)	(11)	(5)		
2010	s1	34	31		29 a	32 ab	38 b	$p < 0.01$	$p < 0.01$
CARROTS		(7)	(6)		(7)	(6)	(5)		
	s2	67 b	58 a	$p < 0.001$	57 a	62 ab	68 b	$p < 0.05$	$p < 0.05$
		(10)	(9)		(9)	(8)	(13)		
	s3	13	19		12	21	15		
		(4)	(13)		(4)	(15)	(6)		
2011	s1	23	20		22	22	20		
LEEK		(7)	(5)		(9)	(5)	(4)		
	s2	97	115		114	102	102		
		(19)	(30)		(15)	(35)	(27)		
	s3*	22	19		19	20	22		
		(6)	(4)		(4)	(6)	(6)		

*sub-subplots that received 30 kg top mineral N dressing ha^{-1}

5.3.2 Mineral N stock and distribution in the 0-90 cm soil profile

In 2009, $Nmin_{0\text{-}90cm}$ did not differ between treatments at any of the sampling occasions. In 2010, at s1, $Nmin_{0\text{-}90cm}$ was significantly positively affected by compost application. $Nmin_{0\text{-}90cm}$ was 91 kg ha^{-1} on average, but was significantly higher for C_{45} (103 kg ha^{-1}) than for C_0 (84 kg ha^{-1}) ($p < 0.05$). In 2010, at s2 and s3, $Nmin_{0\text{-}90cm}$ did not differ between treatments. In 2011, at s1 and s2, $Nmin_{0-90cm}$ did not differ between treatments. At s3, on sub-subplots that received 30 kg top mineral N dressing ha^{-1}, $Nmin_{0-90cm}$ was 80 kg ha^{-1} on average but tended to be affected by tillage practice with a higher value for CT compared to RT (Table 5.5). $Nmin_{0-90cm}$ significantly differed between levels of top mineral N dressing ($p < 0.001$). $Nmin_{0-90cm}$ was significantly higher ($p < 0.001$) on plots that received 60 kg N ha^{-1} top mineral N dressing (114 kg N ha^{-1}) compared to both plots that received no top mineral N dressing (76 kg N ha^{-1}) and plots that received 30 kg N ha^{-1} (80 kg N ha^{-1}).

At the intermediate sampling occasion s2 in 2010, $Nmin_{0-90cm}$ was equally distributed over the different soil layers (Table 5.6), whereas at s2 in both of the other years, most of the mineral N stock was found in the 0-60 cm soil layer (85% in 2009 and 88% in 2011). At s2 in 2011, an interaction between the tillage and layer factor indicated a difference in distribution of mineral N in the soil profile between tillage systems. Under RT, $Nmin_{0-30cm}$ was significantly higher than $Nmin_{30-60cm,}$ whereas under CT, $Nmin_{0-30cm}$ did not differ from $Nmin_{30-60cm}$ (Table 5.6). The ratio between $Nmin_{0-30cm}$ and $Nmin_{0-90cm}$ was significantly higher under RT (52.3%) compared to CT (45.1%) ($p < 0.05$). In 2009, $Nmin_{0-90cm}$ at s3 was equally distributed over the respective soil layers on sub-subplots that received 30 kg top mineral N dressing ha^{-1}. By contrast, in 2010 and 2011, residual soil mineral N was significantly higher in the two subsoil layers compared to the upper 0-30 cm layer (Table 5.6). In 2011 at s3, on sub-subplots that received 30 kg N ha^{-1} top mineral dressing, compost application significantly affected the ratio between $Nmin_{0-30cm}$ and $Nmin_{0-90cm}$ ($p < 0.01$). The highest compost dose, C_{45}, showed the highest portion (29.7%) of the 0-90 cm soil mineral N amount in the 0-30 cm arable layer compared to lower portions for C_0 (24.1%) and C_{15} (23.8%).

Table 5.5 N supply and recovery items of the balance for available N in the plant-soil system and derived apparent net N mineralization (ANM); mean values and standard deviations (between parantheses); significant differences between tillage methods are indicated by p-values (2-way split-plot ANOVA tillage x compost); CT: conventional tillage (ploughing), RT: reduced (non-inversion) tillage; Nmin: soil mineral N content; s1, s2 and s3: first, second and third sampling occasion (Table 5.1); pl: planting date.

	BROCCOLI				LEEK			
	overall	CT	RT	ANOVA	overall	CT	RT	ANOVA
$Nmin_{0-90cm}$ at s1 (kg ha^{-1})	62				58			
$Nmin_{0-90cm}$ at s2 (kg ha^{-1})	186				218			
$Nmin_{0-90cm}$ at s3** (kg ha^{-1})	55				80	86 (20)	75 (14)	$p < 0.1$
base mineral N dressing (kg ha^{-1})	86*				70			
top mineral N dressing (kg ha^{-1})	100				30			
total mineral N dressing (kg ha^{-1})	186				100			
N $uptake_{s1-s2}$ (kg ha^{-1})	40				36	39 (3)	33 (2)	$p < 0.1$
N $uptake_{s2-s3}$** (kg ha^{-1})	164				146			
N $uptake_{s1-s3}$** (kg ha^{-1})	204	196 (35)	212 (27)	$p < 0.01$	182			
pl - s2 (# days)	32				51			
s2 - s3 (# days)	44				76			
pl - s3 (# days)	76				127			
daily N $uptake_{pl-s2}$ (kg ha^{-1} day^{-1})	1.3				0.7			
daily N $uptake_{s2-s3}$** (kg ha^{-1} day^{-1})	3.7				1.9			
daily N $uptake_{pl-s3}$** (kg ha^{-1} day^{-1})	2.7				1.4			
ANM_{s1-s2} (kg ha^{-1})	79				125			
ANM_{s2-s3}** (kg ha^{-1})	-67				-21			
ANM_{s1-s3}** (kg ha^{-1})	12	8 (34)	16 (32)	$p < 0.1$	104	112 (32)	96 (34)	$p < 0.05$
s1 - s2 (# days)	88				71			
s2 - s3 (# days)	44				76			
s1 - s3 (# days)	132				147			
daily ANM_{s1-s2} (kg ha^{-1} day^{-1})	0.9				1.8			
daily ANM_{s2-s3}** (kg ha^{-1} day^{-1})	-1.5				-0.3			
daily ANM_{s1-s3}** (kg ha^{-1} day^{-1})	0.1				0.7			

*26 (mineral N input by farmyard manure) + 60 (mineral N fertilizer)

**in case of LEEK, sub-subplots that received 30 kg top mineral N dressing ha^{-1}

Table 5.6 Mineral N content (Nmin) in the soil profile for the different growing seasons 2009-2011, mean values and standard deviations (between brackets); significant differences between soil layers are indicated by different lowercase letters and p-values (3-way split-plot ANOVA tillage x compost x layer); soil layers 0-30, 30-60 and 60-90 cm and soil profile 0-90 cm; s1, s2 and s3: first, second and third sampling occasion.

Nmin	kg ha^{-1}	0-30	30-60	60-90	ANOVA	Scheffe	0-90
2009	s1	18 a	21 ab	23 b	$p < 0.05$	$p < 0.05$	62
BROCCOLI		(8)	(6)	(7)			
	s2	98	59	28			186
	s3	21	16	18			55
		(10)	(6)	(8)			
2010	s1	33 b	31 b	27 a	$p < 0.001$	$p < 0.05$	91
CARROTS		(7)	(9)	(9)			
	s2	62	58	71			191
		(11)	(14)	(34)			
	s3	16 a	33 b	37 b	$p < 0.001$	$p < 0.001$	86
		(10)	(20)	(25)			
2011	s1	22	16	21			58
LEEK		(6)	(11)	(10)			
	s2	106	85	27			218
		(26)	(24)	(9)			
	s2 / CT	97 b	93 b	27 a	$p < 0.001$	$p < 0.001$	218
		(19)	(28)	(9)			
	s2 / RT	115 c	77 b	26 a	$p < 0.001$	$p < 0.001$	217
		(30)	(16)	(10)			
	s3*	21 a	33 b	27 b	$p < 0.001$	$p < 0.05$	80
		(5)	(9)	(9)			

**sub-subplots that received 30 kg top mineral N dressing ha^{-1}

5.3.3 N uptake and biomass production and apparent N recovery from top mineral N dressing

Compost application did not affect total N uptake or (total) fresh plant biomass for any of the crops. The tillage factor, however, appeared to affect N uptake and biomass production of broccoli and leek. A significantly higher broccoli N uptake was observed under RT compared to CT ($p < 0.01$) (Table 5.5). This coincided with a significantly higher total fresh plant biomass under RT compared to CT ($p < 0.05$) (Table 5.7). N uptake$_{s1-s2}$ by leek tended to be higher under CT than under RT (Table 5.5). This coincided with a significantly higher amount of intermediate total fresh plant biomass under CT compared to RT ($p < 0.05$) (Table 5.7). On sub-subplots that received 30 kg top mineral N dressing ha^{-1}, the total fresh plant biomass at s3 tended to be higher on CT compared to RT, but total N uptake did not differ between tillage types (Table 5.5). Neither compost application nor soil tillage affected carrot yield (Table 5.7).

Table 5.7 Total fresh plant biomass data (root yield for carrots).

	date	Mg ha^{-1}	K	NK	ANOVA
BROCCOLI	7/22-29	58.4	56.0	60.8	$p < 0.05$
CARROTS	9/17	111.8			
LEEK	8/25	13.9	15.3	12.6	$p < 0.05$
	11/8	74.2	77.9	70.5	$p < 0.1$

At s3, N uptake just tended to differ between plots with different top mineral N dressing ($p < 0.1$). Apparent N recovery from top mineral N dressing did not differ between plots with different compost application or soil tillage practice. No significant difference between the apparent N recovery at both doses of top mineral N dressing was observed. The average apparent N recovery of the top mineral N dressed plots was 34% (standard deviation +/- 86%).

5.3.4 Apparent net N mineralization, changes in total N stock in the 0-60 cm soil and potential net N mineralization

5.3.4.1 ANM$_{s1-s3}$

For broccoli in 2009, ANM$_{s1-s3}$ was not affected by compost application, but ANM$_{s1-s3}$ tended to be higher under RT compared to CT (Table 5.5). For leek in 2011, ANM$_{s1-s3}$ was not affected by compost application, but was significantly higher for CT than for RT ($p < 0.05$) (Table 5.5).

5.3.4.2 ANM_{s1-s2} and ANM_{s2-s3}

ANM_{s1-s2} was not affected by any of the factors in either of the two growing seasons under consideration. The daily ANM_{s1-s2} for broccoli in 2009 was half of the daily ANM_{s1-s2} for leek in 2011 (Table 5.5). ANM_{s2-s3} was not affected by any of the factors in either of the two growing seasons under consideration. For broccoli and leek, the reduction in soil mineral N between the second and third sampling occasion (i.e., $Nmin_{0-90cm}$ at s2 + top mineral N dressing after s2 - $Nmin_{0-90cm}$ at s3) was larger than the crop N uptake between both sampling occasions. This resulted in negative ANM_{s2-s3} values.

5.3.4.3 $\Delta Ntot_{0-60cm}$

$Ntot_{0-60cm}$ and $\Delta Ntot_{0-60cm}$ were significantly affected by compost application (ANOVA $p < 0.05$; $C_{45} > C_0$, Scheffe $p < 0.05$). $\Delta Ntot_{0-60\ cm}$ for C_0, C_{15} and C_{45} were -0.38, -0.04 and +0.09 Mg ha^{-1}, respectively, or -5.4, -0.6 and +1.3% of the initial total N stock of 6.99 Mg ha^{-1}, respectively. No tillage effect on $Ntot_{0-60cm}$ was observed. Annual N release from SOM on C_0 subplots was 1.82% of $Ntot_{0-60cm}$ or on average 125 kg N ha^{-1}.

5.3.4.4 Potential net N mineralization

For soil sampled at s2, there was a significant interaction effect on potential net N mineralization between the tillage and layer factor ($p < 0.001$). For the 0-10 cm layer, potential net N mineralization was significantly higher in case of RT (7.9 mg N kg^{-1} dry soil) than in case of CT (5.4 mg N kg^{-1} dry soil) ($p < 0.01$), whereas for the 10-30 cm layer, it tended to be the opposite (RT: 3.0 mg N kg^{-1} dry soil versus CT 4.3 mg N kg^{-1} dry soil) ($p < 0.1$). Potential net N mineralization was significantly higher for the 0-10 cm than for the 10-30 cm soil layer in case of both tillage practices, but this layer effect was much more pronounced for RT than for CT ($p < 0.001$ and $p < 0.05$, respectively). No effect of compost application was found on the potential net N mineralization.

5.4 Discussion

5.4.1 Soil mineral N stock and potential net N mineralization in the arable layer

Assessment of the soil mineral N stock in the arable layer did not indicate any need to adapt N fertilizer recommendation in the short term because effects from the tillage and compost factor on $Nmin_{0-30cm}$ were very limited. These effects occurred only in the second growing season (2010) when carrots were grown and mineral N dressing was low. $Nmin_{0\text{-}30cm}$ at s1 and s2 was affected by autumn application of compost in 2008 and 2009. Although the differences between the highest dose (C_{45}) and the zero treatment were significant, they were only about 10 kg N ha^{-1}, and had disappeared by the end of the growing season. Soil mineral N content may either be positively or negatively affected by compost application depending on compost maturity (Chalhoub et al., 2013) and soil type (Alluvione et al., 2013). At s1 in 2010, $Nmin_{0\text{-}30cm}$ was not affected by differences in tillage practice and therefore the tillage effect on $Nmin_{0\text{-}30cm}$ at s2 was only related to the difference in tillage practice between s1 and s2. Compared to reduced tillage, moldboard ploughing might have caused the soil structure to be looser and may have resulted in a somewhat higher soil temperature, both of which favor N mineralization from SOM in spring. The tillage effect had disappeared towards the end of the growing season.

The lower potential net N mineralization (as measured in the incubation test) in the 0-10 cm soil layer for CT plots compared to RT plots seemed to be compensated by a higher potential net N mineralization in the 10-30 cm layer. This in line with the lack of observable differences in N availability in the 0-30 cm soil layer between tillage types in the leek growing season. The more pronounced difference in N release between both soil layers in the lab experiment for RT, compared to CT, is in line with the observed difference in distribution of soil organic matter between both tillage practices. $TOC_{0\text{-}10\ cm}$ was significantly higher than $TOC_{10\text{-}30\ cm}$ on RT plots, whereas on CT plots the TOC of both layers did not differ (Chapter 3). D'Haene et al. (2008) studied RT and CT fields with comparable soil type and crop rotation. The N mineralization rate derived from an incubation experiment with undisturbed 0-15 cm top soil was on average a 1.55 times larger for RT than for CT fields. The ratio that we have found in our lab experiment with disturbed 0-10 cm top soil was of the same order of magnitude, i.e., 1.46. Kandeler et al. (1999) have also found an acceleration of N mineralization in the 0-10 cm layer with a reduction of tillage intensity, from ploughing, over reduced to minimum tillage. Neither the lab experiment nor the field situation in 2011 showed differences in N availability when using compost.

5.4.2 Mineral N content in the 0-90 cm soil profile

One of our original research questions was whether soil management would affect the soil mineral N content and alter the risk of leaching losses, especially at the end of growing period. Compost application affected $Nmin_{0\text{-}90cm}$ only at s1 in 2010. Even after three consecutive applications, compost did not affect residual soil mineral N under leek in 2011 despite a total N input of 312 and 937 kg ha^{-1} over three years in C_{15} and C_{45}, respectively. Maynard (1994) did not find significant differences in nitrate concentrations in the groundwater under compost-amended plots with four application rates (0, 25, 50, 100 Mg dry matter ha^{-1}). Compost hardly affected N availability in the three-year period of our experiment. On the other hand, compost application, even at a moderate yearly dose (C_{15}), sustained $Ntot_{0\text{-}60cm}$ and can possibly affect future N supply from SOM mineralization, as suggested by Chalhoub et al. (2013). The tillage factor did not significantly affect $Nmin_{0\text{-}90cm}$ at any of the sampling occasions in the different growing seasons. Comparing conventional tillage consisting of disking and chisel plowing with no-tillage, Franzluebbers and Hons (1996) found few differences in soil profile nitrate distribution over a ten-year period. Over a three-year period in our experiment, i.e, at the third sampling occasion in the third growing season, a tendency to a higher $Nmin_{0\text{-}90cm}$ under CT compared to RT was observed, which may be related to the significantly higher $ANM_{s1\text{-}s3}$. At the second sampling occasion in the same season, a higher portion of $Nmin_{0\text{-}90cm}$ was found in the top 0-30 cm layer under RT, which may indicate that the stock of mineral N is less prone to leaching. This is in line with the observation during the incubation test that N release from SOM under RT predominantly took place in the upper 0-10 cm soil layer.

5.4.3 N supply, N uptake, biomass production and residual nitrate-N, and apparent N recovery from top mineral N dressing

The apparent non-recovery of compost N by the crops may be related to the stability of the compost. Chalhoub et al. (2013) found that composts with higher biodegradability exhibit a higher proportion of N recovery by plants during the year following their application, while more stabilized composts increased the N availability mainly through the increase of soil organic N content and mineralization after several compost applications. The proven higher soil mineral N availability on compost-amended plots at the start of the carrot growing season (2010) did not result in a higher crop yield (Table 5.7). Obviously, neither N uptake nor biomass production responded to compost application in any of the growing seasons.

In case of broccoli (2009), tillage practice affected both N uptake and biomass production. There was a higher N uptake under RT compared to CT at an equal level of residual N. The tendency for a higher $ANM_{s1\text{-}s3}$ under RT probably indicates a somewhat higher net N release from SOM resulting in a higher N uptake by broccoli. In case of leek crop (2011), tillage practice did not affect N uptake but tended to affect biomass production (Table 5.7). Giacomini et al. (2010) found no effect of tillage type on fertilizer N losses and plant recovery comparing conventional tillage by moldboard ploughing to a depth of 30 cm with minimum tillage to a depth of 5-8 cm. This finding seems to be partly confirmed by our experiment comparing moldboard with chisel ploughing.

With regard to the leek crop in our experiment, measurements of N supply, N uptake and residual mineral N corresponded quite well with the findings of Thorup-Kristensen and Sørensen (1999). The total N supply for leek at s2, considering only the 0-60 cm soil layer, was 221 kg N ha^{-1} (i.e., the soil mineral N stock of 191 kg ha^{-1} plus 30 kg top mineral N dressing). This was equal to the optimum N supply of 220 kg N ha^{-1} for leek as proposed by Sørensen (1993), who considered a sampling depth up to 50 cm. Total N uptake in our trial (i.e., 182 kg ha^{-1}) was somewhat higher than the N uptake (i.e., 165 kg ha^{-1}) found by Thorup-Kristensen and Sørensen (1999) at optimum N supply. As could be expected from that finding, residual nitrate-N up to 90 cm depth in our trial (i.e., 70 kg ha^{-1}) was somewhat lower than the residual nitrate-N found in the Danish trial (87 kg N ha^{-1} in the 0-100 cm soil profile) at optimum N supply. For carrots, $Nmin_{0\text{-}60cm}$ at s2 was 120 kg N ha^{-1} or twice the optimum N supply of 60 kg N ha^{-1} proposed by Sørensen (1993). Therefore, it was not surprising that the residual nitrate-N up to 90 cm depth in our trial (i.e., 74 kg ha^{-1}) was almost three times as high than the residual nitrate-N (i.e., 27 kg N ha^{-1}, 0-100 cm) at optimum N supply in the Danish experiment. The total N supply for broccoli at s2, considering the 0-60 cm soil layer only, was a soil mineral N stock of 158 kg ha^{-1} plus 100 kg top mineral N dressing. The residual nitrate N up to 90 cm depth was only 35 kg N ha^{-1}. The N supply seemed to have been very well utilized by the broccoli crop.

Top mineral N dressing hardly contributed to plant N uptake and crop growth. By comparing average N uptake and residual soil mineral N values of plots which received either 30 or 60 kg N ha^{-1} top mineral N dressing, it appeared that the N recovery of the additional 30 kg N ha^{-1} was low or non-existent and just increased the level of residual mineral N. A fertilization dose of 100 kg mineral N (70 kg base + 30 kg top mineral N dressing) in combination with approximately the same amount of apparently available N by soil N mineralization did guarantee a steady and healthy crop growth, resulting in a good crop yield in the next spring.

Apparent N recovery from top mineral N dressing did not differ between treatments in our trial. In a field experiment by Giacomini et al. (2010), reduced tillage did not affect the recovery of fertilizer ^{15}N applied as top mineral N dressing on winter wheat. A high

N availability at s2, as well as its high variability have complicated the assessment of apparent N recovery from top mineral N dressing.

5.4.4 Apparent net N mineralization

5.4.4.1 $ANM_{s1\text{-}s3}$

For broccoli, $ANM_{s1\text{-}s3}$ tended to be higher under RT compared to CT due to the higher N uptake under RT at a similar level of residual soil mineral N for both tillage practices. In case of leek, the higher $ANM_{s1\text{-}s3}$ under CT compared to RT was not related to a higher total N uptake but rather to a tendency toward a higher level of residual soil mineral N under CT. Thus, higher N availability due to the tillage practice, either CT or RT, resulted only in case of RT in a higher total N uptake.

For leek, $ANM_{s1\text{-}s3}$ on a daily basis was 0.7 kg ha^{-1} day^{-1}. This resulted from a rather high apparent net N mineralization in the first partial balance period (s1-s2) and an apparent net N immobilization in the second partial balance period (s2-s3). The soil acted as a source of mineral N in the first half of the growing season, whereas it acted as a sink in the second half of the growing season. The same phenomenon appeared under broccoli and carrots in 2009 and 2010, respectively (see below). Feller et al. (2011) found near zero or slightly negative ANM values with respect to the whole growing period in case of vegetable crops with a relatively short growing period and a high N demand and consequently high fertilizer N supply. This is in line with our finding of a considerably higher sink effect in case of broccoli as compared to leek, resulting in a near zero daily $ANM_{s1\text{-}s3}$ (< 0.1 kg ha day^{-1}). The broccoli growth period was 40% shorter than the leek growth period and the broccoli daily N uptake was twice the leek daily N uptake. Daily $ANM_{s1\text{-}s3}$ values for leek and carrots were considerably higher and mutually comparable.

5.4.4.2 $ANM_{s1\text{-}s2}$ and $ANM_{s2\text{-}s3}$

On a daily basis, $ANM_{s1\text{-}s2}$ for broccoli in 2009 was half as large as that for leek in 2011, which might be caused by higher N immobilization rates due to both the incorporated rye stubble and the C-rich and fresh FYM before transplanting broccoli. A limited effect of the FYM application on $ANM_{s2\text{-}s3}$ might have been expected because of the relatively small organic N input by this manure. However, a potential effect of the compost amendment on ANM in the broccoli growing season might have been masked by the FYM application. On the other hand, since the N fertilizer replacement value of compost is very low (about

10%; Petersen, 2003) and as it was already applied in the preceding autumn, a compost effect on ANM in the broccoli growing season was not very likely to happen. The residual effect in the next growing seasons of a single FYM application is supposed to be small (Schroder et al., 2013). In 2011, under leek, the combination of a high soil-derived N availability (high $ANM_{s1\text{-}s2}$) and a base mineral N dressing of 70 kg ha^{-1} may explain that there was no effect from compost application on N availability. Alluvione et al. (2013) suggested that a high native N availability can mask N release from applied compost. From the second sampling occasion on, part of the applied or available soil mineral N was either lost, immobilized, or both, as revealed by negative $ANM_{s2\text{-}s3}$ values in the case of broccoli and leek, and apparently also in the case of carrots (see below). Losses may occur both by leaching or volatilization. Immobilization may consist of N uptake in the root system and N uptake by soil microbiota. For broccoli, the negative $ANM_{s2\text{-}s3}$ coincided with a low soil mineral N content at harvest. The negative value was possibly related to a persisting N immobilization due to the incorporated rye stubble and C-rich FYM. Under leek between s2 and s3, N mineralization and immobilization apparently were in balance since some leaching of nitrate-N might have occurred lowering the balance result to a negative value. Leaching losses were more probable under leek between s2 and s3 in 2011 as this period spanned the colder months of September and October. In contrast, leaching losses are less probable under broccoli between s2 and s3 in 2009, because that period comprised the warmer months of June and July. A limited gaseous loss of the superficially applied ammonium nitrate could be another explanation, but, given the low pH at our site, ammonia volatilization was unlikely to be significant. Whole-plant N uptake was used for calculating ANM, but only a limited part of the root system was harvested in case of leek. In the case of broccoli, no root parts were included in crop sampling. Excluding the (entire) N content of the root system from the calculation lowered the values for $ANM_{s2\text{-}s3}$ causing an overestimation of the share of the N immobilization in the balance result.

5.4.4.3 ANM under carrots in 2010

A steep increase of $Nmin_{0\text{-}90cm}$ appeared in 2010 between s1 and s2 (+ 100 kg N ha^{-1}). Taking the base mineral N dressing of 50 kg N ha^{-1} and a presumed N uptake of 100 kg N ha^{-1} (Feller et al., 2011) into account, this implies an ANM of 150 kg ha^{-1} or 2.0 kg ha^{-1} day^{-1} (s1-s2 75 days), exceeding $ANM_{s1\text{-}s2}$ in 2011 with 25 kg ha^{-1} or with 0.2 kg ha^{-1} day^{-1} ($ANM_{s1\text{-}s2}$ = 100 + 191 – 91 – 50 = 150). This rather high daily mineralization rate was possibly related to the incorporation of the N-rich crop residues of the previous broccoli crop. The yellow mustard cover crop grown after the broccoli took up part of the nitrogen released from the broccoli residues, and this N was probably released (at least partially) in the next growing season. Based on the carrots' gross yield (Table 5.7) and a presumed N content (Feller et al., 2011), another 80 kg N ha^{-1} was assumed to be taken up between s2 and s3. Taking a $Nmin_{0\text{-}90cm}$ decrease of 105 kg ha^{-1} into account, this implies a negative ANM of -25 kg ha^{-1} or -0.3 kg ha^{-1} day^{-1} (s2-s3 spans 91 days), comparable with $ANM_{s2\text{-}s3}$ in 2011 (i.e., -21 kg ha^{-1} or -0.3 kg ha^{-1} day^{-1}) ($ANM_{s2\text{-}s3}$ = 80 + 86 – 191 = -25). The halving of $Nmin_{60\text{-}90cm}$ between s2 and s3 in 2010 may be indicative for N leaching, which can be linked to an above average daily rainfall in this period (Table 5.3). Based on these calculations of ANM values for the partial balance periods, $ANM_{s1\text{-}s3}$ was 125 kg ha^{-1} or, on a daily basis, 0.8 kg ha^{-1} day^{-1} (s1-s3 spans 166 days) in the carrot growing season. A difference of less than 0.1 kg ha^{-1} day^{-1} implies a consistent daily ANM value with regard to the leek and carrot growing season. An aberrantly low daily ANM for the broccoli growing season can be explained by the incorporation of the rye stubble and the application of C-rich FYM.

5.5 Conclusions

Soil organic N stock was substantially sustained by compost application. Reduced tillage practice guaranteed equivalent crop performance compared to moldboard ploughing. In the 3-year experimental term, differences in N dynamics due to differences in soil management practices occurred but not to an extent that would require adjustment of N fertilization. When conventional ploughing significantly positively affected the soil mineral N content, it only happened to an extent that did not seriously increase the risk for N losses. Compost application did not increase neither N availability nor yield level in the short term, however, might guarantee soil N supplying capacity and yield level on the longer term by sustaining soil quality. Compost application sequesters carbon in the soil. Despite a high organic N input, compost application did not result in higher amounts of residual soil mineral N. Apparent net N immobilization values in the second half of each growing season indicated that the soil acted as a sink for soil mineral N in the second half of the growing season.

Chapter 6

Nutrient availability, crop performance and soil quality from on- and off-farm amendments and tillage practices in organic vegetable growing

After: Willekens, K., Vandecasteele, B., Van Gils, B., Fliessbach, A., Sukkel, W., Koopmans, C.J., De Neve, S. (in preparation for submission). Nutrient availability, crop performance and soil quality from on- and off-farm amendments and tillage practices in organic vegetable growing

6.1 Introduction

Soil quality is a top priority in organic agriculture, where soil is regarded as the central production factor. Soil quality may be improved by reducing soil disturbance from tillage practices, by semi-permanent soil cover using green manure crops and by diversified crop rotations, all key practices in conservation agriculture (Scopel et al., 2013). A diversified crop rotation is a standard practice in organic agriculture for reasons such as disease suppressiveness and soil protection. Reduced, non-inversion tillage may favor soil quality in a quite short-term perspective (Berner et al., 2008; Willekens et al., 2014a), however challenges organic producers with regard to weed control, incorporation of crop residues and animal manure, and N availability in spring (Peigne et al., 2007; Koopmans and Bokhorst, 2002). Inversion tillage practices are effectively controlling weed populations, and supporting the destruction and incorporation of green manures, crop residues, and animal manure. Consistent implementation of reduced tillage is particularly difficult in vegetable rotations. Alternating between tillage types, e.g., those which favor soil organic matter (SOM) build-up and others favoring the mineralization process and consequently N release from SOM might be a good strategy.

Biological N fixation (BNF) via leguminous inter- or green manure crops adds N into the plant-soil system without importing P. This is of importance because of legal limitations in P input to prevent or reverse excessively high soil P contents and the related risk for P runoff and leaching. For soils low in plant available P, green manure crops are suggested to mobilize P after destruction and mineralization of their biomass (Cavigelli and Thien, 2003). As an alternative to using symbiotically fixed N by growing a cash crop after the leguminous green manure on the same field, symbiotically fixed N can be used by applying the biomass of a leguminous green manure grown on a different field to the cash crop in form of a cut-and-carry system. In this way, nutrients can be efficiently recycled on-farm, which is an advantage, particularly on farms with limited access to animal manures. The biomass can be conserved e.g., as grass-clover silage, which offers more flexibility for targeted N fertilization when needed in the crop rotation as studied by Sorensen and Thorup-Kristensen (2011) and Carter et al. (2014). Ley pastures including leguminous species are often used for soil fertility building in organic cropping systems (Ball and Douglas, 2003).

Synchrony of the N release from organic amendments with the N uptake requirement of the crop is a challenge for producers, because it is not only depending on the quality of the amendment, but also on moisture and temperature during its decomposition in soil. Legume residues may release N in synchrony and in adequate amounts with the uptake pattern of corn (*Zea Mays*) (Stute and Posner, 1995). Despite a delay in N uptake from a vetch green manure, sustained availability later in the season guaranteed optimum corn grain yield and N uptake (Kramer et al., 2002). Plant available N is an important and valuable production factor. When soil mineral N contents are excessively high, N losses from the system might harm the environment. Excess residual mineral N in the soil profile at the end of the growing season poses a serious nitrate leaching risk. However, a lower potential risk of N leaching appeared from slower N mineralization in organic and low-input farming systems compared to conventional farming systems (Poudel et al., 2002). Campiglia et al. (2014) assessed the effect of cover crops and their residue managements on the following pepper (*Capsicum annuum*) crop productivity. A combination of legume cover crops and strip mulching maximized the productivity in this system (Campiglia et al., 2014). Koller et al. (2008) investigated the influence of green manure management (grass-clover, grass and *Phacelia*) on N delivery for the proceeding crop cabbage.

Balancing between fertilizer types is an important issue in organic vegetable cropping systems in order to provide the crop with sufficient mineral N without overloading the soil with P. A high P surplus may lead to high orthophosphate levels in the soil solution prone to leaching (Vanden Nest et al., 2015). Like composts, cut-and-carry fertilizers from leguminous species are not jeopardizing the nutrient balance as nutrients are recycled on-farm. Farm compost, however, can be prepared with on-farm or off-farm feedstock materials, or both. Compost application sustains or increases SOM by the input of stabilized organic matter (D'Hose et al., 2012; Parkinson et al., 1999; Willekens et al., 2014a). Stabilization of organic matter during the composting process implies mass reduction and consequently an increase in P content (Vandecasteele et al., 2014), which builds a risk for P-over-fertilization. Organic-input based systems succeed to retain N in the system as found in long-term cropping systems studies (Drinkwater et al., 1998; Jenkinson, 2001; Peters et al., 1997), whereas conventional management practices may lead to a reduction of soil fertility (Clark et al., 1998; Mulvaney et al., 2009).

The overall aim of this study was to assess, in a short-term perspective, N and P dynamics in an organic vegetable cropping system, comparing reduced tillage with conventional tillage, while dealing with green manures and organic fertilization. A 2-year field trial was set up at ILVO, Melle, Belgium. In the first year, we investigated (i) N and P availability from a grass-clover ley (mineral N amount and directly available P content, and their distribution in the soil profile), and (ii) leek (*Allium porrum*) crop performance (N and P uptake and biomass yield) under different grass-clover termination strategy and tillage practices. In the next growing season, we assessed the effects of tillage practice and fertilization practice (cut-and-carry fertilizer and farm compost application) on (i) N and P availability and (ii) celeriac (*Apium graveolens var. rapaceum*) crop performance. We hypothesized that:

i. Grass-clover termination practices either restrict or stimulate N and P availability during the leek growing period (Fig. 6.1, rel. 1 & 2) and consequently crop performance (Fig. 6.1, rel. 5). Resulting nutrient availability depends on tillage type (interaction termination strategy x tillage factor).
ii. Cut-and-carry fertilization (grass-clover biomass transfer) and compost application increase N and P availability during the celeriac growing season (Fig. 6.1, rel. 1 & 2) and consequently crop performance (Fig. 6.1, rel. 5). Nutrient availability from these fertilization practices depends on tillage type (interaction fertilization x tillage factor).
iii. Tillage practices either restrict or stimulate N and P availability (Fig. 6.1, rel. 3 & 4) and consequently crop performance (Fig 1, rel. 5)
iv. Tillage practice affects physical soil condition, either positively or negatively, and consequently crop performance (Fig 1, rel. 6)
v. Grass-clover biomass transfer and compost application interact affecting N and P availability and crop performance.

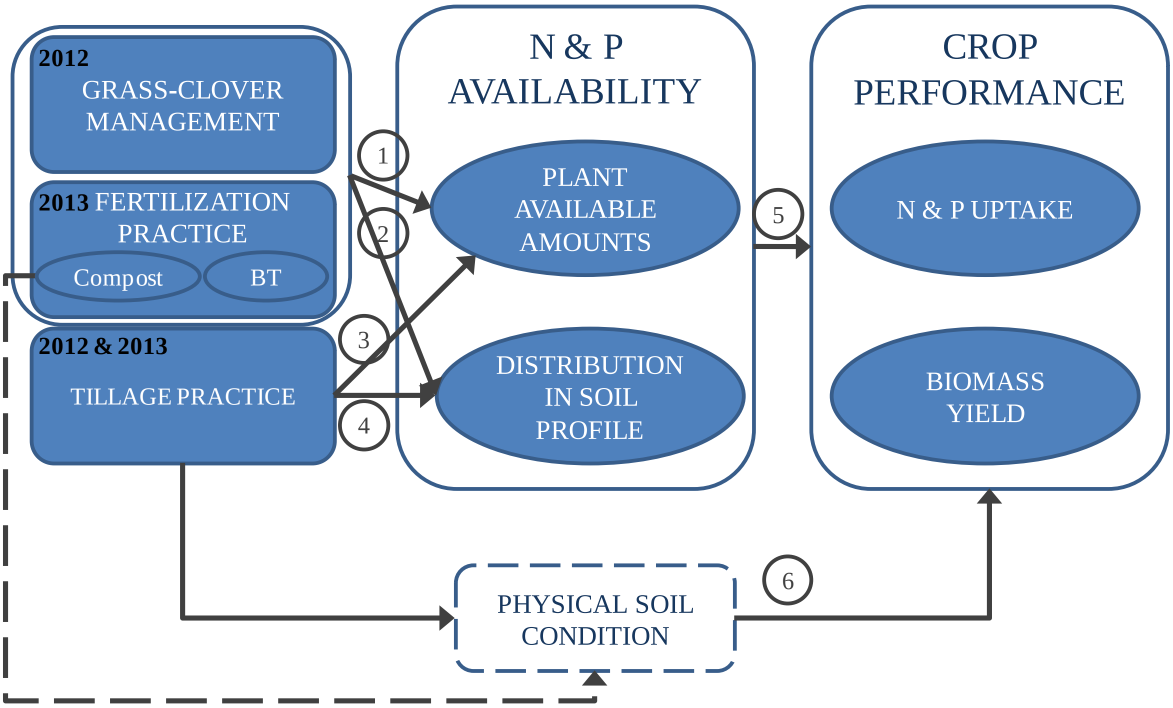

Figure 6.1 Hypothetical relationships between management practices, N and P availability and crop performance; numbers refer to specific relations between factors which are further specified in the manuscript; BT: grass-clover biomass transfer.

6.2 Materials and methods

6.2.1 Experimental setup

A three-factorial field experiment (Tilman-org trial) with a split-split-plot design was set up in spring 2012 (Figure 6.2). The field was located 50°59'8.3" N, 3°47'12.3" E (Melle, Belgium) on a sandy loam soil (66% sand > 50µm, 20% silt 2-50 µm and 14% clay 0-2 µm), classified as Eutric Retisol (Loamic) (Dondeyne et al., 2014; IUSS Working Group WRB, 2015). Previous to the experiment, maize (*Zea mays* subsp. *mays*) was grown in 2009 and flax (*Linum usitatissimum*) in 2010. A grass-clover ley (*Lolium perenne, Trifolium pratense* and *Trifolium repens*) was established in September 2010 after flax. In the growing season 2011, grass-clover cuts were either removed or the biomass remained as mulch on the field. In 2012, the experiment started with tillage (T) as the main factor and grass-clover termination strategy (TS) as a subplot factor. In 2013, farm compost application (C) was added as sub-subplot factor. All treatments were performed in 4 replicates. Individual sub-subplots (48 in total) had a size of 7.5 by 15 m.

On February 24th 2012, samples were taken from the 0-10, 10-30 and 30-60 cm soil layers of each replicate plot (four in total) with an Eijkelkamp gouge auger as a mixed sample of

18 individual soil cores, for analysis of chemical parameters (total organic C (TOC), total N (Ntot), pH-KCl and plant available P, K, Ca and Mg). After a 2-year period, the chemical soil status was reassessed per sub-subplot (48 in total). Samples were taken on March 13th 2014 from the same soil layers mixing 12 individual soil cores.

After a full year of grass-clover in 2011, we tested three ways of grass-clover termination in 2012, selected according to increasing N input from grass-clover aboveground biomass to the following leek crop. The grass-clover ley was destroyed either on March 19th after a single mulching (TS1, early destruction) or on May 18th (late destruction). In case of late destruction, the grass-clover biomass was either cut and removed (TS0) or mulched three times (TS2). Destruction was done by cutting above-ground plant parts from the root system with a cultivator (Actisol©) equipped with overlapping winged tines in a shallow setting, followed by a powered rotary harrow. Tillage depth for grass-clover destruction was approximately 10 cm. After destruction, leek was grown. Preparatory soil tillage just before planting leek on June 20th was done either by conventional tillage (CT) with a mouldboard plough down to 30 cm depth, or by reduced tillage (RT) with a non-inversive chisel plough (Actisol©) down to approximately the same depth. Combining two tillage methods (CT and RT) and three TS variants (TS0, TS1 and TS2) resulted in six treatments.

The N input from grass-clover aboveground biomass and its N and P content were determined for the grass-clover termination strategy variants. We assumed that there were no differences in nutrient input from stubble and roots amongst the treatments. On March 14th (TS1, TS2), April 16th (TS2) and May 8th (TS0 and TS2), grass-clover was cut and collected from 4 strips of 1.6 m by 4 m for each replicate.

In case of removal of a full-grown grass-clover cut (TS0), 87 kg N ha^{-1} and 13 kg P ha^{-1} were exported. The N and P input from grass-clover aboveground biomass was 46 kg N ha^{-1} and 5 kg P ha^{-1} for TS1 and 133 kg N ha^{-1} and 16 kg P ha^{-1} for TS2.

Besides incorporation of the grass-clover, no additional fertilization was applied in order to maximally distinguish the nutrient release and utilization by the leek crop for the different management variants. On a regular basis, mechanical weed control was performed. After the diagnosis of leek moth (*Acrolepiopsis assectella*), the entire field was treated twice with XenTari® (*Bacillus thuringiensis*) in August. Crop yield was determined on October 30th.

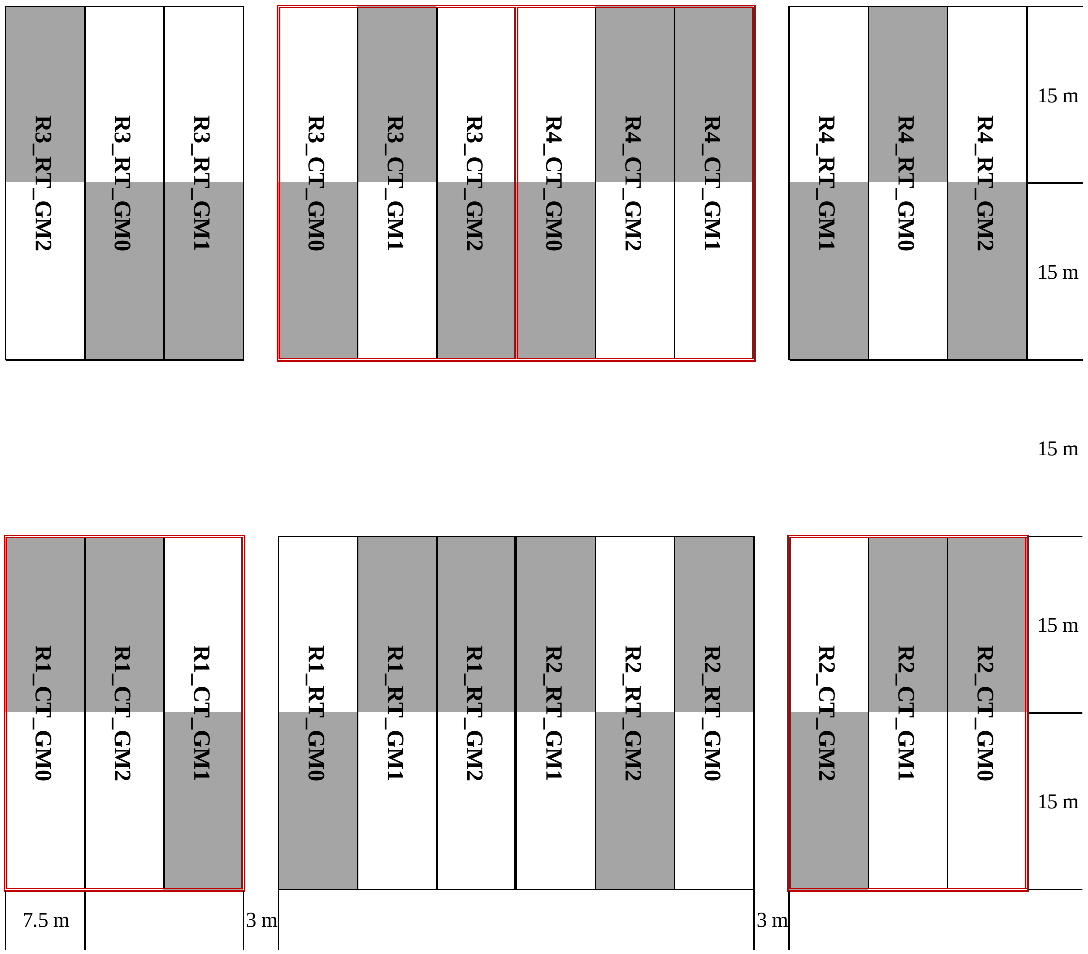

Figure 6.2 Split-split-plot design of the three-factorial field experiment at ILVO, Melle, Belgium; four replicates R1, R2, R3, R4; CT: conventional ploughing (red delineated main plots); RT: reduced tillage; GM: grass-clover management strategy, i.e., grass-clover termination strategy in 2012 (TS1: early destruction on March 19th on GM1 subplots, TS0: late destruction on May 18th after cutting and removal of a full-grown grass-clover cut on GM0 subplots and TS2: late destruction after repeated mulching on GM2 subplots) and grass-clover biomass transfer in 2013 (BT0: zero Mg ha^{-1} on GM0 subplots, BT1: 9.8 Mg ha^{-1} on GM1 subplots and BT2: 19.6 Mg ha^{-1} on GM2 subplots); shaded sub-subplots: 32.9 Mg ha^{-1} farm compost in 2013.

In 2013, celeriac was grown. On April 10th, farm compost was applied at zero rate (C0) and at 32.9 Mg ha^{-1} (C1) corresponding to 185 kg N ha^{-1} (Table 6.1). Farm compost was prepared at ILVO and composed of poplar bark, wood chips, grass clippings, hay, cereal straw and organic chicken manure (Vandecasteele et al., 2014). Grass-clover silage was applied as cut-and-carry fertilizer, i.e., grass-clover biomass transfer (BT) on May 2nd at zero (BT0), 9.8 (BT1) and 19.6 Mg ha^{-1} (BT2), corresponding to zero, 96 and 191 kg N ha^{-1}, respectively. The subplots having received the lowest (TS0), intermediate (TS1) and highest (TS2) N input by the grass-clover aboveground biomass in 2012 received the lowest (BT0), intermediate (BT1) and highest (BT2) N input by grass-clover biomass transfer in 2013, respectively. The doses for BT2 and C1 were calculated to achieve an equal OM, N and K supply by BT2 and C1.

Table 6.1 Cut-and-carry fertilizer (BT) and farm compost (C) doses, nutrients content and input; OM: organic matter.

	Grass-clover biomass transfer					Farm compost			
		BT0	BT1	BT2			C0	C1	
		0	9.8	19.6	Mg ha^{-1}		0	32.9	Mg ha^{-1}
	kg Mg^{-1}	kg ha^{-1}				kg Mg^{-1}	kg ha^{-1}		
N	9.8	0	96	191		5.6	0	185	
P	1.3	0	12	25		3.6	0	117	
K	9.8	0	95	191		6.0	0	199	
Ca	3.9	0	39	77		22.0	0	724	
Mg	1.2	0	12	23		1.9	0	64	
Na	0.2	0	2	5		0.3	0	11	
OM	332	0	3245	6491		180	0	5926	
C/N	18.9					17.8			
C/P	145					28			

On May 16th, celeriac was planted. Preparatory soil tillage just before planting was done either by conventional tillage with a mouldboard plough (CT) or by reduced tillage (RT) with a chisel plough, i.e., deep non-inversion tillage (comparable with ploughing depth). Combining two tillage methods (CT and RT), three grass-clover biomass transfer variants (BT0, BT1 and BT2) and two compost doses (C0 and C1) resulted in 12 different treatments. On a regular basis, mechanical weed control was performed, with some additional manual weeding. Higher sensitivity to leaf spot disease (*Septoria apiicola*) appeared in RT plots. No crop protection agents were used in 2013. Crop yield was determined on October 20th.

6.2.2 Assessment of N and P dynamics and crop response

For assessment of plant N and P availability, soil profile sampling was performed four times during each growing season (Table 6.2). In 2012, soil was sampled at the end of the winter season before grass-clover growth started up (s1), after grass-clover sward destruction before main tillage and planting leek (s2), approximately 8 weeks after planting (s3) and at crop harvest (s4). In 2013, soil was sampled at the end of the winter season before application of compost and cut-and-carry fertilizer (s1), approximately 6 and 15 weeks after planting celeriac (s2 and s3, respectively) and at crop harvest (s4).

At the first 2 sampling occasions (s1 and s2) in 2012, the 0-30 and 30-60 cm soil layers were separately sampled (Table 6.2) for determination of the mineral N amount (kg ha^{-1}), i.e., the quantity of NO_3^--N and NH_4^+-N, in the 0-30 cm arable layer ($Nmin_{0\text{-}30\ cm}$) and the 0-60 cm soil profile ($Nmin_{0\text{-}60\ cm}$), and for the analysis of P-$CaCl_2$, i.e., the directly available P content (mg kg^{-1} dry soil). From the third sampling occasion (s3) in the first growing season, i.e., after a variation with regard to tillage practice, the 0-10, 10-30 and 30-60 cm soil layers were sampled (Table 6.2) and the mineral N amount in the 0-10 cm top layer ($Nmin_{0\text{-}10\ cm}$) was determined as well. At each fourth sampling occasion (s4), the 60-90 cm soil layer was also sampled for determination of the residual soil mineral N amount in the 0-90 cm soil profile at the end of the growing season ($Nmin_{0\text{-}90\ cm}$). Determination of P-$CaCl_2$ was restricted to 30 cm depth, either for the 0-30 cm or the 0-10 and 10-30 cm soil layers. In the second growing season, P-$CaCl_2$ was only determined at s2 and s3.

$Nmin_{0\text{-}10\ cm}$, $Nmin_{0\text{-}30\ cm}$, and $Nmin_{0\text{-}60\ cm}$ were calculated using the bulk densities (BD) of respectively the 0-10, 10-30 and 30-60 cm soil layers. BD was either determined at the start of the growing season (mineral N amount at s1 and s2 in 2012 and mineral N amount at s1 in 2013) or at its end (Nmin on all other sampling occasions). BD was not affected by the treatments, therefore an average was used. $Nmin_{0\text{-}90\ cm}$ was calculated assuming that $BD_{60\text{-}90cm}$ was equal to $BD_{30\text{-}60cm}$. To determine BD's of the 0-10 cm, 10-30 and 30-60 cm layers, three undisturbed soil cores (100 cm^3) were taken with an auger (Eijkelkamp Agrisearch Equipment) at approximately 5 cm, 20 cm and 45 cm below the soil surface, respectively (ISO 11272).

Table 6.2 Soil layer depths at consecutive sampling occasions and corresponding sampling dates.

	sampling occasion	s1	s2	s3	s4
2012	sampling date	2/27	6/14	8/13	10/30
	soil	0-30	0-30	0-10	0-10
	layers	30-60	30-60	10-30	10-30
	(cm)			30-60	30-60
					60-90
2013	date	3/19	6/25	8/26	11/20
	soil	0-10	0-10	0-10	0-10
	layers	10-30	10-30	10-30	10-30
	(cm)	30-60	30-60	30-60	30-60
					60-90

In order to assess the distribution of mineral N in the soil profile, the ratio between $Nmin_{0\text{-}10\ cm}$ and $Nmin_{0\text{-}30\ cm}$ was calculated for each sampling occasion, as well as the ratio between $Nmin_{0\text{-}30\ cm}$ and $Nmin_{0\text{-}60\ cm}$ and the ratio between $Nmin_{0\text{-}60\ cm}$ and $Nmin_{0\text{-}90\ cm}$.

These ratios represent the portion of the mineral N amount in the upper part of the arable layer or soil profile and are a measure of N availability to the crop since the higher mineral N is present in the soil profile the better it is accessible for the root system, and the less it is prone to leaching.

Fresh plant biomass and N and P uptake was determined at s3 and s4. Leek plant biomass (whole plants, inclusive of the upper 2 cm portion of the root system) at s3 was determined by harvesting 4 times 3 meter per subplot in 2 different rows (2 times 3 meter per row). Leek plant biomass at s4 was determined by harvesting 3 times 4 meter per subplot in 3 different rows. Plant dry matter, N and P content were determined in order to calculate leek crop N and P uptake. For leek, no crop residues remained on the field. Celeriac plant biomass (foliage + tuber biomass yield, i.e., tubers inclusive of a part of the root system) at s3 and s4 was determined by harvesting 3 times 5 entire plants per sub-subplot in 3 different rows (5 plants per row). At both sampling occasions, s3 and s4, foliage and tubers were separated and weighed for determination of tuber and foliage biomass. Dry matter, N and P content of tubers and foliage were determined in order to determine N and P uptake by celeriac.

An N balance was calculated in both growing seasons by subtracting N supply from N recovery. N recovery is the sum of crop N uptake and $Nmin_{0\text{-}60\ cm}$ at the end of the considered balance period. N supply is $Nmin_{0\text{-}60\ cm}$ at the beginning of the balance period (no mineral N input by fertilization in this experiment). The balance represents the “apparent” net N mineralization (ANM) from SOM and organic matter applied by fertilization. ANM may also include N losses occurring during the balance period (Feller and Fink, 2002). ANM was calculated for different balance periods between subsequent sampling occasions, i.e., s1-s3, s3-s4 and s1-s4 in both years. Mineral N content in the farm compost applied before celeriac (see section 2.1 above) and N content of leek and celeriac planting material were not accounted for in the balance of plant available N as respective N amounts were considered to be negligible.

Apparent N recovery from fertilizer (grass-clover aboveground biomass, cut-and-carry fertilizer or compost) was calculated as the difference in N uptake between fertilized and non-fertilized treatments divided by the total amount of fertilizer N (Sorensen and Thorup-Kristensen, 2011). Apparent fertilizer N recovery was calculated for the N uptake at s3 and s4 using average N uptake data. When two fertilization types were involved (cut-and-carry fertilizer and compost) apparent fertilizer N recovery of one type was calculated with N uptake data at the zero level of the other type.

6.2.3 Plant and soil analyses

Soil mineral N was extracted (1:5 w/v) in a 1 M KCl solution according to ISO 14256-2 and measured with a Skalar San++ continuous flow analyzer. Soil moisture content was determined as weight loss at 105 °C. P intensity, i.e., the directly available P fraction, was determined as the 0.01 M $CaCl_2$ extractable P (P-$CaCl_2$) (Djodjic and Mattsson, 2013; Hesketh and Brookes, 2000). P-$CaCl_2$ was measured with ICP-OES (Varian Vista-pro axial) after shaking (165 rpm) 10.00 g fresh soil with 100 ml of a 0.01 M $CaCl_2$-solution during 2 h in closed dark-colored lightproof polypropylene 250 ml flasks, and filtration over a Machery Nagel 640w filter (NEN 5704, 1996). Although P-$CaCl_2$ was measured on moist soil samples, P-$CaCl_2$ was recalculated on dry soil basis, taking the soil moisture content into account.

TOC was measured on oven-dried (70 °C) soil samples by dry combustion at 1050 °C with a Skalar Primacs SLC TOC-analyzer according to ISO 10694. Total N (N_{tot}) content was determined by dry combustion (Dumas principle) with a Thermo flash 4000 according to ISO 13878. pH was measured potentiometrically in a 1M KCl solution (1:5 v/v) according to ISO 10390. Plant available P, K, Ca and Mg (mg 10^{-2} g^{-1} dry soil) (P_{AL}, K_{AL}, Ca_{AL} and Mg_{AL}) were determined by extraction of 5.00 g air-dry soil with 100 ml ammonium-lactate acetic acid buffer (pH 3.75) (Egnèr et al., 1960; NEN 5793, 2008) and measuring with ICP-OES after microwave digestion of the filtrate.

Crop subsamples of whole plants or plant parts were dried in a ventilated oven at 70°C during at least 48h to determine crop dry matter content. N and P content were determined on dried and ground plant material with correction of the residual moisture in the air-dried samples. N content was determined according to the Dumas method (ISO 16634-1). To determine total P content, plant material was incinerated and the ash was treated with H_2O, HCl and HNO_3. After filtration, the filtrate was mixed with ammonium molybdate and ammonium metavanadate reagent (Cavell, 2006) and diluted with H_2O. The P in the solution was measured in a spectrophotometer (430nm) (Varian Cary 60 UV-VIS).

6.2.4 Data analysis

Split-plot ANOVA (Gomez and Gomez, 1984) with tillage as main plot factor and either grass-clover termination strategy or biomass transfer as subplot factor was applied. When compost was involved as a third factor, a split-split-plot ANOVA was conducted. If significant interaction effects were found between factors, data analysis was continued either per variant of an interacting factor (ANOVA or split-plot ANOVA) or with data of combinations of variants of the interacting factors (ANOVA). Normality of data was checked using the Kolmogorov-Smirnov test. The Scheffé method was applied for multiple comparison of the means.

6.3 Results

6.3.1 Plant biomass, N and P uptake

6.3.1.1 Leek growing season 2012

Leek plant biomass at s3 (biom $_{s3}$) was 9.0 Mg ha^{-1}. Nutrient uptake in the s1-s3 period (Nupt $_{s3}$, Pupt $_{s3}$) was 32.2 kg N and 2.3 kg P per ha, without differences between tillage practices and TS variants.

TS2 resulted in the highest leek plant biomass at s4 (biom $_{s4}$), significantly different from TS0 (Table 6.3). Under CT, the plant biomass increase in the s3-s4 period before harvest (biom$_{s3\text{-}s4}$) was significantly higher for both TS2 and TS1 compared to TS0, and under RT, biom$_{s3\text{-}s4}$ tended to be higher for TS2 compared to TS1 and TS0. Nupt$_{s3\text{-}s4}$ and Nupt$_{s4}$ were significantly lower for TS0 compared to both other TS variants. Pupt$_{s3\text{-}s4}$ and Pupt$_{s4}$ were significantly lower for TS0 compared to TS2. No significant differences between TS variants appeared with regard to crop N, P and dry matter content.

The tillage factor hardly affected crop growth and nutrient uptake, however on TS2 subplots, biom$_{s3\text{-}s4}$ was significantly higher for RT (45.2 Mg ha^{-1}) compared to CT (41.4 Mg ha^{-1}) (ANOVA, $p < 0.05$) (Table 6.3). This higher growth rate for RT on TS2 subplots coincided with a significantly lower dry matter content of the leek plant biomass at s4 (RT 8.2% versus CT 9.0%) (ANOVA, $p < 0.05$).

In case of TS1, apparent N recovery from N input via grass-clover aboveground biomass was 6% and 41% at s3 and s4, respectively. Apparent N recovery from TS2 was 4% and 16% at s3 and s4, respectively.

Table 6.3 Leek plant biomass at s4 ($biom_{s4}$), N uptake at s4 ($Nupt_{s4}$) and P uptake at s4 ($Pupt_{s4}$), plant biomass increase, N and P uptake in the s3-s4 period ($biom_{s3\text{-}s4}$, $Nupt_{s3\text{-}s4}$, $Pupt_{s3\text{-}s4}$, resp.), the percentage dry matter (DM %) and N and P content of the leek plant biomass (% on DM) at s4 for different grass-clover termination strategies (TS1: early destruction on March 19th, TS0: late destruction on May 18th after cutting and removal of a full-grown grass-clover cut and TS2: late destruction after repeated mulching); mean values (n = 8 or n = 4 in case mean values per tillage variant) and standard deviations between parentheses; significant differences between variants are indicated with superscript lowercase letters.

				TS0		TS1		TS2		ANOVA	Scheffé
t1-t3	$biom_{t3}$	Mg ha^{-1}		8.5	(1.1)	8.9	(0.8)	9.7	(2.2)	-	
	$Nupt_{t3}$	kg ha^{-1}		29.5	(3.8)	32.2	(3.1)	34.8	(7.9)	-	
	$Pupt_{t3}$	kg ha^{-1}		2.2	(0.4)	2.3	(0.3)	2.5	(0.6)	-	
t3-t4	$biom_{t3\text{-}t4}$	Mg ha^{-1}	CT	35.6 ^{a}	(7.4)	42.6 ^{b}	(4.4)	41.4 ^{b}	(5.2)	0.01	0.05
		Mg ha^{-1}	RT	39.9	(5.1)	39.8	(5.7)	45.2	(3.8)	0.1	-
	$Nupt_{t3\text{-}t4}$	kg ha^{-1}		74.0 ^{a}	(17.2)	90.1 ^{b}	(13.2)	90.0 ^{b}	(12.2)	0.05	0.05
	$Pupt_{t3\text{-}t4}$	kg ha^{-1}		9.1 ^{a}	(1.3)	10.3 ^{ab}	(1.3)	11.0 ^{b}	(1.1)	0.05	0.05
t1-t4	$biom_{t4}$	Mg ha^{-1}		46.2 ^{a}	(6.6)	50.1 ^{ab}	(5.4)	53.0 ^{b}	(5.2)	0.01	0.01
	$Nupt_{t4}$	kg ha^{-1}		103.5 ^{a}	(17.4)	122.4 ^{b}	(15.7)	124.8 ^{b}	(12.1)	0.01	0.05
	$Pupt_{t4}$	kg ha^{-1}		11.4 ^{a}	(1.3)	12.6 ^{ab}	(1.4)	13.5 ^{b}	(1.2)	0.01	0.01
	N_{t4}	% on DM		2.9	(0.4)	3.2	(0.3)	3.2	(0.3)	-	
	P_{t4}	% on DM		0.32	(0.03)	0.33	(0.02)	0.35	(0.02)	-	
	DM_{t4}	%	CT	8.8	(0.4)	8.7	(0.6)	9.0	(0.4)	-	
			RT	9.0	(0.8)	9.0	(1.0)	8.2	(0.2)	0.1	-

6.3.1.2 Celeriac growing season 2013

Tuber biomass at s4 (tub $biom_{s4}$) and N uptake at s4 ($Nupt_{s4}$) were significantly higher with grass-clover biomass transfer (cut and carry fertilizer, BT) and compost application as compared to no fertilization, and by the tillage factor in favor of CT (Table 6.4c) as compared to RT. P uptake at s4 ($Pupt_{s4}$) was significantly affected by both fertilizers. Foliage biomass at s4 (fol $biom_{s4}$) was significantly affected by compost application. Differences between tillage variants in tuber biomass at s4 and nutrient uptake at s4 (tub $biom_{s4}$, $Nupt_{s4}$) coincided with differences in tuber development and nutrient uptake in the second half of the growing season (tub $biom_{s3\text{-}s4}$, $Pupt_{s3\text{-}s4}$) (Table 6.4b) whereas differences in tuber biomass and nutrient uptake at s4 (tub $biom_{s4}$, $Nupt_{s4}$, $Pupt_{s4}$) due to grass-clover biomass transfer coincided with differences in crop development and nutrient uptake in the first half of the growing season (fol $biom_{s3}$, tub $biom_{s3}$, $Nupt_{s3}$, $Pupt_{s3}$). Compost affected tuber biomass and nutrient uptake during the whole growing season, excepted N uptake in the second half of the growing season (N $upt_{s3\text{-}s4}$) (Table 6.4a, b, c). Tuber and foliage biomass at s3 and nutrient uptake at s3 were only significantly affected by the fertilization factors and not by tillage practice (Table 6.4a). However, at s3, N and P contents in tuber dry biomass were already significantly higher under CT (2.1% N; 0.55% P) compared to RT (1.9% N; 0.54% P). N and P contents in foliage dry biomass at s3 were also significantly higher under CT compared to RT, but only on BT0 and BT1 subplots (CT-BT0 2.5% N versus RT-BT0 2.1% N and CT-BT1 2.7% N versus RT-BT1 2.0% N; CT-BT0 0.26% P versus RT-BT0 0.23% P and CT-BT1 0.27% P versus RT-BT1 0.24% P). A significantly higher tuber and foliage biomass at s3 on BT2 subplots compared to BT0 subplots (Table 6.4a) coincided with a significantly higher N content in tuber dry biomass on BT2 subplots (2.1% N) compared to BT0 subplots (1.9% N) and, under RT, a significantly higher N content in foliage dry biomass on BT2 subplots (2.5% N) compared to BT0 subplots (2.1% N). Higher tuber biomass at s4 as a result of both CT, compared to RT, and grass-clover biomass transfer (BT2 versus BT0) coincided with a significantly higher N content in tuber dry biomass and a lower tuber dry matter content (Table 6.4c), whereas a higher tuber biomass at s4 as a result of compost application coincided with a significantly higher P content in tuber dry biomass (C0 0.50% P versus C1 0.59% P) in case of a RT practice. Compost application did not lower dry matter content while enhancing tuber biomass at s4. Tuber P content at s3 was also significantly higher for C1 compared to C0 on BT0 and BT1 subplots (results not shown).

Apparent N recovery from BT1 was 18% at s3 and 14% at s4. Apparent N recovery from BT2 was 12% at s3 and 14% at s4, and it was 17% at s3 and 19% at s4, from C1.

Table 6.4 a, b, c Celeriac tuber and foliage biomass at s3 and s4 (tub/fol biom$_{s3}$, biom$_{s4}$, resp.), N uptake at s3 and s4 (Nupt$_{s3}$, Nupt$_{s4}$, resp.) and P uptake at s3 and s4 (Pupt$_{s3}$, Pupt$_{s4}$, resp.) (tables 4a and 4c, resp.), tuber biomass increase and N and P uptake in the s3-s4 period (tub biom$_{s3\text{-}s4}$, Nupt$_{s3\text{-}s4}$, Pupt$_{s3\text{-}s4}$, resp.) (table 4b) and N (% on DM) and dry matter (DM %) content at s4 (table 4c) for the different tillage practices (RT: reduced tillage versus CT: conventional mouldboard), the different grass-clover biomass transfer variants (BT0: zero Mg ha^{-1}, BT1: 9.8 Mg ha^{-1} and BT2: 19.6 Mg ha^{-1}) and both compost variants (C0: zero Mg ha^{-1} and C1: 32.9 Mg ha^{-1}); mean values (n = 24 for tillage variants, n = 16 for biomass transfer (BT) variants and n = 24 for compost variants) and standard deviations between parentheses; significant differences between variants are indicated with superscript lowercase letters.

Table 6.4a s1- s3 period

	tub biom $_{s3}$ Mg ha^{-1}		fol biom $_{s3}$ Mg ha^{-1}		Nupt $_{s3}$ kg ha^{-1}		Pupt $_{s3}$ kg ha^{-1}	
CT	23.4	(2.7)	15.4	(2.0)	102.3	(12.5)	18.2	(2.4)
RT	23.9	(4.7)	15.3	(2.5)	93.6	(20.4)	18.5	
ANOVA	-		-		-		-	
BT0	21.3 ^{a}	(3.4)	14.3 ^{a}	(2.2)	88.1 ^{a}	(16.0)	17.1 ^{a}	(3.1)
BT1	24.1 ^{b}	(3.9)	15.5 ^{ab}	(2.0)	98.4 ^{ab}	(19.3)	18.9 ^{ab}	(3.2)
BT2	25.6 ^{b}	(2.9)	16.3 ^{b}	(2.0)	107.3 ^{b}	(10.7)	19.1 ^{b}	(2.2)
ANOVA	0.001		0.01		0.01		0.05	
Scheffé	0.05		0.01		0.01		0.05	
C0	21.8 ^{a}	(3.4)	14.4 ^{a}	(2.1)	92.8 ^{a}	(17.0)	16.6 ^{a}	(2.5)
C1	25.5 ^{b}	(3.3)	16.3 ^{b}	(1.8)	103.1 ^{b}	(16.5)	20.1 ^{b}	(2.4)
ANOVA	0.001		0.001		0.01		0.001	

Table 6.4b s3- s4 period

	tub biom $_{s3\text{-}s4}$ Mg ha^{-1}		Nupt $_{s3\text{-}s4}$ kg ha^{-1}		Pupt $_{s3\text{-}s4}$ kg ha^{-1}	
CT	30.6 ^{b}	(5.7)	20.6	(17.4)	10.9 ^{b}	(4.0)
RT	22.7 ^{a}	(6.2)	10.8	(18.3)	7.1 ^{a}	(3.8)
ANOVA	0.01		0.1		0.01	
BT0	25.1	(6.5)	15.2	(16.7)	8.3	(3.7)
BT1	26.1	(8.2)	14.3	(21.3)	10.2	(5.1)
BT2	28.8	(6.4)	17.6	(17.8)	8.5	(4.0)
ANOVA	-		-		-	
C0	24.5 ^{a}	(7.4)	14.5	(16.9)	7.3 ^{a}	(3.9)
C1	28.9 ^{b}	(6.3)	16.9	(20.0)	10.7 ^{b}	(4.1)
ANOVA	0.01		-		0.01	

Table 6.4c s1- s4 period

	tub biom $_{s4}$ Mg ha^{-1}		fol biom $_{s4}$ Mg ha^{-1}		Nupt $_{s4}$ kg ha^{-1}		Pupt $_{s4}$ kg ha^{-1}		tub N % $_{s4}$		tub DM % $_{s4}$	
CT	54.1 ^{b}	(7.0)	4.0	(0.7)	122.9 ^{b}	(17.2)	29.1	(5.2)	2.2 ^{b}	(0.3)	9.6 ^{a}	(0.7)
RT	46.6 ^{a}	(9.4)	4.5	(0.8)	104.4 ^{a}	(19.5)	25.6	(5.7)	2.0 ^{a}	(0.2)	10.2 ^{b}	(0.7)
ANOVA	0.05		-		0.05		0.1		0.01		0.05	
BT0	46.4 ^{a}	(9.2)	4.2	(0.8)	103.3 ^{a}	(18.1)	25.4 ^{a}	(5.8)	2.0 ^{a}	(0.3)	10.1	(0.8)
BT1	50.2 ^{ab}	(9.2)	4.4	(0.7)	112.7 ^{ab}	(19.8)	29.0 ^{b}	(6.1)	2.1 ^{ab}	(0.3)	10.0	(0.8)
BT2	54.4 ^{b}	(7.3)	4.1	(0.8)	125.0 ^{b}	(18.4)	27.6 ^{ab}	(4.8)	2.3 ^{b}	(0.2)	9.5	(0.5)
ANOVA	0.01		-		0.01		0.05		0.001		0.1	
Scheffé	0.01				0.01		0.05		0.01			
C0	46.3 ^{a}	(9.2)	4.0 ^{a}	(0.7)	107.4 ^{a}	(19.7)	24.0 ^{a}	(4.6)	2.2	(0.3)	10.0	(0.9)
C1	54.4 ^{b}	(6.9)	4.5 ^{b}	(0.7)	120.0 ^{b}	(19.6)	30.7 ^{b}	(4.6)	2.1	(0.3)	9.8	(0.5)
ANOVA	0.001		0.05		0.01		0.001		-		-	

6.3.2 Soil mineral N amount and distribution in the soil profile

6.3.2.1 Leek growing season 2012

Tillage type affected the mineral N amount and its distribution in the soil profile. At s3, the top 0-10 cm layer under RT showed a 55% higher mineral N amount (25.0 kg ha^{-1}) compared to CT (16.1 kg ha^{-1}) (ANOVA split-plot, $p < 0.05$) resulting in a significantly higher ratio between Nmin$_{0\text{-}10\ cm}$ and Nmin$_{0\text{-}30\ cm}$ under RT (29%) compared to CT (19%) (ANOVA split-plot, $p < 0.05$). At s4, on TS2 subplots, the 0-30 cm arable layer and the 0-60 and 0-90 cm soil profiles showed a 33%, 42% and 29% higher mineral N amount under RT compared to CT (ANOVA, $p < 0.01$, $p < 0.05$, $p < 0.05$), whereas on TS0 subplots Nmin$_{0\text{-}90\ cm}$ was 17% lower under RT compared to CT (ANOVA, $p < 0.05$) (Table 6.5). At s4, the ratio between Nmin$_{0\text{-}60\ cm}$ and Nmin$_{0\text{-}90\ cm}$ was significantly higher under RT (67%) compared to CT (63%) (ANOVA split-plot $p < 0.01$).

Compared to the tillage factor, grass-clover termination strategy showed more pronounced effects on mineral N amount and its distribution at s2, s3 and s4 (Table 6.5). At s1, Nmin$_{0\text{-}60\ cm}$ averaged at 17.8 kg N ha^{-1} under all grass-clover treatments. At s2, i.e., before main tillage and planting, TS1 caused the highest Nmin$_{0\text{-}30\ cm}$ and Nmin$_{0\text{-}60\ cm}$ and TS0 the lowest. Intermediate values appeared for TS2. At s3 and s4, no differences in the top 10 cm were found between grass-clover termination strategy types. At s3, values for 0-30 and 0-60 cm were significantly higher for TS1 compared to TS0. At s4, a significant interaction of grass-clover termination strategy and tillage was found, where Nmin$_{0\text{-}30\ cm}$ was significantly lower (minus 32%) for TS0 compared to TS2 under RT but not under CT (Table 6.5). Under RT, Nmin$_{0\text{-}60\ cm}$ and Nmin$_{0\text{-}90\ cm}$ were ca 40% lower for TS0 compared to both other variants. Under CT, $Nmin_{0\text{-}90\ cm}$ was ca 15% higher for TS1 compared to both other variants. Irrespective the tillage practice, the ratio between $Nmin_{0\text{-}60\ cm}$ and $Nmin_{0\text{-}90\ cm}$ at s4 was significantly lower for TS1 (60%) compared to both other variants (67%) (ANOVA split-plot $p < 0.05$, Scheffé $p < 0.05$) and the ratio between $Nmin_{0\text{-}30\ cm}$ and $Nmin_{0\text{-}60\ cm}$ at s2 was significantly lower for TS1 (72%) compared to both other variants, TS0 (85%) and TS2 (79%) (ANOVA split-plot $p < 0.001$, Scheffé $p < 0.05$).

Table 6.5 Mineral N amounts (e.g., $Nmin_{0\text{-}30\ cm}$) and mineral N distribution (e.g., $Nmin_{0\text{-}30\ cm}$ / $Nmin_{0\text{-}60\ cm}$) in the soil profile at different sampling occasions (s2, s3, s4, see Table 6.2) in the leek growing season 2012 for the different grass-clover termination strategies (TS1: early destruction on March 19th, TS0: late destruction on May 18th after cutting and removal of a full-grown grass-clover cut and TS2: late destruction after repeated mulching) per tillage variant in case of a significant T x TS interaction (CT: conventional ploughing and RT: reduced tillage); mean values (n = 8 and n = 4 in case of mean values per tillage variant) and standard deviations between parentheses; significant differences between TS variants are indicated with superscript lowercase letters.

			TS0		TS1		TS2		ANOVA	Scheffé
s2	$Nmin_{0\text{-}30\ cm}$		43.8^{a}	(6.4)	79.3^{c}	(9.9)	60.9^{b}	(10.6)	0.001	0.05
	$Nmin_{0\text{-}60\ cm}$		51.6^{a}	(7.7)	110.1^{c}	(12.1)	76.8^{b}	(11.6)	0.001	0.01
s3	$Nmin_{0\text{-}10\ cm}$		17.7	(4.4)	20.6	(6.3)	23.3	(9.6)	-	-
	$Nmin_{0\text{-}30\ cm}$		72.9^{a}	(20.1)	99.0^{b}	(22.1)	87.5^{ab}	(13.4)	0.05	0.05
	$Nmin_{0\text{-}60\ cm}$		138.8^{a}	(29.2)	190.5^{b}	(30.6)	163.5^{ab}	(16.7)	0.05	0.05
s4	$Nmin_{0\text{-}10\ cm}$		6.8	(1.1)	6.6	(1.8)	7.2	(2.8)	-	-
	$Nmin_{0\text{-}30\ cm}$	CT	27.9	(5.0)	27.1	(6.0)	27.6	(4.5)	-	-
		RT	24.9^{a}	(2.5)	30.8^{ab}	(4.2)	36.7^{b}	(2.0)	0.01	0.01
	$Nmin_{0\text{-}60\ cm}$	CT	59.4	(7.6)	62.5	(9.4)	60.3	(6.7)	-	-
		RT	51.4^{a}	(4.4)	83.0^{b}	(24.3)	85.5^{b}	(14.5)	0.05	0.05
	$Nmin_{0\text{-}90\ cm}$	CT	90.8^{a}	(3.9)	106.7^{b}	(6.3)	94.4^{a}	(8.1)	0.05	0.05
		RT	74.9^{a}	(6.6)	132.7^{b}	(29.2)	121.8^{b}	(15.4)	0.01	0.05

6.3.2.2 Celeriac growing season 2013

At s1, $Nmin_{0\text{-}30\ cm}$ did not differ between tillage variants established in 2012. On subplots that did not receive aboveground grass-clover biomass in the previous spring (TS0), $Nmin_{0\text{-}10\ cm}$ at s1 was significantly higher under RT compared to CT (Table 6.6). At s1, the ratio between $Nmin_{0\text{-}10\ cm}$ and $Nmin_{0\text{-}30\ cm}$ was significantly higher under RT.

$Nmin_{0\text{-}60\ cm}$ at s2 tended to be higher (ca +20%) under CT compared to RT ($p < 0.1$) which turned into a significantly higher $Nmin_{0\text{-}60\ cm}$ at s3 under CT ($p < 0.01$) (ca +60%) (Figure 6.3). In the s2-s3 period, a depletion of $Nmin_{0\text{-}60\ cm}$ occurred under RT (-30 kg ha^{-1}), whereas under CT the N amount stayed constant at a higher level (ca 140 kg ha^{-1}). $Nmin_{0\text{-}30\ cm}$ at s3 was significantly higher under CT, compared to RT, whereas $Nmin_{0\text{-}10\ cm}$ did not differ between tillage variants in case of cut-and carry fertilizer application (Table 6.6). On plots that received cut-and-carry fertilizer (BT1 and BT2), the ratio between $Nmin_{0\text{-}10\ cm}$ and $Nmin_{0\text{-}30\ cm}$ at s3 was significantly higher under RT compared to CT.

Table 6.6 Mineral N amounts ($Nmin_{0\text{-}10\ cm}$ and $Nmin_{0\text{-}30\ cm}$) and mineral N distribution in the arable layer (ratio $Nmin_{0\text{-}10\ cm}$ / $Nmin_{0\text{-}30\ cm}$) at sampling occasions s1 and s3 (see Table 6.2) in the celeriac growing season (2013) for both tillage practices (CT: conventional ploughing (CT) and RT: reduced non-inversion tillage) per grass-clover termination strategy at s1 (TS1: early destruction on March 19th, TS0: late destruction on May 18th after cutting and removal of a full-grown grass-clover cut and TS2: late destruction after repeated mulching) and per grass-clover biomass transfer variant at s3 (BT0: zero Mg ha^{-1}, BT1: 9.8 Mg ha^{-1} and BT2: 19.6 Mg ha^{-1}) in case of a significant tillage x TS or tillage x BT interaction, respectively; mean values (n = 4 at s1and n = 8 at s3) and standard deviations between parentheses. Significant differences between tillage variants are indicated with superscript lowercase letters.

	s1				s3			
		CT	RT	ANOVA		CT	RT	ANOVA
$Nmin_{0\text{-}10\ cm}$	TS0	9.8 ^{a} (4.9)	19.1 ^{b} (5.6)	0.05	BT0	27.6 ^{b} (8.6)	19.0 ^{a} (7.8)	0.05
	TS1	13.0 (3.6)	15.8 (3.2)	0.1	BT1	25.1 (4.1)	22.4 (6.7)	-
	TS2	13.7 (1.8)	16.4 (3.6)	-	BT2	27.7 (3.7)	34.1 (8.9)	-
$Nmin_{0\text{-}30\ cm}$	TS0	29.2 (9.9)	32.0 (7.6)	-	BT0	78.7 ^{b} (25.6)	45.6 ^{a} (15.2)	0.05
	TS1	31.6 (4.4)	31.6 (6.3)	-	BT1	86.2 ^{b} (15.9)	51.6 ^{a} (15.4)	0.01
	TS2	37.6 (4.1)	30.8 (7.3)	-	BT2	132.0 ^{b} (32.5)	73.0 ^{a} (15.7)	0.01
ratio $Nmin_{0\text{-}10\ cm}$ / $Nmin_{0\text{-}30\ cm}$	TS0	0.32 ^{a} (0.08)	0.59 ^{b} (0.06)	0.05	BT0	0.35 (0.03)	0.41 (0.05)	-
	TS1	0.41 ^{a} (0.06)	0.50 ^{b} (0.02)	0.05	BT1	0.30 ^{a} (0.05)	0.43 ^{b} (0.05)	0.05
	TS2	0.37 ^{a} (0.08)	0.53 ^{b} (0.02)	0.05	BT2	0.22 ^{a} (0.06)	0.47 ^{b} (0.05)	0.01

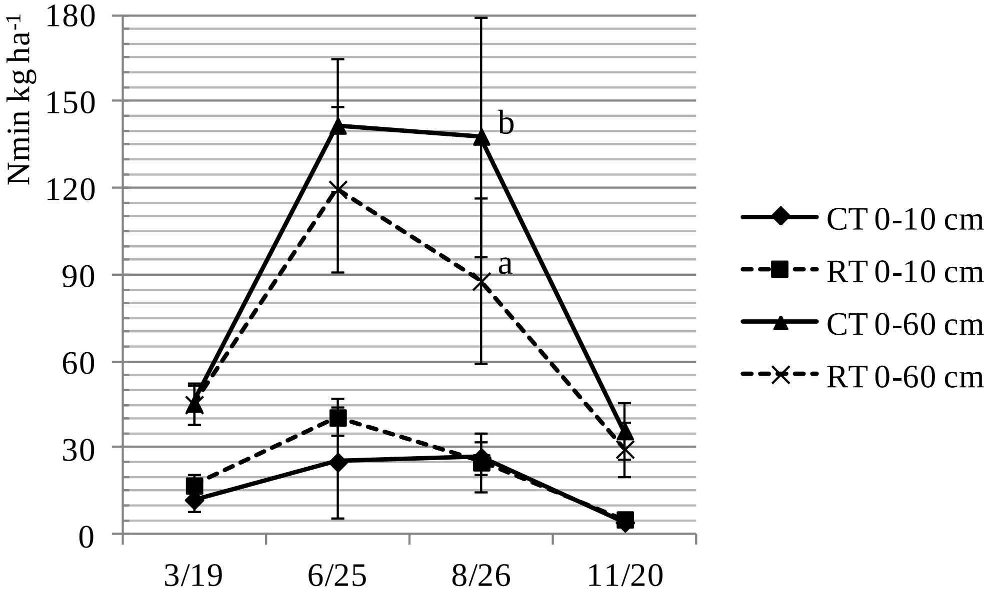

Figure 6.3 Mineral N amounts (Nmin) in the 0-10 and 0-60 cm soil layers at sampling occasions s1-s4 indicated by date (see Table 6.2) during the celeriac growing season 2013 for both tillage practices: conventional mouldboard ploughing (CT) and reduced non-inversion tillage (RT). Values are averages (n=24); error flags are standard deviations; significant differences between variants are indicated with lowercase letters.

Grass-clover termination strategy in the previous spring did not significantly affect mineral N amounts at s1, however, $Nmin_{0\text{-}30\ cm}$ tended to be higher for TS2 compared to TS0 under CT (ANOVA, $p < 0.1$, Scheffé, $p < 0.1$) and $Nmin_{0\text{-}60\ cm}$ tended to be higher for TS2 compared to TS0 (ANOVA, $p < 0.1$, Scheffé, $p < 0.1$). Grass-clover biomass transfer positively affected mineral N amount in the soil profile at s3 and s4 (Figure 6.3, Table 6.7). However, some interactions with the tillage factor appeared, in particular for $Nmin_{0\text{-}10\ cm}$ and $Nmin_{0\text{-}30\ cm}$. At s3, $Nmin_{0\text{-}10\ cm}$ on RT plots, $Nmin_{0\text{-}30\ cm}$ and $Nmin_{0\text{-}60\ cm}$ were significantly higher for BT2 compared to both other BT variants. At s4 smaller but significant differences between BT variants were observed for $Nmin_{0\text{-}30\ cm}$, $Nmin_{0\text{-}60\ cm}$ and $Nmin_{0\text{-}90\ cm}$. Significant differences between BT variants for $Nmin_{0\text{-}10\ cm}$ at s4 ($p < 0.05$) were only found on C1 sub-subplots under RT (interaction BT x C, $p < 0.05$) (results not shown). On CT plots at s3, the ratio between $Nmin_{0\text{-}10\ cm}$ and $Nmin_{0\text{-}30\ cm}$ was significantly lower for BT2 compared to both other variants and the ratio between $Nmin_{0\text{-}30\ cm}$ and $Nmin_{0\text{-}60\ cm}$ was significantly higher for BT2 compared to BT0.

Effects from compost application on soil mineral N amount only occurred at s4. $Nmin_{0\text{-}10\ cm}$ was affected by compost application on BT2 sub-subplots under RT (interaction T x C, $p < 0.01$; interaction BT x C, $p < 0.05$) with a significantly higher $Nmin_{0\text{-}10\ cm}$ for C1

(9.0 kg N ha^{-1}) compared to C0 (4.2 kg N ha^{-1}) ($p < 0.05$). Under RT, the ratio between $Nmin_{0\text{-}10\ cm}$ and $Nmin_{0\text{-}30\ cm}$ was significantly higher (+7%) for C1 (42%) compared to C0 (35%) ($p < 0.01$) (interaction tillage x compost, $p < 0.01$).

Table 6.7 Mineral N amounts (Nmin) and mineral N distribution (ratio $Nmin_{0\text{-}30\ cm}$ / $Nmin_{0\text{-}60\ cm}$) in the soil profile at sampling occasions s3 and s4 (see Table 6.2) in the celeriac growing season (2013) for the different grass-clover biomass transfer variants (BT0: zero Mg ha^{-1}, BT1: 9.8 Mg ha^{-1} and BT2: 19.6 Mg ha^{-1}), per tillage variant in case of a significant tillage x BT interaction (CT: conventional ploughing and RT: reduced tillage); mean values (n = 16 and n = 8 for mean values per tillage variant) and standard deviations between parentheses; significant differences between BT variants are indicated with superscript lowercase letters.

			BT0		BT1		BT2		ANOVA	Scheffé
s3	$Nmin_{0\text{-}10\ cm}$	CT	27.6	(8.6)	25.1	(4.1)	27.7	(3.7)	-	-
		RT	19.0 ^{a}	(7.8)	22.4 ^{a}	(6.7)	34.1 ^{b}	(8.9)	0.05	0.05
	$Nmin_{0\text{-}30\ cm}$	CT	78.7 ^{a}	(25.6)	86.2 ^{a}	(15.9)	132.0 ^{b}	(32.5)	0.001	0.01
		RT	45.6 ^{a}	(15.2)	51.6 ^{a}	(15.4)	73.0 ^{b}	(15.7)	0.05	0.05
	$Nmin_{0\text{-}60\ cm}$		93.5 ^{a}	(37.1)	100.9 ^{a}	(28.4)	144.5 ^{b}	(45.6)	0.001	0.001
	ratio $Nmin_{0\text{-}10\ cm}$ / $Nmin_{0\text{-}30\ cm}$	CT	0.35 ^{b}	(0.03)	0.30 ^{b}	(0.05)	0.22 ^{a}	(0.06)	0.001	0.05
		RT	0.41	(0.05)	0.43	(0.05)	0.47	(0.05)	-	-
	ratio $Nmin_{0\text{-}30\ cm}$ / $Nmin_{0\text{-}60\ cm}$	CT	0.67 ^{a}	(0.05)	0.71 ^{ab}	(0.05)	0.75 ^{b}	(0.04)	0.05	0.05
		RT	0.65	(0.07)	0.64	(0.05)	0.64	(0.06)	-	-
s4	$Nmin_{0\text{-}10\ cm}$	CT	4.1	(0.7)	4.4	(0.5)	4.6	(0.4)	-	-
		RT	4.6	(1.2)	4.9	(0.4)	6.6	(3.0)	(1)	-
	$Nmin_{0\text{-}30\ cm}$		14.2 ^{a}	(3.8)	14.8 ^{a}	(2.7)	17.8 ^{b}	(4.4)	0.01	0.05
	$Nmin_{0\text{-}60\ cm}$		28.9 ^{a}	(10.6)	31.9 ^{ab}	(7.1)	37.7 ^{b}	(9.9)	0.01	0.05
	$Nmin_{0\text{-}90\ cm}$		51.7 ^{a}	(20.5)	61.4 ^{ab}	(17.0)	75.1 ^{b}	(17.5)	0.01	0.01
	ratio $Nmin_{0\text{-}30\ cm}$ / $Nmin_{0\text{-}60\ cm}$		0.51	(0.07)	0.47	(0.07)	0.47	(0.06)	-	-

(1) interaction BT x C, ANOVA split-plot, $p < 0.05$; significant effect on C1 sub-subplots, ANOVA, $p < 0.05$

6.3.3 P availability in the arable layer

6.3.3.1 Leek growing season 2012

At none of the sampling occasions s2-s4, P-$CaCl_2$ was significantly affected by the grass-clover termination strategy factor. Under RT, P-$CaCl_2$ at s3 was significantly higher in the 0-10 cm compared to the 10-30 cm soil layer (one-way ANOVA $p < 0.01$, Scheffé $p < 0.05$) (Figure 6.4). P-$CaCl_{2\ 10\text{-}30\ cm}$ at s3 was significantly higher under CT compared to RT (one-way ANOVA $p < 0.01$, Scheffé $p < 0.05$). Under CT, P-$CaCl_{2\ 10\text{-}30\ cm}$ tended to decrease (Pooled-Variance Two-Sample t-Test, one-sided, $p = 0.053$), and under RT, P-$CaCl_{2\ 0\text{-}10\ cm}$ significantly decreased (Wilcoxon rank-sum test, $p < 0.05$) in the period between s3 and s4. No significant differences appeared at s4.

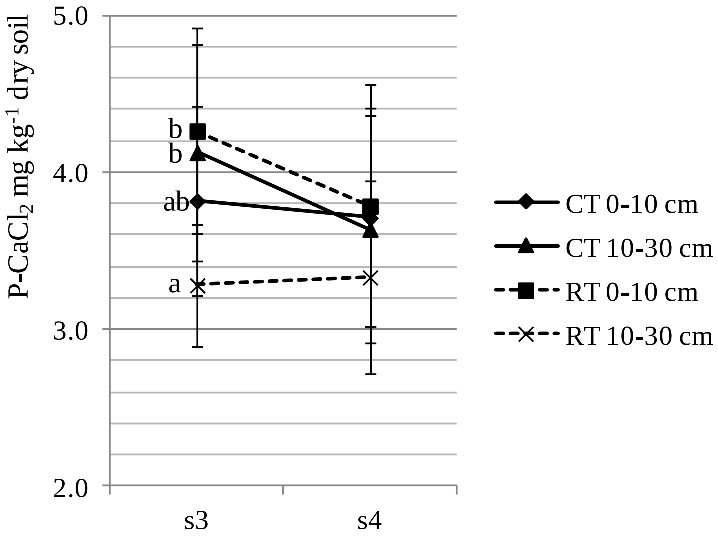

Figure 6.4 P-$CaCl_2$ per tillage variant in the 0-10 and 10-30 cm soil layers at sampling occasions s3 and s4 in 2012 (see Table 6.2); CT: conventional ploughing and RT: reduced tillage; values are mean values (n=12); error flags are standard deviations; significant differences between variants at s3 (one-way ANOVA) are indicated with lowercase letters.

6.3.3.2 Celeriac growing season 2013

For P-$CaCl_2$ of both 0-10 and 10-30 cm soil layers at s2 and s3, significant tillage x BT, tillage x compost and BT x compost interactions occurred. Both at s2 and s3, P-$CaCl_{2\ 0\text{-}10\ cm}$ was significantly positively affected by compost application on RT plots whereas P-$CaCl_{2\ 10\text{-}30\ cm}$ was significantly positively affected by compost application on CT plots (one-way ANOVA with log transformed data $p < 0.001$, Scheffé $p < 0.05$)) (Figure 6.5). These differences in P-$CaCl_2$ between compost amended and non-amended plots increased in the s2-s3 period since P-$CaCl_2$ significantly increased on compost amended plots (two-way ANOVA with square root transformed data $p < 0.001$ and Welch modified two-sample t-test $p < 0.05$) and P-$CaCl_2$ significantly decreased on non-amended plots (Wilcoxon rank-sum test, $p < 0.05$). At s3, P-$CaCl_{2\ 10\text{-}30\ cm}$ under RT and P-$CaCl_{2\ 0\text{-}10\ cm}$ under CT were also significantly positively affected by compost application (one-way ANOVA with log transformed data $p < 0.001$, Scheffé $p < 0.05$) (Figure 6.5).

On compost amended plots, a significantly higher P-$CaCl_{2\ 0\text{-}10\ cm}$ was found under RT compared to CT at s2 and s3 (one-way ANOVA with log transformed data $p < 0.001$, Scheffé $p < 0.05$) (Figure 6.5). On compost amended plots, a significantly higher P-$CaCl_{2\ 10\text{-}30\ cm}$ was found under CT compared to RT at s3 (one-way ANOVA with log transformed data $p < 0.001$, Scheffé $p < 0.05$).

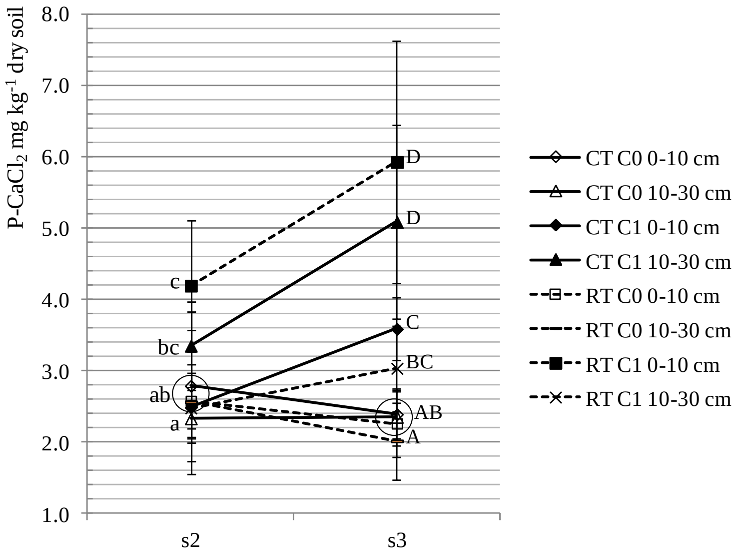

Figure 6.5 P-$CaCl_2$ per tillage x compost variant in the 0-10 and 10-30 cm soil layers at sampling occasions s2 and s3 in 2013 (see Table 6.2); CT: conventional ploughing and RT: reduced tillage; compost variants C0: zero Mg ha^{-1} and C1: 32.9 Mg ha^{-1}; mean values (n = 12); error flags are standard deviations; significant differences between variants (one-way ANOVA with log transformed data) at s2 and s3 are indicated with lowercase and uppercase letters, respectively.

Grass-clover biomass transfer significantly positively affected P-$CaCl_{2\ 0\text{-}10\ cm}$ at s2 on RT plots without compost ($p < 0.05$) with a significant difference between BT0 (2.0 mg kg^{-1} dry soil) and BT2 (3.0 mg kg^{-1} dry soil) ($p < 0.05$) and P-$CaCl_{2\ 0\text{-}10\ cm}$ at s3 on RT plots ($p < 0.05$) with a significant difference between BT0 (3.4 mg kg^{-1} dry soil) and BT2 (5.0 mg kg^{-1} dry soil) ($p < 0.05$). The highest readily available P concentrations were found for the treatments with compost application.

6.3.4 Apparent net N mineralization

6.3.4.1 Leek growing season 2012

ANM $_{s1\text{-}s3}$ was significantly lower for TS0 compared to TS1 (Table 6.8) and ANM $_{s1\text{-}s4}$ was significantly lower for TS0 compared to both other variants. Negative values appeared for ANM $_{s3\text{-}s4}$. ANM $_{s3\text{-}s4}$ was significantly lower under CT compared to RT.

6.3.4.2 Celeriac growing season 2013

$ANM_{s1\text{-}s3}$ was significantly higher under CT compared to RT and significantly higher for BT2 compared to BT1 and BT0 (Table 6.8). Negative values appeared for $ANM_{s3\text{-}s4}$. ANM $_{s3\text{-}s4}$ was significantly lower for CT compared to RT and significantly lower for BT2 compared to both other variants. ANM $_{s1\text{-}s4}$ only significantly differed between compost variants, 93.7 kg N ha^{-1} for C0 and 108.7 kg N ha^{-1} for C1 (ANOVA split-split-plot, $p < 0.01$).

Table 6.8 Apparent net N mineralization (ANM) for the balance periods s3, s3-s4 and s4 for the different tillage practices (RT: reduced tillage and CT: conventional), for the different grass-clover termination strategies in 2012 (TS1: early destruction on March 19th, TS0: late destruction on May 18th after cutting and removal of a full-grown grass-clover cut and TS2: late destruction after repeated mulching) and for the different biomass transfer variants in 2013 (BT0: zero Mg ha^{-1}, BT1: 9.8 Mg ha^{-1} and BT2: 19.6 Mg ha^{-1}); mean values (LEEK: n = 12 for tillage variants and n = 8 for TS variants; CELERIAC: n = 24 for tillage variants and n = 16 for BT variants) and standard deviations between parentheses; significant differences between TS and BT variants are indicated with superscript lowercase letters.

LEEK	CT		RT		ANOVA	TS0		TS1		TS2		ANOVA	Scheffe
ANM $_{s1\text{-}s3}$	183.6	(35.4)	173.7	(36.8)	-	150.0 ^{a}	(31.5)	205.4 ^{b}	(30.8)	180.5 ^{ab}	(22.1)	0.01	0.01
ANM $_{s3\text{-}s4}$	-24.7	(27.8)	-0.4	(26.1)	0.01	-9.4	(25.6)	-27.6	(31.2)	-0.6	(27.0)	-	
ANM $_{s1\text{-}s4}$	158.9	(25.1)	173.3	(34.5)	-	140.6 ^{a}	(21.6)	177.8 ^{b}	(30.7)	179.9 ^{b}	(22.4)	0.001	0.01
CELERIAC	CT		RT		ANOVA	BT0		BT1		BT2		ANOVA	Scheffé
ANM $_{s1\text{-}s3}$	194.9	(44.4)	136.3	(44.5)	0.01	140.1 ^{a}	(49.3)	154.3 ^{a}	(41.4)	202.4 ^{b}	(48.7)	0.001	0.001
ANM $_{s3\text{-}s4}$	-81.5	(40.9)	-47.4	(29.1)	0.01	-49.5 ^{b}	(34.3)	-54.6 ^{b}	(32.2)	-89.1 ^{a}	(39.9)	0.001	0.01
ANM $_{s1\text{-}s4}$	113.4	(21.1)	89.0	(26.6)	0.1	90.6	(28.4)	99.7	(25.3)	113.3	(22.7)	0.1	

6.3.5 Changes in chemical soil status

According to the Belgian P fertility categories, initial P soil status (Table 6.9) was above the medium level (120-180 mg kg^{-1} dry soil) and even excessive according to regulations in other European countries (Jordan-Meille et al., 2012). Initial plant available K and Ca soil contents were slightly below the medium levels, whereas plant available Mg soil content was above the medium level (Maes et al., 2012).

For all investigated soil parameters in the 0-10 cm layer, significant interactions occurred between the tillage and compost factor. Under RT, compost application significantly affected all parameters (Table 6.9). $Ntot_{0\text{-}10\ cm}$ and $K_{AL\ 0\text{-}10\ cm}$ on RT plots were also significantly affected by grass-clover termination strategy and biomass transfer. Ntot was significantly higher for TS2/BT2 (1.15 g kg^{-1}) compared to TS1/BT1 (1.03 g kg^{-1}) (ANOVA split-plot $p < 0.05$, Scheffé $p < 0.05$) and K_{AL} differed between all TS/BT variants with values 12.6, 15.9 and 19.2 mg 10^{-2} g^{-1} dry soil for TS0/BT0, TS1/BT1 and TS2/BT2, respectively (ANOVA split-plot $p < 0.001$, Scheffé $p < 0.001$). For P_{AL}, pH-KCl, K_{AL} and Ca_{AL} in the 10-30 cm soil layer, significant interactions occurred between the tillage and compost factor and effects from compost application on P_{AL}, K_{AL} and Ca_{AL} were only found under CT, and for K_{AL} only in case of TS0/BT0 (significant interaction TS/BT x C). pH-KCl $_{10\text{-}30\ cm}$ was significantly higher by compost application under both CT (Table 6.9) and RT (C0 5.8 and C1 5.9, $p < 0.05$). Compost application did not affect TOC, Ntot and Mg_{AL} in the 10-30 cm soil layer.

Table 6.9 Chemical soil status at the start and the end of the two-year experimental period for the 0-10 and 10-30 cm soil layers; CT: conventional ploughing and RT: reduced tillage; compost variants C0: zero Mg ha^{-1} and C1: 32.9 Mg ha^{-1}; mean values (INITIAL n = 4; FINAL n = 48; n = 24 under CT/RT and n = 12 under RT-C0/C1 and CT-C0/C1) and standard deviations between parentheses.

Soil Layer 0-10 cm		INITIAL		FINAL	CT		RT C0		RT C1		ANOVA
TOC	%	1.06	(0.04)		1.18	(0.17)	1.18	(0.11)	1.27	(0.10)	0.01
pH-KCl		5.3	(0.1)		5.8	(0.2)	5.5	(0.2)	6.0	(0.2)	0.001
Ntot	%	0.10	(0.003)		0.10	(0.01)	0.10	(0.01)	0.11	(0.01)	0.01
P_{AL}	mg 10^{-2} g^{-1} dry soil	26.1	(5.1)		29.9	(4.7)	27.5	(4.3)	32.5	(4.9)	0.001
K_{AL}		11.9	(1.6)		14.8	(2.3)	14.8	(3.4)	17.0	(3.8)	0.01
Ca_{AL}		75.3	(5.8)		90.1	(8.2)	79.9	(9.4)	115.8	(25.6)	0.01
Mg_{AL}		15.5	(1.0)		19.8	(2.2)	16.3	(2.0)	18.8	(2.6)	0.01

Soil Layer 10-30 cm		INITIAL		FINAL			CT C0		CT C1		ANOVA	RT	
TOC	%	1.03	(0.04)	1.07	(0.08)								
pH-KCl		5.9	(0.1)				5.8	(0.2)	6.0	(0.2)	0.05	5.8	(0.2)
Ntot	%	0.09	(0.002)	0.09	(0.01)								
P_{AL}	mg 10^{-2} g^{-1} dry soil	28.7	(5.3)				29.4	(3.4)	32.3	(3.7)	0.001	28.2	(4.6)
						GM0/CCF0	12.6	(1.2)	15.6	(1.6)	0.01		
K_{AL}		12.9	(2.5)			GM1/CCF1	13.1	(1.7)	13.1	(2.0)	-	12.6	(2.3)
						GM2/CCF2	14.3	(2.3)	14.4	(2.4)	-		
Ca_{AL}		91.9	(6.7)				90.3	(7.5)	104.5	(12.1)	0.01	93.5	(13.0)
Mg_{AL}		22.9	(1.6)	22.2	(3.6)								

6.4 Discussion

6.4.1 N and P availability and crop performance as affected by grass-clover termination strategy and fertilization practice, and interactions with tillage practice

6.4.1.1 Grass-clover termination strategy tested in 2012

At the start of (s2) and during the growing season (s3), late destruction of the grass-clover sward with removal of a cut (TS0) showed lowest mineral N amounts while early destruction (TS1) showed the highest mineral N amounts. Late destruction with mulching (TS2) showed a higher biomass yield compared to late destruction with removal of a cut (TS0). At the end of the growing season (s4), an interaction with the tillage factor appeared with regard to the level of residual soil mineral N in the 0-90 cm soil profile and with regard to the leek biomass increase before harvest (s3-s4 period). Irrespective of the tillage practice, mineral N was located higher in the soil profile in case of late destruction at the start (s2) and at the end of the growing season (s4). Regarding N, our first hypothesis is confirmed. Grass-clover termination strategy affected N availability and consequently leek crop performance (Fig 1, rel. 1, 2 and 5), interacting with tillage practice.

Early incorporation of a small amount of grass-clover aboveground biomass (TS1) resulted in comparable or higher mineral N amounts in the soil profile than late incorporation of a much larger amount (TS2). Despite the almost three times higher N input from grass-clover aboveground biomass in TS2, the amount of mineral N under the leek crop on TS2 subplots apparently never exceeded the amount on TS1 subplots. A similar magnitude of the apparent net N mineralization between sampling occasions s1 and s4 ($ANM_{s1\text{-}s4}$) (180 kg ha^{-1}) at a lower N input from grass-clover aboveground biomass for TS1 compared to TS2 may indicate either that mineralization from organic residues proceeded at a higher rate in case of early incorporation or that mineralization of SOM was more stimulated by early incorporation, i.e., a positive priming effect. Apparently, plant N availability from the high N input by TS2 was somehow restricted, which might be related to processes occurring either before or after incorporation of the gras-clover sward. Before termination of the grass-clover, N input from mulch (TS2) might be partly recycled to grass-clover regrowth. However, in a 3-year field experiment with ^{15}N-labelled shoot material, Dahlin et al. (2011) found that only 2.8% of the N contained in mulch of red clover/perennial ryegrass was recycled to the ley regrowth between the first and second mulching event. On the other hand, a fraction of N released from decomposing grass-clover mulch might be lost by gaseous

N emissions before incorporation of the grass-clover ley. Losses of mulch-derived N before incorporation amounted 18% in the study of Dahlin et al. (2011) but were significantly lower for mixed than for pure clover stands. The non-detected N input surplus by TS2 might be also related to embedment of N in SOM after incorporation of the sward. Under a standing crop, the balance between N mineralization and N immobilization might be in favor of the latter process. From mineral N measurements after incorporation of the sward, Dahlin et al. (2011) concluded that a minimum of 17% of the mulch-derived N from mixed stands entered in the more stable fractions of SOM. A lower contribution to SOM content from the TS1 variant can be expected considering both the lower grass-clover aboveground biomass input and the higher apparent fertilizer N recovery.

The higher mineral N amount in the soil profile at the start of the growing season (s2) in case of early destruction did not result in a better initial crop performance ($Nupt_{s1\text{-}s3}$, $biom_{s1\text{-}s3}$). The ratio between $Nmin_{0\text{-}30\ cm}$ and $Nmin_{0\text{-}60\ cm}$ was lower on TS1 subplots (early destruction) compared to TS0 and TS2 subplots (both late destruction). Both findings are indicative for a minor utilization of early-season mineralized N on TS1 subplots since N release in the soil and crop N uptake were not synchronized. Seventy-two percent of the leek N uptake took place between sampling occasions s3 and s4, which was even lower than the percentage for the corresponding period derived from the N uptake curve presented by Feller et al. (2011), i.e., 85%. A bad synchrony between N release and crop N uptake increases the risk for leaching losses at exceptional rain events. At s4, a lower portion of the mineral N amount in the 0-90 cm soil profile was found in the upper part of the profile for TS1 compared to both other variants. Berntsen et al. (2006) reported large amounts of N leached in the first and second year after destruction of a 3-year old grass-clover field by ploughing. Eriksen et al. (2004) studied the effect of four modified organic systems on crop yields and nitrate leaching in an improved dairy crop rotation and found highest nitrate leaching losses after the three crops following ploughing of grass-clover leys. However, compared with crop rotations without green manure, Askegaard et al. (2011) found that including a grass-clover green manure on 25% of the area did not increase N leaching. According to Brozyna et al. (2013), a share of 25% grass-clover green manure would be sufficient to provide the N required in a stockless organic farming system.

Neither a higher soil mineral N amount at the start of the growing period under TS1 nor extra N input from grass-clover aboveground biomass by TS2 did mutually differentiate for crop N uptake and biomass yield. Plant N availability seemed to be equal for these TS variants. The low apparent fertilizer N recovery in case of TS2 and the similar N uptake for TS1 and

TS2 at different N input levels might indicate that N derived from SOM, inclusive of grass-clover belowground biomass, prevailed on N recycled from mulch. Apparently, surplus $Nmin_{0\text{-}60\ cm}$ at s3 under TS1 (27 kg ha^{-1}) was immobilized in the second part of the growing season given the negative $ANM_{s3\text{-}s4}$.

The lowest mineral N amounts during the growing season were found under TS0 and coincided with the lowest $ANM_{s1\text{-}s3}$, $ANM_{s1\text{-}s4}$, crop N uptake and biomass yield. The lowest residual mineral N implies the lowest risk for N leaching losses. These observations under TS0 were clearly related to both the late destruction and the zero N input from grass-clover aboveground biomass due to the removal of a full-grown cut representing 87 kg N ha^{-1}. In a Swiss field experiment investigating the influence of cutting and soil incorporation of grass-clover green manure (cultivated from September to May) on N delivery for the succeeding crop cabbage, its yield was not affected by the cutting regimes, either twice mulched or mown with removing of the biomass from the field (Koller et al., 2008).

P-$CaCl_2$ was not affected by grass-clover termination strategy, probably due to small differences between the treatments in total P input in comparison with 2013. With regard to the cycling of other plant nutrients, we assume that differences between grass-clover termination strategy variants would not have resulted in differences in availability for the main crop.

6.4.1.2 Fertilization practice tested in 2013

Fertilization practice, i.e., grass-clover biomass transfer and compost application positively affected N and P availability, N and P uptake and celeriac biomass yield. However, differences with regard to N and P availability due to fertilization practice depended on tillage practice which was decisive for N and P increase in specific soil layers and consequently for N and P distribution in the profile. Grass-clover biomass transfer enhanced mineral N in the soil profile at s3 and s4. Grass-clover biomass transfer enhanced P-$CaCl_2$ in the 0-10 cm top layer at s2 and s3 under RT. In contrast to mineral N, P-$CaCl_2$ instantaneously increased by compost application. At s2, P-$CaCl_2$ increase started in the 0-10 cm soil layer under RT and in the 10-30 cm soil layer under CT. Compost only affected the mineral N amount in the 0-10 cm soil layer at s4 on BT2 plots under RT, and on compost amended sub-subplots (C1) under RT, significant differences were found between BT variants for the mineral N amount in the 0-10 cm soil layer at s4. These finding indicates that cut-and-carry fertilizer application enhanced N release from compost and vice versa.

Our fifth hypothesis was confirmed. Grass-clover biomass transfer and compost application interacted affecting N availability.

Our second hypothesis seems to be confirmed as well. Fertilization practice, both grass-clover biomass transfer and compost application, affected N and P availability, interacting with tillage practice. Fertilization practice also affected celeriac crop performance, however, it is questionable to which extent differences in crop performance were caused by differences in N and P availability induced by grass-clover biomass transfer and compost application (Fig 1, rel. 5).

6.4.1.2.1 Grass-clover biomass transfer

On average, 86% of the N uptake by the celeriac crop took place in the first half of the growing season, i.e., from planting until s3. Apparent N recovery from N input via grass-clover biomass transfer was low and of the same order of magnitude for both BT1 and BT2 and both sampling occasions (s3 and s4) (10-20%). Sorensen and Thorup-Kristensen (2011) found that, at an equal amount of applied N, apparent N recovery was higher at a lower C : N ratio of the plant material. In one of their experiments, apparent N recovery by a leek crop was just 10% applying 228 kg N ha^{-1} with ensilaged grass-clover with a C : N ratio of 19, similar to the C : N ratio of the grass-clover silage in our experiment. N uptake at s4 for BT2 was ca. only 20 kg N ha^{-1} higher than N uptake at s4 for BT0, irrespective the sampling occasion (s3 or s4) as recovery from cut-and-carry fertilizer N input mainly occurred between sampling occasions s1 and s3. Due to the low apparent N recovery from cut-and-carry fertilizer N input and an apparently low crop N demand in the second part of the growing season (s3-s4 period), excess mineral N, i.e., non-utilized mineral N, appeared in the 0-60 cm soil profile at s3, in particular for BT2. A negative ANM_{s3-s4} shows that this excess mineral N was either immobilized and thereby embedded in SOM, or lost, or both. N losses by leaching were unlikely considering a drier weather period in the summer. A negative ANM_{s3-s4} result for BT0 may indicate that even N release from SOM between sampling events s1 and s3 caused excess mineral N. Net N mineralization in the first half of the growing season was followed by net N immobilization in the second half. This phenomenon was already formerly described by Willekens et al. (2014b) for a conventional vegetable rotation. The significantly higher Ntot in the 0-10 cm layer under RT by TS2/BT2 (1.15 g kg^{-1}) compared to TS1/BT1 (1.03 g kg^{-1}) just after a two-year experimental period might seem exceptional considering that after 10 years differential management in a long-term experiment, total N in the top 15 cm of soil was 0.33 g N kg^{-1} higher in an organic

4-year rotation (1.46 g N kg^{-1}) (N from legumes and composted manures) compared to a conventional 4-year rotation (1.13 g N kg^{-1}) (N from synthetic fertilizers) (Poudel et al., 2001). However, besides the difference in organic N input between TS1/BT1 and TS2/BT2, a higher decomposition rate of SOM on early destructed TS1 plots, i.e., the formerly suggested priming effect, might be an additional cause of a lower Ntot under TS1/BT1. Due to the stratification of organic matter from organic inputs under a RT practice (D'Haene et al., 2009; Willekens et al., 2014a), differences in Ntot in the 0-10 cm top layer might be perceived on the short term.

The clear reduction of vegetative growth speed and related N uptake by the celeriac crop from s3 on might have been caused by a drier weather period in summer or by some occurrence of leaf spot disease (*Septoria apiicola*), or by both. However, the percentage of the N uptake by the celeriac crop from planting until s3 in our experiment (86%) was quite in line with the N uptake curve presented by Feller et al. (2011) (80%). On average, tuber biomass more than doubled in the s3-s4 period with dislocation of nutrients (and water) from foliage to tubers. Tuber biomass yield increased with the cut-and-carry fertilizer dose. No shortage of mineral N appeared considering the low fertilizer N recovery and the excess mineral N in the soil at the end of the growing season. Therefore, yield increase due to grass-clover biomass transfer was probably caused by the supply of other nutrients than N, in particular potassium as tuber crops have a high K requirement and less probable P as soil P status and readily available P concentrations were both very high.

6.4.1.2.2 Compost application

A clear effect of compost application on tuber and foliage biomass at s3 and s4 was perceived. Although compost did not affect mineral N amount in the soil profile during the growing season, it positively affected N uptake. However, it is not likely that compost enhanced tuber biomass yield by N supply. Surplus tuber N uptake at s4 by compost application (12%) was 6% lower than surplus tuber biomass at s4 (18%). A higher tuber biomass yield per kg N uptake, for C1 compared to C0, implies a higher N use efficiency by compost application due to the supply of other nutrients or due to a positive impact of compost on overall soil fertility, or due to both. At equal N input for C1 compared to BT2, N recovery by the celeriac crop from compost application was 5% higher than N recovery from grass-clover biomass transfer. However, irrespective of fertilization type (compost or cut-and-carry fertilizer), the excess mineral N at s3, the low N uptake between sampling events s3-s4 and the negative $ANM_{s3\text{-}s4}$ all suggest that N availability was not limiting the yield.

Compost clearly increased the readily available P concentrations ($P\text{-}CaCl_2$) due to a high P input which was related to the use of chicken manure in the feedstock mixture. Since tillage practice determined the placement of compost in the 0-30 cm arable layer, $P\text{-}CaCl_2$ increase by compost application started either in the upper 0-10 cm part under RT and in the lower 10-30 cm part under CT. As no interaction appeared between the tillage and compost factor with regard to their effect on P uptake and yield, the current soil P status apparently met the celeriac P requirement. High $P\text{-}CaCl_2$ values may imply a risk of P loss by leaching, as $P\text{-}CaCl_2$ (0.01 M) is an environmental soil test that can predict P leaching risks (Maguire and Sims, 2002; Vanden Nest et al., 2015). By a leaching experiment, Maguire and Sims (2002) found that above 1.6 mg $P\text{-}CaCl_2$ kg^{-1} dry soil, dissolved reactive phosphorus in the leachate increased seven times as rapidly per unit increase in $P\text{-}CaCl_2$. Small effects of added P on $P\text{-}CaCl_2$ were found at a P input level that corresponded to crop needs for two years by Djodjic and Mattsson (2013) studying in situ P dynamics in long-term fertility field experiments in Sweden. So, the increase in $P\text{-}CaCl_2$ by C1 in our experiment might be also indicative for an excessive compost derived P input. BT2 was found to be a good alternative for C1 on soils with a high P load, resulting in equal yields but lower P load increase and lower in $P\text{-}CaCl_2$ concentrations. Organic matter, N and K input were of the same order of magnitude for C1 and BT2. Under RT, both C1 and BT2 enhanced $Ntot_{0\text{-}10\ cm}$, however, TOC was only positively affected by C1. The presumably stronger degradation potential of grass-clover biomass C compared to compost C can explain this observation.

6.4.2 N and P availability and crop performance as affected by tillage practice

6.4.2.1 N and P availability and crop performance as affected by tillage practice in 2012

Tillage practice affected the distribution of mineral N in the 0-30 cm arable layer at s3 and in the 0-90 cm soil profile at s4. Under a RT practice, a higher portion of the mineral N amount was found in the upper part. These differences in mineral N distribution did not result in differences in leek biomass yield. When soil mineral N is located higher in the profile, it might be better accessible for the root system and less prone to leaching. $P\text{-}CaCl_2$ in the lower part of the arable layer (10-30 cm) at s3 was higher under CT compared to RT. The additional crop growth before harvest (bioms3-s4) on TS2 subplots was higher under RT compared to CT, which was related to a higher level of mineral N in the soil profile at s4 on

TS2 subplots under RT, but did not result in differences with regard to total leek biomass yield.

With regard to the leek growing season, our third hypothesis is only partly confirmed. Tillage practice affected mineral N and P-$CaCl_2$ distribution (Fig. 6.1, rel. 4) and mineral N amount on TS2 subplots at s4 (Fig. 6.1, rel. 3) consequently affecting $biom_{s3\text{-}s4}$ (Fig. 6.1, rel. 5), but not for total yield.

6.4.2.2 N and P availability and crop performance as affected by tillage practice in 2013

RT did not lower $Nmin_{0\text{-}30\ cm}$ and $Nmin_{0\text{-}60\ cm}$ in early spring at s1. Moreover, $Nmin_{0\text{-}10\ cm}$ at s1 was higher under RT compared to CT on TS0 subplots. So, RT did not seem to lower N mineralization at the beginning of the growing season as was found by Koopmans and Bokhorst (2002).

At s3, the 0-30 cm arable layer and the 0-60 cm soil profile showed a lower mineral N amount under RT compared to CT, which coincided with a reduction of celeriac tuber biomass yield under RT. Tillage practice affected the distribution of mineral N and P-$CaCl_2$ in the arable layer interacting with grass-clover termination strategy at the start of the growing season (s1) and fertilization practice during the growing season (s2 & s3). Differences in distribution did not result in differences in crop performance. With regard to the celeriac growing season, our third hypothesis seems to be confirmed. Tillage practice affected N and P availability (Fig 1, rel. 3 and 4), interacting with fertilization practice. Tillage practice affected crop performance as well, however, it is questionable if the effect of tillage practice on crop performance is related to its effect on N and P availability (Fig 1, rel. 5).

Differences between BT variants with regard to $Nmin_{0\text{-}10\ cm}$ at s3 only occurred under RT, since due to RT, the cut-and-carry fertilizer was mainly placed in the 0-10 cm top layer. However, on subplots that received cut-and-carry fertilizer, $Nmin_{0\text{-}10\ cm}$ at s3 was not higher under RT compared to CT. $Nmin_{0\text{-}30\ cm}$ at s3 being approximately 75% higher under CT, compared to RT, at a similar $Nupt_{s3}$, reveals a higher net N release in the 0-30 cm layer under CT from either the cut-and-carry fertilizer or SOM, or from both. This is related to a better soil condition for mineralization under CT, compared to RT, as reflected by the approximately 40% higher $ANM_{s1\text{-}s3}$. A similar level of $Nmin_{0\text{-}10\ cm}$ at s3 under RT, compared to CT, indicates that the lower N release in the arable layer under RT resulted from lower N mineralization rates in the lower 10-30 cm part of the arable layer. Visual soil assessment revealed that rooting depth under RT was limited till a depth of 15 cm due to a compacted zone beneath that depth. Soil compaction might have limited aeration and consequently organic matter decomposition. This soil compaction was caused by the late leek harvesting activity in 2012. Due to non-suitable soil conditions in spring, compaction in the lower part of the arable layer could not be relieved by deep non-inversion tillage (RT) whereas it was relieved by ploughing (CT). Besides a lower mineral N amount under RT compared to CT, a limitation of rooting depth under RT might have negatively affected nutrient and water availability and consequently celeriac crop performance. This matches with our fourth hypothesis that crop performance is affected by tillage practice due to its effect on physical soil condition.

6.4.3 N, P and dry matter content of the celeriac crop as affected by fertilization practice and tillage practice

The increase in tuber biomass yield was significant for all three factors and percentagewise of a same order of magnitude, i.e., +16% for CT compared to RT, +17% for BT2 compared to BT0 and +18% for C1 compared to C0. By contrast, dry tuber biomass at s4 only increased by compost application (+17%) (result not shown). Therefore, fresh tuber biomass at s4 increase by CT and cut-and-carry fertilizer application must be partly related to a percentagewise higher moisture content, as confirmed by the significantly lower dry matter content for CT compared to RT. This agrees with enhanced availability of mineral N in the rootable soil layers during the growing season under CT and BT2, more specifically at s3 (Fig. 6.3 and Table 6.6). Sorensen et al. (1995) reported a decline in dry matter content of leek plant parts with increased N supply. This higher N availability under CT and BT2 compared to RT and BT0, respectively, also resulted in a higher N content in the foliage at s3 and a higher N content in the tuber at s3 and s4. By contrast, with regard to the compost factor, no N but P enrichment in the plant tissue took place with a higher foliage P content at s3 for C1 compared to C0 (results not shown) and a higher tuber P content in case of RT at s4. This agrees with the higher P-$CaCl_2$ by compost application in the 0-10 cm soil layer under RT and in the 10-30 cm soil layer under CT at s2, and in both soil layers under both tillage variants at s3. Enrichment of either N or P in the plant tissue at a high biomass level is indicative of luxury consumption. So, neither N nor P availability seemed to have been the yield limiting factors. Compost and cut-and-carry fertilizer (BT2) supplied a considerable amount of K. This K supply resulted in significant increase of plant available K in the 0-10 cm layer under a RT practice. The K supply might have caused the yield increase, but at the same time benefitted the soil K status. At a comparable K input, the effects of compost application and grass-clover biomass transfer on tuber biomass yield were purely additive. This indicates that compost enhanced yield by benefitting also other soil quality parameters than the soil K status, as perceived by the positive effect of compost on all investigated soil parameters in the 0-10 cm soil layer under RT.

6.5 Conclusions

Grass-clover termination strategy in spring, prior to ley destruction clearly affected N availability during the growing season and N utilization by the leek crop. Tillage practice interacted with grass-clover termination strategy towards the end of the growing period affecting crop growth and mineral N amount. Differences in tillage practice did not result in differences in N uptake and biomass yield. Late destruction of the grass-clover sward with removal of a full-grown cut (TS0) clearly lowered yield and residual mineral N in the soil profile. A higher mineral N amount at the start of the growing season in case of early destruction (TS1) compared to late destruction (TS0 and TS2) did not result in higher initial N uptake and crop growth. Both the higher mineral N amount at the start of the growing season, not resulting in a better initial crop performance, and a lower portion of the mineral N amount in the upper part of the soil profile, in case of early destruction, were indicative for a non-synchronized crop N demand and N availability in the soil. Compared to early destruction, late destruction of the sward after repeated mulching, with the highest N input from grass-clover aboveground biomass, did not result in higher mineral N amounts and N uptake but apparently resulted in a higher storage of mulch-derived N in SOM. Overall, N derived from mineralization from SOM, inclusive of belowground grass-clover biomass prevailed on N recycled by mulching.

Each of both fertilization factors (grass-clover biomass transfer and compost application) interacted with tillage practice affecting mineral N amount and P-$CaCl_2$ and their distribution in the arable layer. P-$CaCl_2$ was at highest in the soil layer where the compost was placed. Grass-clover biomass transfer mainly affected N availability whereas compost application mainly affected P availability. Compost application and grass-clover biomass transfer additively improved celeriac crop performance. However, their positive effect on tuber yield was not related to enhanced N and P availability, but probably to their K input, and in case of compost to its benefits to general soil quality. RT was not effective in relieving soil compaction in the lower part of the arable layer due to the leek harvest, which jeopardized celeriac tuber yield.

On soils with a high P load, the application of the cash-and-carry fertilizer allowed to supply the soil with N, K and organic matter, without further increasing the P load of the soil, the readily available P concentration in the soil, and the related risk for P leaching.

Chapter 7

Final discussion and general conclusions

In a first part of this final chapter, the course of plant N availability in the soil as observed both in the field survey and in the field trials was focused on. N availability is interpreted in relation to soil quality and soil quality improving management practices. The effect of changes in N availability on crop performance and risk for N leaching losses is evaluated. Subsequently, the practice-oriented question is answered: what may these findings imply for decision tools or recommendation systems for N fertilization? In a second part, the performance of (a set) of soil management practices is evaluated with regard to soil quality improvement. In a third part, soil quality improving management systems were evaluated with regard to nutrients' balance and environmental impact.

Each section starts with a conclusion pertaining to that section. At last, some ideas for future research are presented.

7.1 Plant N availability in the soil

7.1.1 Pattern of N availability

In our field survey and trials, N availability was found to follow a cyclic pattern, i.e., net N mineralization in the first half of the growing season (spring-early summer) and net N immobilization in the second half of the growing season (late summer-autumn).

When N losses are not considered, N availability is the net result of N mineralization, N immobilization and crop N uptake. Both in the field survey and the multi-year field trials, partial balances of plant available N showed that N mineralization prevailed over N immobilization in a young (i.e., little developed) crop, i.e., during stages of low N uptake in the first half of the growing season, whereas at a high N uptake by a well developed crop in the second half of the growing season, N immobilization prevailed over N mineralization. The result of the balance for plant available N represents the net N mineralization from SOM and organic matter applied with fertilization (ANM). Feller et al. (2011) found near-zero or slightly negative ANM values in the whole growing period in case of vegetable crops with a relatively short growing period and a high N demand. Our results suggest that N availability under vegetable crops follows a cyclic rather than a linear pattern. In the course of the growing season, apparently, a transition occurs from a bare soil stage where N release from SOM prevails to a 'plant-soil system' where immobilization prevails. We may assume that under an established crop, with a root system that extensively occupies the soil volume, soil microbial life is strongly activated by root exudates. Total microbial counts (number of cells cm^{-3}) increase in the rhizosphere (Paul and Clark, 1996), apparently resulting in net N immobilization. In the field survey, the amount of N immobilized in the second half of the growing season was indeed significantly and positively correlated with the microbial biomass measured in the arable layer. Additionally, both in the field survey and in the Tilman-org trial, a larger apparent net N mineralization in the first half of the growing season was compensated by a larger net N immobilization in the second half of the growing season. The finding of net N immobilization under a well developed crop in the second half of the growing season is new to the best of our knowledge. This phenomenon lowers the risk of excessive residual mineral N, however, one can expect that harvesting will result in net N mineralization in the postharvest period (Paul and Clark, 1996). N losses from this increased mineralization may be mitigated by sowing a catch crop.

7.1.2 N availability and soil quality

7.1.2.1 N availability and soil quality in the field survey

Soil quality as reflected by SOM positively affects N availability in the soil in the first half of the growing season, and biomass yield in the second half of the growing season. The latter coincides with a better utilization of plant available N and decreased the amount of residual mineral N.

In the survey in 2009 on leek fields, N availability in the soil in the first half of the growing season (reflecting net N mineralization) was related to total N content (Ntot) and mineral N dressing. Ntot was thus found to reflect potential N release from SOM, i.e., soil N mineralization potential (Ros, 2011). SOM content is reflected by TOC and Ntot in the soil, with higher values being related to a better soil quality. Ntot also positively affected mineral N amounts in both the arable layer and the 0-90 cm soil profile at the very beginning of the growing season. Ntot was decisive for total N uptake probably due to its effect on N availability. Biomass yield was not related to N availability but was positively affected by Ntot due to a higher utilization of plant available N at a higher SOM content resulting in a lower residual NO_3^--N amount in the 0-90 cm soil profile. A better soil quality thus resulted in a higher yield and lower residual mineral N due to a better N utilization. Neither N availability nor crop performance (N uptake and biomass yield) differed between the distinguished field groups reflecting soil quality, based on a set of physical and chemical soil parameters.

In the survey of 2010 and 2011, the effects of a broad range of crop related and soil quality defining factors on residual soil mineral N were assessed. In contrast with the previous year in which leek was the standard crop, both Ntot and mineral N dressing affected residual soil mineral N in the arable layer. Residual soil mineral N in the arable layer also differed between field groups reflecting soil quality, based on a set of physical and chemical soil parameters. Residual NO_3^--N amount in the 0-90 cm soil profile was related to crop group (i.e., cereals, potatoes or vegetables) since fertilizer effective N also differed between crop groups. The amount of residual NO_3^--N in the 0-90 cm soil profile was not related to Ntot. In the last two years of the field survey, soil quality, as reflected by Ntot, positively affected residual mineral N in the arable layer, but did not affect the nitrate N residue level.

7.1.2.2 N availability and soil quality in the multiyear field trials

The contribution of soil N mineralization (ANM) to total N availability is high in crops with a long growing season and in organic cultivation. SOM stock should be sustained by compost or other organic amendments in order to maintain the level of soil N mineralization.

The sum of the initial soil mineral N amount and the mineral N input by fertilization (i.e., N supply) plus the apparent net N mineralization represents the total N availability (TNA), which is recovered as crop N uptake and residual soil mineral N. The contribution of ANM to TNA was 7% in the broccoli and 42% in the leek growing season for the Vegtilco trial. The portion of TNA utilized by the respective crops was 85 and 77%. In the Tilman-org trial, the contribution of ANM to TNA was 90% in the leek and 69% in the celeriac growing season. The portion of TNA utilized by the respective crops was 64 and 78%. The contribution from ANM to TNA was substantially lower in the Vegtilco trial, compared to the Tilman-org trial, due to the use of mineral N fertilizers. The utilization of TNA by a leek crop was somewhat higher (+13%) in the Vegtilco trial, compared to the Tilman-org trial. Limitation of utilization of plant available N might be related to site-specific conditions affecting yield potential. In the Tilman-org trial the contribution of aboveground grass-clover biomass to ANM is probably not that high regarding the low apparent N recovery and the low surplus residual mineral N with these amendments. In the leek growing season of the Vegtilco trial, the contribution of ANM to TNA (42%) equaled the contribution of mineral fertilizer N input to TNA (42%).

In the Vegtilco trial, N release from SOM over the three-year experimental period was determined based on the evolution of the total N stock in the 0-60 cm soil layer on the plots that did not receive compost. The yearly N release from SOM amounted to 125 kg ha^{-1} or 1.82% of the total N stock. ANM under leek, a crop with a long growing season, was of the same order of magnitude. In a long-term perspective, mineralization of Ntot should be compensated. This was tested in the field trials by adding compost and/or cut-and-carry fertilizer. In the Vegtilco trial, the yearly amount of N released from SOM was not fully compensated by a yearly compost application of 15 Mg compost ha^{-1}. However, compost N input by this yearly dose (on average 104 kg ha^{-1} year^{-1}) seemed to have been fully recovered in SOM stock comparing $\Delta Ntot_{0\text{-}60\ cm}$ on both C_0 and C_{15} plots while assuming a same decrease due to soil N mineralization under both variants. With a yearly compost application of 45 Mg compost ha^{-1} total N stock increased, however, only half of the compost N input seemed to have been recovered in SOM stock. Compost application clearly counteracted the organic N decrease caused by N release from SOM in the Vegtilco trial. Besides compost, grass-clover residues, either mulched or applied by biomass transfer in the Tilman-org trial, appeared to sustain Ntot as well.

7.1.3 N availability and soil quality improving practices

7.1.3.1 N availability and tillage practice

The effect of tillage practice on N availability was not straightforward, probably due to a variable effect of tillage practice on physical soil conditions that are decisive for soil N mineralization. Differences in N availability between tillage practices are rather small, except in case of serious soil compaction prior to tillage, which may largely reduce N availability under RT if it fails to relieve the compaction. Mineral N is located higher in the soil profile under RT, possibly preventing leaching losses.

The tillage factor affected mineral N amounts in the Vegtilco trial to a limited extent. ANM under broccoli tended to be higher under RT compared to CT whereas ANM under leek was significantly higher (+17%) under CT compared to RT. N release from SOM probably differed due to differences in physical soil conditions. This resulted in small but significant differences in crop performance, i.e., crop N uptake and biomass yield. The young leek performed better under CT, whereas broccoli performed better under RT.

In the Tilman-org trial, tillage type hardly affected N availability from the incorporated grass-clover sward to the leek crop. In the celeriac growing season, compaction in the lower part of the arable layer under RT seriously lowered the mineral N amount, probably due to a reduced N release from SOM. RT reduced crop N uptake and celeriac tuber biomass yield, however it is questionable that this yield effect was caused by a lower N availability. It might have been also the effect of a lower water availability as the compacted zone limited root depth and thus the amount of water available to the crop. During the winter, the field was in a bare and compacted state due to late leek harvesting. Possibly the soil lacked a coherent macrostructure at the time of main tillage in spring and the non-inversion tillage failed to relieve the compaction. Sowing a cover crop in properly tilled soil in autumn may facilitate a reduced tillage practice in the following spring.

In both multi-year field trials, the mineral N amount in the arable layer at soil sampling in spring was never affected by the tillage practice in the previous year. So, RT did not seem to lower N mineralization at the beginning of the growing season contrary to what was found by Koopmans and Bokhorst (2002).

Tillage affected occasionally mineral N distribution in the soil profile in both multiyear field trials, with a higher share of the mineral amount in the upper part of the soil profile under a RT practice. Under the young leek crop (s2) in the Vegtilco trial, the ratio between $Nmin_{0–30\ cm}$ and $Nmin_{0–90\ cm}$ was significantly higher (+7%) under RT compared to CT, apparently not affecting crop performance as the young leek crop performed better under CT. This stratification of mineral N due to a RT practice also appeared in the Tilman-org trial in 2012 with regard to the ratio between $Nmin_{0-10\ cm}$ and $Nmin_{0-30\ cm}$ at s3 (+10%) under the young leek crop and with regard to the ratio between $Nmin_{0-60\ cm}$ and $Nmin_{0-90\ cm}$ at s4 (+4%) under the full-grown leek crop. Also in 2013 this kind of stratification appeared at s1 with regard to the ratio between $Nmin_{0-10\ cm}$ and $Nmin_{0-30\ cm}$ (+17%, interaction with the grass-clover management factor) and at s3 on plots that received cut-and-carry fertilizer with regard to the ratio between $Nmin_{0-10\ cm}$ and $Nmin_{0-30\ cm}$ (+19%, interaction with the biomass transfer factor). These increases were relatively low, but might increase if stratification of SOM becomes more pronounced when non-inversion tillage is practiced over a longer period. When soil mineral N is located higher in the profile, it is better accessible for the root system and less prone to leaching.

7.1.3.2 N availability and compost application

Effects of compost application on plant N availability in the short term were infrequent and small and appeared to occur outside of the growing season. However, on the long term, repeated compost application sustains or increases N availability since it positively affects SOM.

Compost application had no or only a small effect on mineral N amounts in the soil profile in the short term. In the Vegtilco trial, compost application did not affect ANM. On the contrary, in the celeriac growing season of the Tilman-org trial, a higher ANM (+16%) appeared on compost amended plots compared to the non-amended ones. This higher N availability coincided with a higher crop N uptake on compost amended plots and not with a higher residual soil mineral N amount. With regard to the Vegtilco trial, compost application only positively affected the mineral N amount in the carrots growing season comparing the highest dose with the zero one (by only 10 kg ha^{-1}), which did not affect crop performance. Before sowing carrots, the mineral N amount in the 0-90 cm soil profile was 20 kg ha^{-1} higher on plots with the highest compost dose compared to the non-amended ones. At the end of the celeriac growing season in the Tilman-org trial, compost application affected the mineral N amount in the 0-10 cm soil layer on subplots with the highest level of green manuring (TS2/BT2) (+5 kg), which coincided with a higher foliage biomass.

Compost affected N availability in both multi-year field trials to a limited extent. On the other hand, compost application, even at a moderate yearly dose of 15 Mg ha^{-1} $year^{-1}$ sustained the total N content in the soil in the Vegtilco-trial. By its contribution to SOM, compost application probably positively affects future N availability from soil N mineralization, as suggested by Chalhoub et al. (2013).

7.1.3.3 N availability and green manuring

By an optimal grass-clover termination strategy prior to ley destruction, N availability and N demand from the main crop can be synchronized. N utilization from biomass transfer through cut-and-carry fertilizer depends on both crop N demand and soil N mineralization potential. However, N recovery from aboveground grass-clover biomass and biomass transfer seems to be generally low (< 20%). Still, these organic N inputs sustain or increase SOM content. Therefore, they probably contribute to N availability from soil N mineralization in the long term rather than by a direct effect in the short term.

In the first year of the Tilman-org trial, the apparent N recovery was low (16%) in case of late destruction and recurrent mulching with the highest N input from grass-clover aboveground biomass. The leek N uptake did not differ between late destruction with a high N input (recurrent mulching) and early destruction with a much lower N input (one-time mulching). Both findings indicate that N derived from SOM, inclusive of grass-clover belowground biomass, by soil N mineralization prevailed on N recovered from mulch. A higher N availability at the start of the growing period in case of early destruction did not result in a better leek crop performance compared to late destruction with recurrent mulching. For both these variants, N availability was not a limiting factor for crop performance, as it was for late destruction with removal of a full-grown cut. Mulching increased N availability, irrespective destruction moment (+26-28%), compared to late destruction with removal of a cut.

In the second year of the Tilman-org trial, apparent N recovery from the cut-and-carry fertilizer by the celeriac crop was low (10-20%), not surpassing apparent N recovery from compost. Biomass transfer positively affected N availability and celeriac crop performance. However, the higher tuber biomass yield seemed not to be related to enhanced N availability. In the celeriac growing season, ANM did not differ between biomass transfer variants, although biomass transfer affected N availability during the growing season.

7.1.3.4 Residual soil mineral N and soil improving management practices

Regular use of farmyard manure, compost and cover crops as soil improving practices may help to control residual soil mineral N.

In the survey, fields with soil improving practices (i.e., the use of farmyard manure, compost and green manuring) had lower residual mineral N in the arable layer (-43%) compared to fields without these practices. By contrast, fields with a presumed frequent slurry application showed higher residual soil nitrate N in the 0-90 cm soil profile (+63%) compared to fields of farms without cattle. Cereals in a crop rotation with vegetables decreased short-term N availability. By monitoring of the soil N mineralization, it was found that N immobilization in the leek crop (first year of the field survey) in the second half of the growing season was positively affected by Cmic. So, enhancing Cmic by any soil improving practice might reduce the amount of residual soil mineral N. Farm compost application increased microbial carbon content in the arable layer (D’Hose et al., 2014).

7.1.3.5 Extra N release from SOM due to agronomic practices (positive priming effects)

Positive priming effects increased N availability, as was observed in case of early cultivation, excessive mineral N input and by combined application of organic amendments. However some of these effects are likely difficult to predict.

In the first year of the field survey, early cultivation (fertilization-tillage-planting) enhanced N availability under a leek crop due to extra N release from SOM. Enhancement of N availability in the growing season by early cultivation may be desirable for crops with a high N demand and a short growing period. Besides early cultivation, excessively high base mineral N dressing caused extra N release from SOM as well. Recurrent excessive mineral N input may result in SOM decline and soil degradation due to priming (Mulvaney et al., 2009). In the Tilman-org trial, an equally high ANM in case of early compared to late destruction may indicate a positive priming effect due to early cultivation. In the celeriac growing season of the Tilman-org trial, the combination of biomass transfer (highest dose) and compost application apparently caused a priming effect. Compost application positively affected the mineral N amount in the 0-10 cm soil layer at the end of the growing season on subplots with the highest level of green manuring (TS2/BT2) and vice versa, however the extra N availability was small.

7.1.4 Improvement of N fertilizer recommendation systems

Adopting soil quality improving management strategies do not require changes in N fertilization strategies on the short term. Regarding the cyclic pattern of N availability throughout the growing season, plant N availability should be assessed in a different way in the second part of the growing season compared to the first part of the growing season. N fertilizer recommendation systems should take into account enhancement of N availability due to early cultivation.

Compost application and a successful reduced tillage operation hardly affected plant N availability in the short term. Small short-term changes in overall N availability due to these soil improving practices do not require changes in N fertilization strategy or additional precautions regarding residual soil mineral N. The effect of tillage on mineral N distribution might be taken into account for decisions on N fertilization, especially when practicing reduced tillage in a long-term perspective. A better availability of N for the crop, when N is located higher in the soil profile, might enhance its utilization lowering the need for fertilizer N input.

Fertilizer recommendation systems rely on the assessment of plant available N, which necessitates an estimation of soil N mineralization. The contribution of soil N mineralization to plant N availability is rather high, particularly in case of crops with a longer growing period, and should be accounted for in fertilizer recommendation systems.

Regarding the cyclic pattern of N availability, it has to be questioned how useful mineral N measurements can be to decide on N fertilization, especially on additional top dressing in the second half of the growing season.

N availability rapidly increases in the first half of the growing season due to fertilization and net N mineralization. A base mineral N dressing should be based on both a measurement of the mineral N amount and a well-estimated soil N mineralization. Measuring the mineral N amount in the soil profile at the start of the growing season was already shown to reflect N mineralization potential. Total N content was the best predictor of soil N mineralization. For the estimation of soil N mineralization, one should take positive priming effects into account. Priming by early cultivation is beneficial in case of a high crop N demand early in the growing season as it improves the synchrony between N availability and crop N demand. Towards the end of the period of net N mineralization it is still useful to measure the mineral N amount to decide on top mineral N dressing. Regarding the phenomenon of net N immobilization in the second half of the growing season, we assume that a measurement of the mineral N amount does not longer reflect the potential availability. N immobilized by microorganisms in the rhizosphere is also potentially plant available in the longer term. Bell et al. (2015) found that microbial biomass N decreases during periods of peak plant growth and N uptake which shows that plants benefit from the N reserve occluded in the microbial biomass in their rhizosphere.

Crop N demand is related to crop type but also depends on yield potential related to climatic conditions and site characteristics, particularly the soil structure that influences hydrology and rooting ability (Groenevelt et al., 1984). Also weather conditions and artificial watering facilities are decisive for yield potential. Fertilizer N recommendation obviously should account for site specific yield potential. In our field survey, utilization of the N supply by the leek crop was related to SOM content. In the last growing season of the Vegtilco trial, yield potential was obviously limited by another factor than N availability regarding that the leek crop did not respond to an extra 30 kg ha^{-1} top mineral N dressing. Knowledge of and coping with the yield-limiting factors is important from the scope of enhancement of N utilization, and this knowledge should be used to select a parcel-specific yield potential.

7.2 Soil quality as affected by soil management practices

Soil quality improving practices increased SOM, soil nutrient contents and/or pH in the topsoil, with an important interaction between soil tillage and amendment of organic matter (compost or grass-clover biomass transfer). Both compost application and grass-clover biomass transfer positively affected soil nutrients contents. Both compost application and green manuring sustained SOM while a reduced tillage practice resulted in a favorable stratification of SOM and nutrients, preventing them from being leached. Both compost application and a reduced tillage practice increased microbiota in the 0-10 cm soil layer. Compost application positively affected the pH.

Under a reduced tillage practice, soil organic matter and nutrients derived from fertilization and crop residues were predominantly located in the upper 0-10 cm part of the arable layer. In the Vegtilco trial, $TOC_{0\text{-}10\ cm}$ was significantly higher than $TOC_{10\text{-}30\ cm}$ on RT plots irrespective of the compost dose. Compared to CT, RT increased soil microbiota in the 0-10 cm soil layer. Repeated compost application (15 and 45 Mg ha^{-1} yr^{-1}) in the Vegtilco trial significantly positively affected C stocks in the 0-60 cm soil profile. A significant increase in soil organic C content in the 30-60 cm subsoil layer on compost amended plots indicated that organic components of compost moved downward the soil profile by leaching. However, C leaching from the arable layer was limited by a reduced tillage practice given the difference in ranking of ΔTOC values of the three soil layers between tillage practices. Obviously, RT reduced organic C leaching due to stratification of SOM. Apparent C recovery from compost over a depth of 60 cm was considerably higher for C_{15} (71%) than C_{45} (39%). Both recovery of compost C and N input in SOM stock were approximately 50% lower for C_{45} compared to C_{15}. Alluvione et al. (2013) reported 55.1% recovered C from added compost in a short-term experiment and considering 0-30 cm C stock changes. Non recovered C is either respired or lost. Losses by leaching out of the depth of 60 cm are presumably small. A study by Kindler et al. (2011) showed that C losses by leaching of dissolved organic carbon (DOC) were of an order of magnitude of 40 kg ha^{-1} yr^{-1} for croplands. Aeolian losses might have occurred particularly for the compost applied in autumn 2010 because the compost was not incorporated. As we presume organic C losses, particularly on plough-tilled plots, also organic N losses would have occurred. Since compost application hardly contributed to N availability in the short term, compost N was either recovered in SOM or was lost in an organic form. From measurements of plant available K and Mg in the successive soil layers, we could deduce that K and Mg moved downward by leaching beyond the 0-30 cm arable layer under CT. RT not only limited C leaching but also limited leaching of base cations. Leaching of base cations from the arable layer under CT might have been caused by acidification due to the decomposition of organic residues in a less aerated soil environment. We have to remark that the soil of the Vegtilco trial is a Stagnosol that is quite vulnerable with regard to waterlogging.

In the Tilman-org trial, an effect of compost application (33 Mg ha^{-1}) on TOC and total N content was only perceived in the 0-10 cm soil layer under a RT practice (interaction tillage x compost). Apparently, a single compost application sustained SOM. By contrast, recurrent compost application in the Vegtilco trial affected the organic C content of the 0-10 cm soil layer irrespective of the tillage practice, which can be explained by the fact that under CT, soil inversion moved compost to the lower part of the arable layer in one year but moved it partly to the upper part in the subsequent year. Soil microbiota in the 0-10 cm soil layer increased by the highest compost dose. Organic C and N input by green manuring in the Tilman-org trial, i.e., recurrent mulching of a grass-clover sward prior to its destruction in 2012 followed by grass-clover biomass transfer in 2013, also sustained SOM. This was detected from differences in total N in the 0-10 cm soil layer between the respective variants under an RT practice.

Recurrent compost application buffered soil pH in the Vegtilco trial, irrespective the dose (15 or 45 Mg ha^{-1}). Even a single compost application (33 Mg ha^{-1}) in the Tilman-org trial positively affected soil pH, as was detected either in the 0-10 cm soil layer under RT and in the 10-30 cm soil layer under CT.

7.3 Soil quality improving management systems and nutrients’ balance

Soil quality improving strategies should aim at (i) maximizing C input, (ii) obtaining synchrony between N availability and crop N demand and (iii) preventing P surpluses. Regarding these purposes, this study allows to make some conclusions with regard to green manuring, compost application and a RT practice.

7.3.1 Findings in conventional field vegetable cropping systems

Organic matter building practices do not increase the risk for excessively high residual mineral N. On the contrary, by increasing SOM, and consequently soil quality, N utilization is ameliorated thus lowering that risk.

Compost application counteract soil quality decline in an intensive vegetable cropping system by sustaining SOM and buffering pH. A RT practice enhances the effectiveness of compost. Compared to RT, the risk of leaching losses of C and base cations is higher in a plough-tilled soil, probably coinciding with an adverse pH effect. With an average yearly compost application of 15 Mg ha^{-1}, it is feasible to sustain SOM without surpassing fertilization limits for N and P_2O_5. High yearly compost doses, e.g., 45 Mg ha^{-1} year^{-1}, are apparently not desirable since such a practice lowers apparent C recovery and add excessively high P amounts.

On the short term fertilizer N application has not to be adapted to tested soil improving practices. Recurrent compost application sustains soil N mineralization. N fertilization should account for this soil N supply. If recurrent compost application results in higher SOM and soil quality, it enhances soil N mineralization and crop N utilization. A distinctly better stratification of mineral N in the soil profile by a repeated RT practice will probably also increase N utilization. Therefore, recurrent C saving management practices will probably result in a lower need for fertilizer N use as the mineral N supply from SOM will increase.

7.3.2 Findings in an organic field vegetable cropping system

A green manure with a leguminous component enhances soil N mineralization. Green manure termination strategy is decisive for the level and timing of N release from the residues, and should be tuned to the crop growing period and N demand. Apparent N recovery by the main crop from mulched green manure biomass or from biomass transfer in a cut-and-carry system depends on the soil N mineralization potential and the crop N demand.

Both green manuring and compost application sustain SOM, however, compost application usually implies a higher off-farm amendment of nutrients by which the risk occurs for too high P input compared to P output. In a cut-and-carry fertilizer system or in case of on-farm composting with on-farm feedstock materials, nutrients circulate within the farm which might prevent or reduce excessively high levels of plant available P in soils. However, it might be necessary to compensate for export of other nutrients.

Inclusion of green manure crops may ameliorate the soil structure. A good soil structure is a prerequisite for a successful RT practice. Well-designed termination techniques have to enable or facilitate a RT practice in organic agriculture.

7.4 Future research

From this study, some new research questions arose that pertain both fundamental and practical aspects. With regard to N fertilization strategies: How to account with priming effects in fertilizer recommendation systems? How to assess (potential) N availability under a developing crop, accounting for the cyclic pattern of N availability? How to improve soil quality assessment for estimation of yield potential in function of N fertilizer recommendation?

With regard to soil improving management strategies: How can compost quality be ameliorated in order to maximize apparent C recovery in SOM stock, in dependence of soil characteristics, mode and time of application? How much can a RT practice be facilitated by newly developed strategies to prevent/relieve soil compaction and for cover crop termination?

References

Aase, J.K., Pikul, J.L., 1995. Crop and soil response to long-term tillage practices in the Northern Great-Plains. Agron. J. 87, 652-656.

Abawi, G.S., Widmer, T.L., 2000. Impact of soil health management practices on soilborne pathogens, nematodes and root diseases of vegetable crops. Appl. Soil Ecol. 15, 37-47.

Alluvione, F., Fiorentino, N., Bertora, C., Zavattaro, L., Fagnano, M., Chiaranda, F.Q., Grignani, C., 2013. Short-term crop and soil response to C-friendly strategies in two contrasting environments. Eur. J. Agron. 45, 114-123.

Alluvione, F., Halvorson, A.D., Del Grosso, S.J., 2009. Nitrogen, tillage, and crop rotation effects on carbon dioxide and methane fluxes from irrigated cropping systems. J. Environ. Qual. 38, 2023-2033.

Alvarez, R., 2005. A review of nitrogen fertilizer and conservation tillage effects on soil organic carbon storage. Soil Use Manag. 21, 38-52.

Amlinger, F., Gotz, B., Dreher, P., Geszti, J., Weissteiner, C., 2003. Nitrogen in biowaste and yard waste compost: dynamics of mobilisation and availability - a review. Eur. J. Soil Biol. 39, 107-116.

Amlinger, F., Peyr, S., Geszti, J., Dreher, P., Weinfurtner, K., Nortcliff, S., 2007. Beneficial effects of compost application on fertility and productivity of soils, Literature study. Federal Ministry for Agriculture and Forestry, Environment and Water Management (Ed.), 225 p.

Annabi, M., Houot, S., Francou, F., Poitrenaud, M., Le Bissonnais, Y., 2007. Soil aggregate stability improvement with urban composts of different maturities. Soil Sci. Soc. Am. J. 71, 413-423.

Anonymous, 2000. Praktijkgids Bemesting. Nutriënten Management Instituut NMI, Wageningen, ISBN 90-804058-2-5, p. M37.

Anonymous, 2006. Thematic Strategy for Soil Protection. Communication from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions. COM(2006)231, Brussels, September 22, 12p.

Anonymous, 2008. Normen en richtwaarden, editie 2009. Vlaamse Landmaatschappij.

Anonymous, 2011. Decreet houdende wijziging van het Mestdecreet van 22 december van 2006. Belgisch Staatsblad, 27876–27894.

Appel, T., 1994. Relevance of soil N mineralization, total N demand of crops and efficiency of applied N for fertilizer recommendations for cereals - theory and application. Z. Pflanzenernähr. Bodenkd. 157, 407-414.

Armbruster, M., Laun, N., Heger, A., Wiesler, F., 2013. Nitrogen efficiency in intensive field vegetable production, in: Fontana, E., Grignani, C., Nicola, S. (Eds.), International Workshop on Nitrogen, Environment and Vegetables, B. Abstr., Dipartimento di Scienze Agrarie, Forestali e Alimentari - Università degli Studi di Torino, pp. 41-42.

Arthur, E., Cornelis, W., Vermang, J., De Rocker, E., 2011. Amending a loamy sand with three compost types: impact on soil quality. Soil Use Manag. 27, 116-123.

Askegaard, M., Olesen, J. E., Rasmussen, I. A., Kristensen, K., 2011. Nitrate leaching from organic arable crop rotations is mostly determined by autumn field management. Agric. Ecosyst. Environ. 142, 149-160.

Ball, B.C., Douglas, J. T., 2003. A simple procedure for assessing soil structural, rooting and surface conditions. Soil Use Manag. 19, 50-56.

Balser, T.C., 2001. The impact of long-term nitrogen addition on microbial community composition in three Hawaiian forest soils. Sci. World J. 1, 500-504.

Beare, M.H., Parmelee, R.W., Hendrix, P.F., Cheng, W.X., Coleman, D.C., Crossley, D.A., 1992. Microbial and faunal interactions and effects on litter nitrogen and decomposition in agroecosystems. Ecol. Monogr. 62, 569-591.

Bell, C.W., Asao, S., Calderon, F., Wolk, B., Wallenstein, M. D., 2015. Plant nitrogen uptake drives rhizosphere bacterial community assembly during plant growth. Soil Biol. Biochem. 85, 170-182.

Bending, G.D., Turner, M.K., Rayns, F., Marx, M.C., Wood, M., 2004. Microbial and biochemical soil quality indicators and their potential for differentiating areas under contrasting agricultural management regimes. Soil Biol. Biochem. 36, 1785-1792.

Benincasa, P., Guiducci, M., Tei, F., 2011. The nitrogen use efficiency: meaning and sources of variation - Case studies on three vegetable crops in Central Italy. Horttechnology 21, 266-273.

Bernard, E., Larkin, R.P., Tavantzis, S., Erich, M.S., Alyokhin, A., Sewell, G., Lannan, A., Gross, S.D., 2012. Compost, rapeseed rotation, and biocontrol agents significantly impact soil microbial communities in organic and conventional potato production systems. Appl. Soil Ecol. 52, 29-41.

Berner, A., Hildermann, I., Fliessbach, A., Pfiffner, L., Niggli, U., Mader, P., 2008. Crop yield and soil fertility response to reduced tillage under organic management. Soil Tillage Res. 101, 89-96.

Berntsen, J., Grant, R., Olesen, J. E., Kristensen, I. S., Vinther, F. P., Molgaard, J. P., Petersen, B. M., 2006. Nitrogen cycling in organic farming systems with rotational grass-clover and arable crops. Soil Use Manag. 22, 197-208.

Bertrand, I., Delfosse, O., Mary, B., 2007. Carbon and nitrogen mineralization in acidic, limed and calcareous agricultural soils: apparent and actual effects. Soil Biol. Biochem. 39, 276-88.

BGK e.V., 2005. Organische düngung. Grundlagen der guten fachlichen Praxis. Schriftenreihe für die Landwirtschaft', Bundesgütegemeinschaft Kompost e.V., Köln

Blank, D., 2008. A fresh look at life below the surface, in: Goddard, T., Zoebisch, M., Gan, Y., Ellis, W., Watson, A., Sombatpanit, S. (Eds.), No-Till Farming Systems. World Association of Soil and Water Conservation, Bangkok, pp. 73-81.

Blevins, R.L., Thomas, G.W., Cornelius, P.L., 1977. Influence of no-tillage and nitrogen-fertilization on certain soil properties after 5 years of continuous corn. Agron. J. 69, 383-386.

Bligh, E.G., Dyer, W.J., 1959. A rapid method of total lipid extraction and purification. Can. J. Biochem. Physiol. 37, 911-917.

Bokhorst, J., ter Berg, C., 2001. Handboek mest & compost: behandelen, beoordelen en toepassen, Louis Bolk Instituut, 292 p.

Brozyna, M.A., Petersen, S. O., Chirinda, N., Olesen, J. E., 2013. Effects of grass-clover management and cover crops on nitrogen cycling and nitrous oxide emissions in a stockless organic crop rotation. Agric. Ecosyst. Environ. 181, 115-126.

Buchan, D., Moeskops, B., Ameloot, N., De Neve, S., Sleutel, S., 2012. Selective sterilisation of undisturbed soil cores by gamma irradiation: Effects on free-living nematodes, microbial community and nitrogen dynamics. Soil Biol. Biochem. 47, 10-13.

Campiglia, E., Radicetti, E., Brunetti, P., Mancinelli, R., 2014. Do cover crop species and residue management play a leading role in pepper productivity? Sci. Hortic.-Amsterdam 166, 97-104.

Cannell, R.Q., 1985. Reduced tillage in Northwest Europe - a review. Soil Tillage Res. 5, 129-177.

Carter, M.S., Sorensen, P., Petersen, S. O., Ma, X. Z., Ambus, P., 2014. Effects of green manure storage and incorporation methods on nitrogen release and N_2O emissions after soil application. Biol. Fert. Soils 50, 1233-1246.

Carvalhais, L.C., Dennis, P. G., Fedoseyenko, D., Hajirezaei, M. R., Borriss, R., von Wiren, N., 2011. Root exudation of sugars, amino acids, and organic acids by maize as affected by nitrogen, phosphorus, potassium, and iron deficiency. J. Plant Nutr. Soil Sc. 174, 3-11.

Cavell, A., 2006. The colorimetric determination of phosphorus in plant materials. The Journal of the Science of Food and Agriculture 6, 479-480.

Cavigelli, M.A., Thien, S.J., 2003. Phosphorus bioavailability following incorporation of catch crops. Soil Sci. Soc. Am. J. 67, 1186-1194.

Chalhoub, M., Garnier, P., Coquet, Y., Mary, B., Lafolie, F., Houot, S., 2013. Increased nitrogen availability in soil after repeated compost applications: Use of the PASTIS model to seperate short and long-term effects. Soil Biol. Biochem. 65, 144-157.

Chan, C.W., Wood, R.K., Holmes, R.G., 1993. Powered harrow operating parameters - effects on soil physical properties. Trans. ASAE 36, 1279-1285.

Chaves, B., Piulats, L., De Neve, S., Hofman, G., Van Cleemput, O., 2006. Conserving N from high N crop residues under field conditions by using on- and off-farm organic biological waste materials. Proceedings of the International Symposium towards Ecologically Sound Fertilisation Strategies For Field Vegetable Production 249-254

Clark, M.S., Horwath, W. R., Shennan, C., Scow, K. M., 1998. Changes in soil chemical properties resulting from organic and low-input farming practices. Agron. J. 90, 662-671.

Collange, B., Navarrete, M., Montfort, F., Mateille, T., Tavoillot, J., Martiny, B., Tchamitchian, M., 2014. Alternative cropping systems can have contrasting effects on various soil-borne diseases: relevance of a systemic analysis in vegetable cropping systems. Crop Prot. 55, 7-15.

Coopman, F., Van Nevel, B., Van de Sande, T., Verhaeghe, M., De Reycke, L., Crappé, S., De Nies, J., Goovaerts, E., Elsen, A., Bries, J., Vandendriessche, H., De Neve, S., Ameloot, N., Willekens, K., Van Haecke, D., Boonen, M., Druyts, N., Van Mechelen, M., 2014. Het documenteren en milieukundig bijstellen van het KNS en andere bemestingsadviessystemen in de tuinbouw met het oog op een ruimere toepassing in de tuinbouw zoals voorzien in het Actieprogramma 2011-2014 (MAP4): Eindrapport, Studie uitgevoerd in opdracht van de Vlaamse Landmaatschappij (VLM), 233 p.

Curtis, M. J., Claassen, V. P., 2009. Regenerating topsoil functionality in four drastically disturbed soil types by compost incorporation. Restor. Ecol. 17, 24-32.

Dahlin, A.S., Stenberg, M., Marstorp, H., 2011. Mulch N recycling in green manure leys under Scandinavian conditions. Nutr. Cycl. Agroecosyst. 91, 119-129.

Dakora, F.D., Phillips, D. A., 2002. Root exudates as mediators of mineral acquisition in low-nutrient environments. Plant and Soil 245, 35-47.

De Neve, S., Hofman, G., 1998. N mineralization and nitrate leaching from vegetable crop residues under field conditions: a model evaluation. Soil Biol. Biochem. 30, 2067-2075.

de Vries, F.T., van Groenigen, J.W., Hoffland, E., Bloem, J., 2011. Nitrogen losses from two grassland soils with different fungal biomass. Soil Biol. Biochem. 43, 997-1005.

Dexter, A.R., Radke, J. K., Hewitt, J.S., 1983. Structure of a tilled soil as influenced by tillage, wheat cropping, and rainfall. Soil Sci. Soc. Am. J. 47, 570-575.

D'Haene, K., Salomez, J., De Neve, S., De Waele, J., Hofman, G., 2014. Environmental performance of nitrogen fertiliser limits imposed by the EU Nitrates Directive. Agric. Ecosyst. Environ. 192, 67-79.

D'Haene, K., Sleutel, S., De Neve, S., Gabriels, D., Hofman, G., 2009. The effect of reduced tillage agriculture on carbon dynamics in silt loam soils. Nutr. Cycl. Agroecosyst. 84, 249-265.

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. 28, 449-460.

D'Hose, T., Cougnon, M., De Vliegher, A., Vandecasteele, B., Viaene, N., Cornelis, W., Van Bockstaele, E., Reheul, D., 2014. The positive relationship between soil quality and crop production: a case study on the effect of farm compost application. Appl. Soil Ecol. 75, 189-198.

D'Hose, T., Cougnon, M., De Vliegher, A., Willekens, K., Van Bockstaele, E., Reheul, D., 2012. Farm compost application: effects on crop performance. Compost Sci. Util. 20, 49-56.

Diacono, M., Montemurro, F., 2010. Long-term effects of organic amendments on soil fertility. A review. Agron. Sustain. Dev. 30, 401-422.

Diez, T., Kraus, M., 1997. Wirkung langjähriger kompostdüngung auf pflanzenertrag und bodenfruchtbarkeit. Agribiol. Res. Band 50, S. 78 – 84

Djodjic, F., Mattsson, L., 2013. Changes in plant-available and easily soluble phosphorus within 1year after P amendment. Soil Use Manag. 29, 45-54.

Dolan, M.S., Clapp, C.E., Allmaras, R.R., Baker, J.M., Molina, J.A.E., 2006. Soil organic carbon and nitrogen in a Minnesota soil as related to tillage, residue and nitrogen management. Soil Tillage Res. 89, 221-231.

Dondeyne, S., Vanierschot, L., Langohr, R., Van Ranst, E., Deckers, S., 2014. The soil map of the Flemish region converted to the 3rd edition of the World Reference Base for soil resources (41 map sheets at scale 1:40 000, 1 map sheet at 1:250 000). KU Leuven, Universiteit Gent, Administratie van de Vlaamse Regering, Brussels, Belgium.

Doran, J.W., 1980. Soil microbial and biochemical changes associated with reduced tillage. Soil Sci. Soc. Am. J. 44, 765-771.

Dougherty, M. (Ed.), 1999. Field guide to on-farm composting. NRAES-114, Ithaca, New York, 118 p.

Drinkwater, L.E., Wagoner, P., Sarrantonio, M., 1998. Legume-based cropping systems have reduced carbon and nitrogen losses. Nature 396, 262-265.

Du Laing, G., Vanthuyne, D.R.J., Vandecasteele, B., Tack F.M., Verloo, M.G., 2007. Influence of hydrological regime on pore water metal concentrations in a contaminated sediment-derived soil. Environ. Pollut. 147, 615-625.

Duong, T.T.T., Verma, S.L., Penfold, C., Marschner, P., 2013. Nutrient release from composts into the surrounding soil. Geoderma 195, 42-47.

Egnèr, H., Riehm, H., Domingo, W.R., 1960. Untersuchungen über die chemische Bodenanalyse als Grundlage für die Beurteilung des Nährstoffzustandes der Böden. II. Chemische Extraktionsmethoden zur Phosphor- und Kaliumbestimmung. Ann. Royal Agric. Coll. Swed. 26, 199-215.

Ekeberg, E., Riley, H.C.F., 1997. Tillage intensity effects on soil properties and crop yields in a long-term trial on morainic loam soil in southeast Norway. Soil Tillage Res. 42, 277-293.

Emmerling, C., 2001. Response of earthworm communities to different types of soil tillage. Appl. Soil Ecol. 17, 91-96

Eriksen, J., Askegaard, M., Kristensen, K., 2004. Nitrate leaching from an organic dairy crop rotation: the effects of manure type, nitrogen input and improved crop rotation. Soil Use Manag. 20, 48-54.

Feller, C., Fink, M., Laber, H., Maync, A., Paschold, P., Scharpf, H.C., Schlaghecken, J., Strohmeyer, K., Weier, U., Ziegler, J., 2011. Düngung im Freilandgemüsebau. In: Fink, M. (Ed.), Schriftenreihe des Leibniz-Instituts für Gemüse-und Zierpflanzen-bau (IGZ), 3. Auflage, Heft 4, Großbeeren.

Feller, C., Fink, M., 2002. Nmin target values for field vegetables. Acta Hortic. 571, 195-201.

Fink, M., 2001. Yield and external quality of kohlrabi as affected by soil mineral nitrogen residue at harvest. J. Hortic. Sci. Biotech. 76, 419-423.

Fonder, N., Deneufbourg, M., Vandenberghe, C., Xanthoulis, D., Marcoen, J.M., 2010. Monitoring of nitrate leaching in croplands by lysimeters. Biotechnol. Agron. Soc. Environ. 14, 17-25.

Franzluebbers, A.J., Hons, F.M., 1996. Soil-profile distribution of primary and secondary plant-available nutrients under conventional and no tillage. Soil Tillage Res. 39, 229-239.

Frey, S.D., Elliott, E.T., Paustian, K., 1999. Bacterial and fungal abundance and biomass in conventional and no-tillage agroecosystems along two climatic gradients. Soil Biol. Biochem. 31, 573-585.

Garbeva, P., Postma, J., van Veen, J.A., van Elsas, J.D., 2006. Effect of above-ground plant species on soil microbial community structure and its impact on suppression of Rhizoctonia solani AG3. Environ. Microbiol. 8, 233-246.

Ge, Y., Zhang, J.B., Zhang, L.M., Yang, M., He, J.Z., 2008. Long-term fertilization regimes affect bacterial community structure and diversity of an agricultural soil in Northern China. J. Soils Sediments 8, 43-50.

Gerzabek, M.H., Pichlmayer, F., Kirchmann, H., Haberhauer, G., 1997. The response of soil organic matter to manure amendments in a long-term experiment at Ultuna, Sweden. Eur. J. Soil Sci. 48, 273-282.

Ghani, A., Dexter, M., Perrot, K.W., 2003. Hot-water extractable carbon in soils: a sensitive measurement for determining impacts of fertilization, grazing and cultivation. Soil Biol. Biochem. 35, 1231-1243.

Giacomini, S.J., Machet, J.M., Boizard, H., Recous, S., 2010. Dynamics and recovery of fertilizer N-15 in soil and winter wheat crop under minimum versus conventional tillage. Soil Tillage Res. 108, 51-58.

Gomez, K.A., Gomez, A.A., 1984. Statistical Procedures for Agricultural Res., second ed. John Wiley & Sons, Inc., Chichester, UK.

Gonzalez-Dugo, V., Durand, J.L., Gastal, F., 2010. Water deficit and nitrogen nutrition of crops. A review. Agron. Sustain. Dev. 30, 529-544.

Green, H., Bengtsson, M., Duval, X., Pedersen, H.L., Hockenhull, J., Larsen, J., 2006. Influence of urea on the cherry leaf spot pathogen, Blumeriella jaapii, and on microorganisms in decomposing cherry leaves. Soil Biol. Biochem. 38, 2731-2742.

Groenevelt, P.H., Kay, B.D., Grant, C.D., 1984. Physical assessment of a soil with respect to rooting potential. Geoderma 34, 101-114.

Hamer, U., Potthast, K., Makeschin, F., 2009. Urea fertilisation affected soil organic matter dynamics and microbial community structure in pasture soils of Southern Ecuador. Appl. Soil Ecol. 43, 226-233.

Haynes, R.J., 2005. Labile organic matter fractions as central components of the quality of agricultural soils: an overview. Adv. Agron. 85, 221-268.

Haynes, R.J., Francis, G.S., 1993. Changes in microbial biomass-C, soil carbohydrate-composition and aggregate stability induced by growth of selected crop and forage species under field conditions. J. Soil Sci. 44, 665-675.

Hermanson, R., Pan, W., Perillo, C., Stevens, R., Stockle, C., 2000. Nitrogen use by crops and the fate of nitrogen in the soil and vadose zone. A Literature Search. Washington State University and Washington Department of Ecology. Publication No. 00-10-015.

Hesketh, N., Brookes, P. C., 2000. Development of an indicator for risk of phosphorus leaching. J. Environ. Qual. 29, 105-110.

Hofman, G., Van Ruymbeke, M., Ossemerct, C., Ide, G., 1981. Residual nitrate nitrogen in sandy loam soils in a moderate marine climate. Pedologie 31, 329–346.

Holland, J.M., 2004. The environmental consequences of adopting conservation tillage in Europe: reviewing the evidence. Agric. Ecosyst. Environ. 103, 1-25.

IUSS Working Group WRB, 2015. World Reference Base for Soil Resources 2014, update 2015 International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports No. 106. FAO, Rome.

Jackson, L.E., Ramirez, I., Yokota, R., Fennimore, S.A., Koike, S.T., Henderson, D.M., Chaney, W.E., Calderon, F.J., Klonsky, K., 2004. On-farm assessment of organic matter and tillage management on vegetable yield, soil, weeds, pests, and economics in California. Agric. Ecosyst. Environ. 103, 443-463.

Jackson, L.E., Wyland, L.J., Stivers, L.J., 1993. Winter cover crops to minimize nitrate losses in intensive lettuce production. J. Agric. Sci. 121, 55-62.

Jenkinson, D.S., 2001. The impact of humans on the nitrogen cycle, with focus on temperate arable agriculture. Plant Soil 228, 3-15.

Joergensen, R.G., 1996. The fumigation-extraction method to estimate soil microbial biomass: Calibration of the k(EC) value. Soil Biol. Biochem. 28, 25-31.

Jordan-Meille, L., Rubaek, G., Ehlert, P., Genot, V., Hofman, G., Goulding, K., Recknagel, J., Provolo, G., Barraclough, P., 2012. An overview of fertilizer-P recommendations in Europe: soil testing, calibration and fertilizer recommendations. Soil Use Manag. 28, 419-435.

Kader, M.A., Sleutel, S., Begum, S.A., D'Haene, K., Jegajeevagan, K. & De Neve, S., 2010. Soil organic matter fractionation as a tool for predicting nitrogen mineralization in silty arable soils. Soil Use Manag. 26, 494-507.

Kandeler, E., Tscherko, D., Spiegel, H., 1999. Long-term monitoring of microbial biomass, N mineralisation and enzyme activities of a Chernozem under different tillage management. Biol. Fert. Soils 28, 343-351.

Kindler, R., Siemens, J., Kaiser, K., Walmsley, D.C., Bernhofer, C., Buchmann, N., Cellier, P., Eugster, W., Gleixner, G., Grunwald, T., Heim, A., Ibrom, A., Jones, S.K., Jones, M., Klumpp, K., Kutsch, W., Larsen, K.S., Lehuger, S., Loubet, B., McKenzie, R., Moors, E., Osborne, B., Pilegaard, K., Rebmann, C., Saunders, M., Schmidt, M.W.I., Schrumpf, M., Seyfferth, J., Skiba, U., Soussana, J.F., Sutton, M.A., Tefs, C., Vowinckel, B., Zeeman, M.J., Kaupenjohann, M., 2011. Dissolved carbon leaching from soil is a crucial component of the net ecosystem carbon balance. Glob. Change Biol. 17, 1167-1185.

Koller, M., Vieweger, A., Total, R., Bauermeister, R., Suter, D., Mader, P., 2008. Nitrogen effects of green manuring on organic cabbage crops. Agrarforschung 15, 264-269.

Koopmans, C.J., Bokhorst, J., 2002. Nitrogen mineralisation in organic farming systems: a test of the NDICEA model. Agronomie 22, 855-862.

Kramer, A.W., Doane, T. A., Horwath, W. R., Kessel, C. V., 2002. Combining fertilizer and organic inputs to synchronize N supply in alternative cropping systems in California. Agric. Ecosyst. Environ. 91, 233-243.

Kuzyakov, Y., Friedel, J.K., Stahr, K., 2000. Review of mechanisms and quantification of priming effects. Soil Biol. Biochem. 32, 1485-1498.

Lal, R., Logan, T.J., Fausey, N.R., 1990. Long-term tillage effects on a mollic Ochraqualf in North-West Ohio. III. Soil Nutrient Profile. Soil Tillage Res. 15, 371-382.

Langmaack, M., Schrader, S., Rapp-Bernhardt, U., Kotzke, K., 2002. Soil structure rehabilitation of arable soil degraded by compaction. Geoderma 105, 141-152.

Lee, J., 2012. Evaluation of composted cattle manure rate on bulb onion grown with reduced rates of chemical fertilizer. Horttechnology 22, 798-803.

Leroy, B., Bommele, L., Reheul, D., Moens, M., De Neve, S., 2007. The application of vegetable, fruit and garden waste (VFG) compost in addition to cattle slurry in a silage maize monoculture: effects on soil fauna and yield. Eur. J. Soil Biol. 43, 91-100.

Linn, D.M., Doran, J.W., 1984. Aerobic and anaerobic microbial-populations in no-till and plowed soils. Soil Sci. Soc. Am. J. 48, 794-799.

Little, I.P., Ringrosevoase, A.J., Ward, W.T., 1992. Surface-structure in gray clays of Northwestern New-South-Wales in relation to micromorphology, Cation Suite and Particle-Size Attributes. Aust. J. Soil Res. 30, 1-16.

Loch, R.J., 1994. Effects of Fallow Management and cropping history on aggregate breakdown under rainfall wetting for a range of Queensland soils. Aust. J. Soil Res. 32, 1125-1139.

Lorenz, H.P., Schlaghecken, J., Engl, G., 1989. Ordnungsgemässe stickstoffversorgung im freiland-gemüsebau nach dem "Kulturbegleitenden Nmin-Sollwerte (KNS) - System". Ministerium Landwirtschaft Weinbau Forsten Rheinland.

Maes, S., Elsen, A., Tits, M., Boon, W., Deckers, S., Bries, J., Vogels, N., Vandendriessche, H., 2012. Detailed look at the soil fertility of arable and grass lands in Belgium (2008-2011) (In Dutch). Soil Service of Belgium, Heverlee, Belgium, 198 p

Maguire, R.O., Sims, J. T., 2002. Soil testing to predict phosphorus leaching. J. Environ. Qual. 31, 1601-1609.

Malhi, S.S., Nyborg, M., Goddard, T., Puurveen, D., 2011a. Long-term tillage, straw and N rate effects on some chemical properties in two contrasting soil types in Western Canada. Nutr. Cycl. Agroecosyst. 90, 133-146.

Malhi, S.S., Nyborg, M., Solberg, E. D., McConkey, B., Dyck, M., Puurveen, D., 2011b. Long-term straw management and N fertilizer rate effects on quantity and quality of organic C and N and some chemical properties in two contrasting soils in Western Canada. Biol. Fert. Soils 47, 785-800.

Maynard, A.A., 1994. Effect of annual amendments of compost on nitrate leaching in nursery stock, Compost Sci. Util. 2, 54–55.

Maynard, A.A., Hill, D. E., 2000. Cumulative effect of leaf compost on yield and size distribution in onions. Compost Sci. Util. 8, 12-18.

Miransari, M., Mackenzie, A., 2012. Corn (*Zea mays* L.) Grain and stover yield as affected by soil residual mineral nitrogen. Commun. Soil Sci. Plan. 43, 799-810.

Moeskops, B., Sukristiyonubowo, Buchan, D., Sleutel, S., Herawaty, L., Husen, E., Saraswati, R., Setyorini, D., De Neve, S., 2010. Soil microbial communities and activities under intensive organic and conventional vegetable farming in West Java, Indonesia. Appl. Soil Ecol. 45, 112-120.

Mulvaney, R.L., Khan, S.A., Ellsworth, T.R., 2009. Synthetic nitrogen fertilizers deplete soil nitrogen: a global dilemma for sustainable cereal production. J. Environ. Qual. 38, 2295-2314.

Naidu, R., McClure, S., McKenzie, N.J., Fitzpatrick, R.W., 1996. Soil solution composition and aggregate stability changes caused by long-term farming at four contrasting sites in south Australia. Aust. J. Soil Res. 34, 511-527.

Neeteson, J.J., Booij, R, Whitmore, A. P., 1999. A review on sustainable nitrogen management in intensive vegetable production systems. Acta Hortic.506, 17-26.

Neff, J.C., Townsend, A.R., Gleixner, G., Lehman, S.J., Turnbull, J., Bowman, W.D., 2002. Variable effects of nitrogen additions on the stability and turnover of soil carbon. Nature 419, 915-917.

Nicola, S., Fontana, E., Monaco, S., Grignani, C., 2013. The application of the Nitrates Directive to vegetable crops: tools and strategies from NEV2013 for an integrated fertilisation management. In: D'Haene, K., Vandecasteele, B., De Vis, R. Crappé, S., Callens, D., Mechant, E., Hofman, G., De Neve, S. (Eds.), Proceedings NUTRIHORT: Nutrient management, innovative techniques and nutrient legislation in intensive horticulture for an improved water quality, September 16-18, Ghent, Belgium, 2-8.

Nortcliff, S., Amlinger, F., 2001. Compost impacts on soil biology and anti-phytopathogenic potential. In: Amlinger, F., Dreher, P., Nortcliff, S., Weinfurtner, K. (Eds.), Applying Compost, Benefits And Needs. Seminar Proceedings, Brussels, November, 22 – 23, p.147-152.

Parkinson, R.J., Fuller, M. P., Groenhof, A. C., 1999. An evaluation of greenwaste compost for the production of forage maize (Zea mays L). Compost Sci. Util. 7, 72-80.

Paul, D.K., Black, A.P.S., Conyers, D.M., 2001. Development of nitrogen mineralisation gradients through surface soil depth and their influence on surface soil pH. Plant Soil 234, 239-246.

Paul, E.A., Clark, F.E., 1996. Soil microbiology and biochemistry. Academic Press. 340 p.

Peigne, J., Ball, B. C., Roger-Estrade, J., David, C., 2007. Is conservation tillage suitable for organic farming? A review. Soil Use Manag. 23, 129-144.

Peters, S.E., Wander, M.M., Saporito, L.S., Harris, G.H., Friedman, D.B., 1997. Management impacts on SOM and related soil properties in a long-term farming systems trial in Pennsylvania: 1981-1991. In: Paul, E.A., Paustian, K., Elliot, E.T., Cole, C.V. (Eds) Soil Organic Matter in Temperate Agroecosystems. CRC Press, Boca Raton, pp. 183-196.

Petersen, J., 2003. Nitrogen fertilizer replacement value of sewage sludge, composted household waste and farmyard manure. J. Agric. Sci. 140, 169-182.

Pfotzer, G.H., Schuler, C., 1997. Effects of different compost amendments on soil biotic and faunal feeding activity in an organic farming system. Biol. Agric. Hortic. 15, 177-183.

Poudel, D.D., Horwath, W. R., Lanini, W. T., Temple, S. R., Van Bruggen, A. H. C., 2002. Comparison of soil N availability and leaching potential, crop yields and weeds in organic, low-input and conventional farming systems in northern California. Agric. Ecosyst. Environ. 90, 125-137.

Poudel, D.D., Horwath, W. R., Mitchell, J. P., Temple, S. R., 2001. Impacts of cropping systems on soil nitrogen storage and loss. Agr. Syst. 68, 253-268.

Rahn, C., De Neve, S., Bath, B., Bianco, V., Dachler, M., Cordovil, C., Fink, M., Gysi, C., Hofman, G., Koivunen, M., Panagiotopoulos, L., Poulain, D., Ramos, C., Riley, H., Setatou, H., Sorensen, J., Titulaer, H., Weier, U., 2001. A comparison of fertiliser recommendation systems for cauliflowers in Europe. Acta Hortic. 563, 39-45.

Rahn, C., 2013. The challenges of knowledge transfer in the implementation of the Nitrates Directive, in: D'Haene, K., Vandecasteele, B., De Vis, R., Crappé, S., Callens, D., Mechant, E., Hofman, G., De Neve, S. (Eds.), NUTRIHORT: Nutrient management, innovative techniques and nutrient legislation in intensive horticulture for an improved water quality, Proc., Ghent, pp. 9-15.

Rasmussen, K.J., 1999. Impact of ploughless soil tillage on yield and soil quality: a Scandinavian review. Soil Tillage Res. 53, 3-14.

Rasmussen, P.E., Collins, H.P., 1991. Long-term impacts of tillage, fertilizer, and crop residue on soil organic-matter in temperate semiarid regions. Adv. Agron. 45, 93-134.

Raun, W.R., Johnson, G.V., Phillips, S.B., Westerman, R.L., 1998. Effect of long-term N fertilization on soil organic C and total N in continuous wheat under conventional tillage in Oklahoma. Soil Tillage Res. 47, 323-330.

Reeves, D.W., 1997. The role of soil organic matter in maintaining soil quality in continuous cropping systems. Soil Tillage Res. 43, 131-167.

Rink, R. (Ed.), 1992. On-farm composting handbook. NRAES-54, Ithaca, New York, 186 p.

Ritz, K., Young, I.M., 2004. Interactions between soil structure and fungi. Mycologist 18 (2), 52-59.

Ros, G.H., 2012. Predicting soil N mineralization using organic matter fractions and soil properties: A re-analysis of literature data. Soil Biol. Biochem. 45, 132-135.

Ros, G.H., Temminghoff, E.J.M., Hoffland, E., 2011. Nitrogen mineralization: a review and meta-analysis of the predictive value of soil tests. Eur. J. Soil Sci. 62, 162-173.

Schroder, J., de Visser, W., Assinck, F., Velthof, G., 2013. Effects of short-term nitrogen supply from livestock manures and cover crops on silage maize production and nitrate leaching. Soil Use Manag. 29, 151-160.

Scopel, E., Triomphe, B., Affholder, F., Da Silva, F.A.M., Corbeels, M., Xavier, J.H.V., Lahmar, R., Recous, S., Bernoux, M., Blanchart, E., Mendes, I.D., De Tourdonnet, S., 2013. Conservation agriculture cropping systems in temperate and tropical conditions, performances and impacts. A review. Agron. Sustain. Dev. 33, 113-130.

Scotti, R., D'Ascoli, R., Caceres, M., Bonanomi, G., Sultana, S., Cozzolino, L., Scelza, R., Zoina, A., Rao, M., 2015. Combined use of compost and wood scraps to increase carbon stock and improve soil quality in intensive farming systems. Eur. J. Soil Sci. 66, 463-475.

Six, J., Elliott, E.T., Paustian, K., 2000. Soil macroaggregate turnover and microaggregate formation: a mechanism for C sequestration under no-tillage agriculture. Soil Biol. Biochem. 32, 2099-2103.

Sørensen, J.N., 1993. Use of the Nmin-method for optimization of vegetable nitrogen nutrition. Acta Hortic. 339, 179-192.

Sørensen, J.N., Johansen, A.S., Kaack, K., 1995. Marketable and nutritional quality of leeks as affected by water and nitrogen supply and plant age at harvest. J. Sci. Food Agr. 68, 367-373.

Sørensen, J.N., Thorup-Kristensen, K., 2011. Plant-based fertilizers for organic vegetable production. J. Plant Nutr. Soil Sc. 174, 321-332.

Steel, H., Vandecasteele, B., Willekens, K., Sabbe, K., Moens, T., Bert, W., 2012. Nematode communities and macronutrients in composts and compost-amended soils as affected by feedstock composition. Appl. Soil Ecol. 61, 100-112.

Strong, D. T., Sale, P. W. G., Helyar K. R., 1998. The influence of the soil matrix on nitrogen mineralisation and nitrification. I. Spatial variation and a hierarchy of soil properties. Aust. J. Soil Res. 36, 429-447.

Stute, J.K., Posner, J. L., 1995. Synchrony between legume nitrogen release and corn demand in the upper midwest. Agron. J. 87, 1063-1069.

Tejada, M., Dobao, M.M., Benitez, C., Gonzalez, J.L., 2001. Study of composting of cotton residues. Bioresource Technol. 79, 199-202.

ten Berge, H.F.M., Radersma, S., Burgers, S.L.G E., 2010. Feed the crop or feed the soil? A case study in leek (*Allium porrum* L.). Acta Hortic. 852, 85-95.

Terbrügge, F., 2003. No-tillage visions - protection of soil, water and climate and influence on management and farm income. In: García, L., Torres et al. (Eds.), Conservation Agriculture, 327-340.

Thompson, R.B., Martinez-Gaitan, C., Gallardo, M., Gimenez, C., Fernandez, M.D., 2007. Identification of irrigation and N management practices that contribute to nitrate leaching loss from an intensive vegetable production system by use of a comprehensive survey. Agric. Water Manag. 89, 261-274.

Thorup-Kristensen, K., Sørensen, J.N., 1999. Soil nitrogen depletion by vegetable crops with variable root growth. Acta Agr. Scand. B-S P 49, 92-97.

Thorup-Kristensen, K., 2006. Effect of deep and shallow root systems on the dynamics of soil inorganic N during 3-year crop rotations. Plant Soil 288**,** 233-248.

Tits, M., Elsen, A., Bries, J., Vandendriessche, H., 2014. Short-term and long-term effects of vegetable, fruit and garden waste compost applications in an arable crop rotation in Flanders. Plant Soil 376, 43-59.

Truu, M., Truu, J., Ivask, M., 2008. Soil microbiological and biochemical properties for assessing the effect of agricultural management practices in Estonian cultivated soils. Eur. J. Soil Biol. 44, 231-237.

Van den Bossche, A., De Bolle, S., De Neve, S., Hofman, G., 2009. Effect of tillage intensity on N mineralization of different crop residues in a temperate climate. Soil Tillage Res. 103, 316-324.

Van den Putte, A., Govers, G., Diels, J., Gillijns, K., Demuzere, M., 2010. Assessing the effect of soil tillage on crop growth: a meta-regression analysis on European crop yields under conservation agriculture. Eur. J. Agron. 33, 231-241.

van Dijk, W., Smit, A.L., 2006. How to meet the EC-nitrate directive in dutch vegetable growing? in: Tei, F., Benincasa, P., and Guiducci, M. (Eds.), Towards Ecologically Sound Fertilisation Strategies for Field Vegetable Production, Proceedings ISHS symposium in Perguia, 7-10 June 2004. International Society of Horticulturals Science, Leuven, pp. 191-197.

van Grinsven, H.J.M., ten Berge, H.F.M., Dalgaard, T., Fraters, B., Durand, P., Hart, A., Hofman, G., Jacobsen, B.H., Lalor, S.T.J., Lesschen, J.P., Osterburg, B., Richards, K.G., Techen, A.K., Vertes, F., Webb, J., Willems, W.J., 2012. Management, regulation and environmental impacts of nitrogen fertilization in northwestern Europe under the Nitrates Directive; a benchmark study. Biogeosciences 9, 5143-5160.

Van Ranst, E., Verloo, M., Demeyer, A., Pauwels, J.M., 1998. Manual for the soil chemistry and fertility laboratory. Analytical methods for soils and plants, equipment and management of consumables. UGent, Ghent.

Vandecasteele, B., Reubens, B., Willekens, K., De Neve, S., 2014. Composting for increasing the fertilizer value of chicken manure: effects of feedstock on P availability. Waste and Biomass Valorization 5, 491-503.

Vandecasteele, B., Willekens, K., Zwertvaegher, A., Degrande, L., Tack, F.M.G., Du Laing, G., 2013. Effect of composting on the Cd, Zn and Mn content and fractionation in feedstock mixtures with wood chips from a short-rotation coppice and bark. Waste Manage. 33, 2195-2203.

Vanden Nest, T., Ruysschaert, G., Vandecasteele, B., Cougnon, M., Merckx, R., Reheul, D., 2015. P availability and P leaching after reducing the mineral P fertilization and the use of digestate products as new organic fertilizers in a 4-year field trial with high P status. Agric. Ecosyst. Environ. 202, 56-67.

Vanden Nest, T., Vandecasteele, B., Ruysschaert, G., Merckx, R., 2014. Incorporation of catch crop residues does not increase phosphorus leaching: a soil column experiment in unsaturated conditions. Soil Use and Management 30, 351-360

Viaene, J., Van Lancker, J., Vandecasteele, B., Willekens, K., Bijttebier, J., Ruysschaert, J., De Neve, S., Reubens, B., 2015. Opportunities and barriers to on-farm composting and compost application: A case study from northwestern Europe. Waste Management, in press.

Vinten, A.J.A., Dunn, S.M., 2001. Assessing the effects of land use on temporal change in well water quality in a designated nitrate vulnerable zone. Sci. Total Environ. 265, 253-268.

Voroney, R.P., Winter, J.P., Beyaert, R.P., 2008. Soil Microbial Biomass C, N, P, and S. in: Carter, M.R. (Ed.), Soil Sampling and Methods of Analysis CRC Press, Taylor & Francis Group, Boca Raton, FL, Canada, pp. 637-651.

Wang, J.G., Bakken, L. R., 1997. Competition for nitrogen during decomposition of plant residues in soil: Effect of spatial placement of N-rich and N-poor plant residues. Soil Biol. Biochem. 29, 153-62.

Wang, Z.H., Li, S. X., Vera, C. L., Malhi, S. S., 2005. Effects of water deficit and supplemental irrigation on winter wheat growth, grain yield and quality, nutrient uptake, and residual mineral nitrogen in soil. Commun. Soil Sci. Plan. 36, 1405-1419.

Wang, X., Tang, C., Guppy, C., Sale, P., 2008. Phosphorus acquisition characteristics of cotton (*Gossypium hirsutum* L.), wheat (*Triticum aestivum* L.) and white lupin (*Lupinus albus* L.) under P deficient conditions. Plant Soil 312, 117-128.

Wardle, D.A., 1995. Impacts of disturbance on detritus food webs in agro-ecosystems of contrasting tillage and weed management practices. Adv. Ecol. Res. 26, 105-185.

Weatherly, A.B., Dane, J. H., 1979. Effect of tillage on soil-water movement during corn growth. Soil Sci. Soc. Am. J. 43, 1222-1225.

Weber J., Karczewska, A., Drozd, J., Licznar, M., Licznar, S., Jamroz, E., Kocowicz, A., 2007. Agricultural and ecological aspects of a sandy soil as affected by the application of municipal solid waste composts. Soil Biol. Biochem. 39, 1294-1302.

Weller, D.M., Raaijmakers, J. M., Gardener, B. B. M., Thomashow, L. S., 2002. Microbial populations responsible for specific soil suppressiveness to plant pathogens. Annu. Rev. Phytopathol. 40, 309-+.

Wiesler, F., Horst, W. J., 1992. Differences between maize cultivars in yield formation, nitrogen uptake and associated depletion of soil nitrate. J. Agron. Crop Sci. 168, 226-237.

Willekens, K., Vandecasteele, B., Buchan, D., De Neve, S., 2014a. Soil quality is positively affected by reduced tillage and compost in an intensive vegetable cropping system. Appl. Soil Ecol. 82, 61-71.

Willekens, K., Vandecasteele, B., De Neve, S., 2014b. Limited short-term effect of compost and reduced tillage on N dynamics in a vegetable cropping system. Sci. Hortic.-Amsterdam 178, 79-86.

Woomer, P.L., Martin, A., Albrecht, A., Resck, D.V.S., Scharpenseel, H.W., 1994. The importance and management of soil organic matter in the tropics. In: Woomer, P.L., Swift, M.J. (Eds.), The Biological Management of Tropical Soil Fertility. John Wiley, Chichester, pp. 47±80.

Yaduvanshi, N.P.S., Setter, T.L., Sharma, S.K., Singh, K.N., Kulshreshtha, N., 2010. Waterlogging effects on wheat yield, redox potential, manganese and iron in different soils of India. In: Proceedings of the World Congress of Soil Science, Soil Solutions for a Changing World, 1-6 August 2010, Brisbane, Australia, 45-48.

Yague, M. R., Quilez, D., 2013. Residual effects of fertilization with pig slurry: double cropping and soil. Agron. J. 105, 70-78.

Yevdokimov, I.V., Gattinger, A., Buegger, F., Schloter, M., Munch, J. C., 2012. Changes in the structure and activity of a soil microbial community caused by inorganic nitrogen fertilization. Microbiology 81, 743-749.

Zdruli, P, Pagliai, M., Kapur, S., Faz Cano, A., 2010. Land Degradation and Desertification: Assessment, Mitigation and Remediation, first ed. Springer.

Zebarth, B.J., Neilsen, G.H., Hogue, E., Neilsen, D., 1999. Influence of organic waste amendments on selected soil physical and chemical properties. Can. J. Soil Sci. 79 (3), 501-504.

Curriculum Vitae

Personal information

Name: Koen Willekens

Address: Gavergrachtstraat 23, 9031 Gent (Drongen), Belgium

Phone: +32 485 179 391

E-mail: koen.willekens@ilvo.vlaanderen.be

Date of birth: 4th of October 1965

Place of birth: Geel

Nationality: Belgian

Civil class: Married

Education

1977-1983: Latin-Sciences, Xaveriuscollege, Borgerhout

1983-1989: Master of Bioscience Engineering - Soil Sciences
Faculty of Bioscience Engineering, Ghent University, Ghent

2008-2016: Doctoral School Bioscience Engineering, Ghent University, Ghent

Job

Current position:

1999-2016: Research associate soil management and cropping systems
Institute for Agricultural and Fisheries Research (ILVO), Merelbeke

2008-2016: PhD-student Ghent University

Previous positions:

1990-1991: Civil service, IONA biodynamic farm, Kessel

1992-1993: Farmers' assistance association, Boerenbond, Leuven

1992-1999: Freelance commitments:

- Control and certification body TÜV NORD INTEGRA, Berchem
- On-farm advice soil management and fertilization, farm advisory service BIOconsult
- Study and support commissioned by organic farmers' extension service BLIVO and organic farmers' association BELBIOR

Scientific publications in journals with peer review

Bobev, S.G., Willekens, K., Goeminne, G., Maes, M., 2004. Resistance to air-borne diseases and pests induced by compost in substrate cultivation of strawberry. Communications in Agricultural and *Applied Biological Sciences* 69(4):591-3.

Casagrande, M., Peigné, J., Payet, V., Mäder, P., Sans, F.X., Blanco-Moreno, J.M., Antichi, D., Bàrberi, P., Beeckman, A., Bigongiali, F., Cooper, J., Dierauer, H., Gascoyne, K., Grosse, M., Heß, J., Kranzler, A., Luik, A., Peetsmann, E., Surböck, A., Willekens, K., David, C., 2015. Organic farmers' motivations and challenges for adopting conservation agriculture in Europe". Organic Agriculture. Accepted.

D'Hose, T., Cougnon, M., De Vliegher, A., Willekens, K., Van Bockstaele, E., Reheul, D., 2012. Farm compost application: effects on crop performance. *Compost Science & Utilization* 20, 49-56.

Lavu, R.V.S., Du Laing, G., Van De Wiele, T., Pratti, V.L., Willekens, K., Vandecasteele, B., Tack, F., 2012. Fertilizing soil with selenium fertilizers: impact on concentration, speciation, and bioaccessibility of selenium in leek (*Allium ampeloprasum*). *Journal of Agricultural and Food Chemistry* 60, 10930-10935.

Peigné, J., Casagrande, M., Payet, V., David, C., Sans, F.X., Blanco-Moreno, J.M., Cooper, J., Gascoyne, K., Antichi, D., Bàrberi, P., Bigongiali, F., Surböck, A., Kranzler, A., Beeckman, A., Willekens, K., Luik, A., Matt, D., Grosse, M., Heß, J., Clerc, M., Dierauer, H., Mäder, P., 2015. How organic farmers practice conservation agriculture in Europe. *Renewable Agriculture and Food Systems*. Available on CJO2015.

Steel, H., de la Peña, E., Fonderie, P., Willekens, K., Borgonie, G., Bert, W., 2010. Nematode succession during composting and the potential of the nematode community as an indicator of compost maturity. *Pedobiologia* 53, Issue 3, 181-190.

Steel, H., Vandecasteele, B., Willekens, K., Sabbe, K., Moens, T., Bert, W., 2012. Nematode communities and macronutrients in composts and compost-amended soils as affected by feedstock composition. *Applied Soil Ecology* 61, 100-112.

Vandecasteele, B., Reubens, B., Willekens, K., De Neve, S., 2014. Composting for increasing the fertilizer value of chicken manure: effects of feedstock on P availability. *Waste and Biomass Valorization* 5, Issue 3, 491-503.

Vandecasteele, B., Willekens, K., Zwertvaegher, A., Degrande, L., Tack, F.M.G., Du Laing, G., 2013. Effect of composting on the Cd, Zn and Mn content and fractionation in feedstock mixtures with wood chips from a short-rotation coppice and bark. *Waste Management* 33, 2195-220310.

Viaene, J., Van Lancker, J., Vandecasteele, B., Willekens, K., Bijttebier, J., Ruysschaert, G., De Neve, S., Reubens, B., 2015. Opportunities and barriers to on-farm composting and compost application: A case study from northwestern Europe. *Waste Management* 10/2015. In press.

Willekens, K., Vandecasteele, B., Buchan, D., De Neve, S., 2014. Soil quality is positively affected by reduced tillage and compost in an intensive vegetable cropping system. *Applied Soil Ecology* 82, 61-71.

Willekens, K., Vandecasteele, B., De Neve, S., 2014. Limited short-term effect of compost and reduced tillage on N dynamics in a vegetable cropping system. *Scientia Horticulturae* 178, 79-86.

Conference proceedings

Bobev, S.G., Kehajov, D.K., Maes, M., Willekens, K., Bost, M.A., 2012. Compost influence on some air-borne diseases and pests in strawberry. In: Castilla, N., Sase, S., Schnitzler, W.H. (eds.) Proceedings of the International Symposium on Greenhouse 2010 and Soilless Cultivation, XXVIII International Horticultural Congress on Science and Horticulture for People (IHC2010), August 22-27, 2010, Lisbon, Portugal. Acta Horticulturae 927, 959-966.

Casagrande, M., Peigné, J., David, C., Sans, F.X., Blanco-Moreno, J.M., Cooper, J.M., Gascoyne, K., Antichi, D., Bàrberi, P., Bigongiali, F., Surböck, A., Kranzler, A., Beeckman, A., Willekens, K., Luik, A., Peetsman, E., Grosse, M., Heß, J., Clerc, M., Dierauer, H., Mäder, P., 2014. Organic Farmers in Europe: motivations and problems for using Conservation agriculture practices. "TILMAN-ORG SESSION" In: Rahmann, G., Aksoy, U. (eds.) Proceedings of the 4th ISOFAR Scientific Conference, 'Building Organic Bridges', at the 18th IFOAM Organic World Congress, 13-15 October, Istanbul, Turkey. Thünen Report 20, 295-298.

Cooper, J.M., Baranski, M., Nobel de Lange, M., Barberi, P., Fliessbach, A., Peigne, J., Berner, A., Brock, C., Casagrande, M., Crowley, O., David, C., De Vliegher, A., Doring, T., Entz, M., Grosse, M., Haase, T., Halde, C., Hammerl, V., Huiting, H., Leithold, G., Messmer, M., Schloter, M., Sukkel, W., van der Heijden, M., Willekens, K., Wittwer, R., Mäder, P., 2014. Effects of reduced tillage in organic farming on yield, weeds and soil carbon: meta-analysis results from the TILMAN-ORG project. In: Rahmann, G., Aksoy, U. (eds.) Proceedings of the 4th ISOFAR Scientific Conference, 'Building Organic Bridges', at the 18th IFOAM Organic World Congress, October 13-15, Istanbul, Turkey. Thünen Report 20, 1163-1166.

De Vliegher, A., Willekens, K., Carlier, L., 2007. Behaviour of maize varieties under organic and conventional farming conditions. Proceedings of the 16th International Symposium of the International Scientific Centre for Fertilisers (CIEC), 'Mineral versus Organic Fertilization, Conflict or Synergism?', September 16-19, Faculty of Bioscience Engineering, Ghent University, Belgium, 161-166.

D'Hose, T., Ruysschaert, G., Heungens, K., Viaene, N., De Vliegher, A., Willekens, K., 2013. Soil organic matter management within the legal constraints of the fertilization laws – BOPACT field trial. In: D'Haene, K., Vandecasteele, B., De Vis, R. Crappé, S., Callens, D., Mechant, E., Hofman, G., De Neve, S. (eds.) Proceedings NUTRIHORT: Nutrient management, innovative techniques and nutrient legislation in intensive horticulture for an improved water quality, September 16-18, Ghent, Belgium, 314-321.

Hofman, G. , De Vis, R., Crappé, S., Van de Sande, T., Mechant, E., D'Haene K., Amery, F., Vandecasteele, B., Willekens, K., De Neve, S., 2013. Benchmark study on nutrient legislation for horticultural crops in some European countries. In: D'Haene, K., Vandecasteele, B., De Vis, R. Crappé, S., Callens, D., Mechant, E., Hofman, G, De Neve, S. (eds.) Proceedings NUTRIHORT: Nutrient management, innovative techniques and nutrient legislation in intensive horticulture for an improved water quality, September 16-18, Ghent, Belgium, 211-227.

Vandecasteele, B., Reubens, B., Willekens, K., Beeckman, A., Delanote, L., De Neve, S., 2012. Composting for increasing the fertilizer value of chicken manure: effects of feedstock on P availability. In: Proceedings of the 8th International Conference ORBIT2012, 'Global Assessment of Organic Resources and Waste Management', June 12-15, Rennes, France, 71-76.

Vandecasteele, B., Willekens, K., Du Laing, G., De Vliegher, A., Tack, F. M. G., Carlier, L., 2008. The use of ground bark and wood chips from a short rotation plantation for on farm composting: effect of tree species on the micronutrient content. In: Proceedings of the 6th International Conference ORBIT2008, 'Moving Organic Waste Recycling Towards Resource Management and Biobased Economy', October 13-15, Wageningen, the Netherlands, 776-782.

Vandecasteele, B., Willekens, K., Du Laing, G., Van Waes, J., Tack, F.M.G., 2014. Designer compost: facts or fantasy? A case study on compost rich in lignin and low in phosphorus. In: Biala, J., Prange, R., Raviv, M. (eds.) Proceedings of the I International Symposium on Organic Matter Management and Compost Use in Horticulture 2011, April 4-7, 2011, Adelaide, Australia. ISHS, Acta Horticulturae 1018, 683-692.

Vandecasteele, B., Willekens, K., Du Laing, G., Van Waes, J., Tack, F.M.G., 2014. Effect of feedstock, organic matter content and pH on Cd, Zn and Mn availability in farm compost based on bark and wood chips. In: Biala, J., Prange, R., Raviv, M. (eds.) Proceedings of the I International Symposium on Organic Matter Management and Compost Use in Horticulture 2011, April 4-7, Adelaide, Australia. ISHS, Acta Horticulturae 1018, 661-668.

Vandecasteele, B., Willekens, K., Van Delm, T., Van Waes, J., Baets, W., 2014. Changes in chemical and physical properties of compost-amended growing media during strawberry cropping: monitoring depletion of nutrients with petiole sap measurements. In: Biala, J., Prange, R., Raviv, M. (eds.) Proceedings of the I International Symposium on Organic Matter Management and Compost Use in Horticulture 2011, April 4-7, Adelaide, Australia. ISHS, Acta Horticulturae 1018, 541-549.

Viaene, J., Nelissen, V., Vandecasteele, B., Willekens, K., De Neve, S., Reubens, B., 2015. Composting or ensiling cattle slurry solid fraction to improve product quality and limit nutrient losses. RAMIRAN 2015 - 16th International Conference, 'Rural-Urban Symbiosis', September 8-10, Hamburg University of Technology, Germany, Proceedings article, 4p.

Viaene, J., Reubens, B., Vandecasteele, B., Willekens, K., De Neve, S., 2013. Valorisation of by-products from agriculture and nature management: Opportunities for potting media, composting or as soil improver. In: Proceedings of RAMIRAN 2013, 'Recycling of Organic Residues in Agriculture: From Waste Management to Ecosystem Services', June 3-5, Versailles, France, 5p.

Willekens, K., De Neve, S., Vandecasteele, B., Carlier, L., 2009. Nitrogen dynamics on horticultural land with a late season leek croIn: Acutis, M., Grignani, C., Zavattarro, L. (eds.) Proceedings of the 16th Nitrogen Workshop 'Connecting different scales of Nitrogen Use in Agriculture', June 28 - July 1, Turin, Italy, 287-288.

Willekens, K., De Vliegher, A., Vandecasteele, B., Carlier, L., 2008. Effect of Compost versus Animal Manure Fertilization on Crop Development, Yield and Nitrogen Residue in the Organic Cultivation of Potatoes. In: Proceedings of the 2nd ISOFAR Scientific Conference, 'Cultivating the Future based on Science', at the 16th IFOAM Organic World Congress, June 18-20, Modena, Italy, Vol. 1, 576-579.

Willekens, K., De Vliegher, A., Vandecasteele, B., Ruysschaert, G., Carlier, L., 2008. Multiyear experiment with fertilization and soil tillage in an organic arable crop rotation. Proceedings of the 4th International QLIF Training and Exchange workshop 'Soil Nitrogen: Research and Extension', February 13-15, Louis Bolk Institute, Driebergen, The Netherlands, 2p.

Willekens, K., Desmet, E., Vandecasteele, B., Carlier, L., Baets, W., 2007. Influence of compost and organic versus mineral fertilization in an autumn strawberry crop on growing medium in a glasshouse. Proceedings of the 16th International Symposium of the International Scientific Centre for Fertilisers (CIEC), 'Mineral versus Organic Fertilization, Conflict or Synergism?', September 16-19, Faculty of Bioscience Engineering, Ghent University, Belgium, 534-539.

Willekens, K., Reubens, B., Vandecasteele, B., Beeckman, A., Delanote, L., De Neve, S., 2012. N availability from pre-treated chicken and goat manure in an organic cropping system. In: Richards, K.G., Fenton, O., Watson, C.J. (eds.) Proceedings of the 17th International Nitrogen Workshop, Innovations for sustainable use of nitrogen resources, June 26-29, Wexford, Ireland, 154-155.

Willekens, K., Van Gils, B., De Vliegher, A., Delanote, L., Beeckman, A., Vandecasteele, B., 2014. The effect of tillage practices on a leek crop's nitrogen utilisation from a grass-clover sward. In: Rahmann, G., Aksoy, U. (eds.) Proceedings of the 4th ISOFAR Scientific Conference, 'Building Organic Bridges', at the 18th IFOAM Organic World Congress, 13-15 October, Istanbul, Turkey. Thünen Report 20, 57-60.

Willekens, K., Vandecasteele, B., De Neve, S., 2012. N dynamics and priming effect in horticultural fields as influenced by application of mineral fertilizer N. In: Richards, K.G., Fenton, O., Watson, C.J. (eds.) Proceedings of the 17th International Nitrogen Workshop, Innovations for sustainable use of nitrogen resources, June 26-29, Wexford, Ireland, 156-157.

Willekens, K., Vandecasteele, B., De Neve, S., 2013. Strong effect of compost and reduced tillage on C dynamics but not on N dynamics in a vegetable cropping system. In: D'Haene, K., Vandecasteele, B., De Vis, R. Crappé, S., Callens, D., Mechant, E., Hofman, G., De Neve, S. (eds.) Proceedings NUTRIHORT: Nutrient management, innovative techniques and nutrient legislation in intensive horticulture for an improved water quality, September 16-18, Ghent, Belgium, 162-169.

Willekens, K., Vandecasteele, B., De Neve, S., 2015. Sustaining soil quality by farm compost application and non-inversion tillage, and resulting nitrogen dynamics. RAMIRAN 2015 - 16th International Conference, 'Rural-Urban Symbiosis', September 8-10, Hamburg University of Technology, Germany, Proceedings article, 4p.

Willekens, K., Vandecasteele, B., De Vliegher, A., 2014. Soil quality and crop productivity as affected by different soil management systems in organic agriculture. In: Rahmann, G., Aksoy, U. (eds.) Proceedings of the 4th ISOFAR Scientific Conference, 'Building Organic Bridges', at the 18th IFOAM Organic World Congress, 13-15 October, Istanbul, Turkey. Thünen Report 20, 65-68.

Conferences and Symposia

Bufe, C., Willekens, K., Van Gils, B., Delfosse, P., 2014. GHG emissions and soil quality in differently tilled soils at an organic experimental field at ILVO (Merelbeke, Belgium). ELS 2014, The Earth Living Skin: Soil, Life and Climate Changes, September 22-25, Bari, Italy. Book of Abstracts.

D'Hose, T., Ruysschaert, G., Nelissen, V., De Vliegher, A., Willekens, K., Vandecasteele, B., 2013. The use of compost and biochar to increase soil organic carbon content without increasing nutrient leaching. International Conference Biochars, Composts, and Digestates, October 17-20, Bari, Italy. Book of Abstracts.

D'Hose, T., Ruysschaert, G., Van Vaerenbergh, J., De Vliegher, A., Goeminne, M., Willekens, K., 2014. The effect of soil improving practices on potato yield, quality and diseases in slurry fertilized land. In: 19th Triennial Conference of the European Association for Potato Research. July 6-11, Brussels, Belgium. Abstracts Book.

Steel, H., Bert, W., de la Peña, E., Fonderie, P., Willekens, K., Borgonie, G., 2008. Nematode Succession during Controlled Microbial Composting. Fifth International Congress of Nematology, July 13-18, Brisbane, Australia. Book of Abstracts.

Steel, H., de la Peña, E., Fonderie, P., Willekens, K., Borgonie, G., Bert, W., 2009. Nematode Community as potential indicator of compost maturity and quality. 61st International Symposium on Crop Protection, May 19, Ghent, Belgium. Book of Abstracts.

Viaene, J., Nelissen, V., Vandecasteele, B., Willekens, K., De Neve, S., Reubens, B., 2015. Limiting nutrient losses and improving product quality during storage of cattle manure by composting and ensiling. RAMIRAN 2015 - 16th International Conference, 'Rural-Urban Symbiosis', September 8-10, Hamburg University of Technology, Germany, Abstract book, ISBN: 978-3-941492-95-0, p 126.

Viaene, J., Reubens, B., Vandecasteele, B., Willekens, K., De Neve, S., 2013. Removing vegetable crop residues for composting and ensilaging: effects on N, P and organic matter. NUTRIHORT: Nutrient management, innovative techniques and nutrient legislation in intensive horticulture for an improved water quality, September 16-18, Ghent, Belgium. Book of Abstracts.

Viaene, J., Reubens, B., Vandecasteele, B., Willekens, K., De Neve, S., 2013. Use of by-products as system innovation: GeNeSys: Closing cycles trough composting. 9th International Conference on Renewable Resources & Biorefineries, June 5-7, Antwerp, Belgium. Book of Abstracts.

Viaene, J., Van Lancker, J., Reubens, B., Vandecasteele, B., Willekens, K., 2014. Composting: the solution to closing cycles and improving soil quality in the transition towards a bio-economy? ISEE Conference, August 13-15, Reykjavik, Iceland. Book of Abstracts.

Willekens, K., De Neve, S., Vandecasteele, B., Chaves, B., Carlier, L., 2008. Immobilization of Nitrogen Released from Incorporated Crop Residues by Low Doses of High Quality Refined Products. Second International Conference on Soil and Compost Eco-Biology soilACE2008, November 26-29, Puerto de la Cruz, Tenerife, Spain, Book of Abstracts.

Willekens, K., De Neve, S., Vandecasteele, B., Van Waes, J., 2010. Effect of Probiotica or Biostimulators on N-Release out of Incorporated Crop Residues. Symposium 14 Organic Horticulture: productivity and sustainability at the 28th International Horticultural Congress, Lisbon, August 22-27. Abstracts Volume II.

Willekens, K., Reubens, B., Vandecasteele, B., Beeckman, A., Delanote, L., De Neve, S., 2013. Crop response of leek on fertilizer N from raw and composted chicken manure in organic horticulture. NUTRIHORT: Nutrient management, innovative techniques and nutrient legislation in intensive horticulture for an improved water quality, September 16-18, Ghent, Belgium. Book of Abstracts.

Willekens, K., Van Gils, B., Delanote, L., Beeckman, A., 2014. Potential of grass-clover as a green-manure and a cut-and-carry fertilizer under conventional and reduced tillage regimes in organic vegetable production. In Fliessbach, A. (ed.) Reduced Tillage and Green Manures for Sustainable Organic Cropping Systems. TILMAN-ORG Final meeting, June 25-27, Lyon, France, Book of Abstracts.

Willekens, K., Viaene, J., Nelissen, V., Reubens, B., De Neve, S., Vandecasteele, B., 2015. Vegetable crop residues as feedstock for composting and silage - Production cost and product quality. RAMIRAN 2015 - 16th International Conference, 'Rural-Urban Symbiosis', September 8-10, Hamburg University of Technology, Germany, Abstract book, ISBN: 978-3-941492-95-0, p 62.

Willekens, K., Vandecasteele, B., De Neve, S., 2013. Factors affecting nitrogen residue on intensively cultivated fields with high N demanding vegetable crops in the rotation. In: Fontana E., Grignani, C., Silvana, N. (eds.) International workshop on Nitrogen, Environment and Vegetables NEV2013, April 15-17, Turin, Italy. Book of Abstracts.

Willekens, K., Vandecasteele, B., Van Gils, B., De Vliegher, A., Delanote, L., Beeckman, A., De Neve, S., 2013. Nutrient utilization from a grass-clover sward by a leek crop in relation to time and tillage practices. 7th ORC Organic Producers Conference, 'Making producer-led innovation a reality', January 22-23, Birmingham, United Kingdom. Book of Abstracts.

Scientific reports

Agneessens, L., Vandecasteele, B., Van De Sande, T., Goovaerts, E., Crappé, S., Elsen, A., Willekens, K., De Neve,.S., 2014. Onderzoek naar het beheer van oogstresten bij vollegrondsgroenten en mogelijkheden van vanggewassen en teeltrotaties met het oog op de waterkwaliteitsdoelstellingen van het Actieprogramma 2011-2014 (MAP4): Hoofdrapport, Studie uitgevoerd in opdracht van de Vlaamse Landmaatschappij (VLM), 149 p.

Amery, F., Vandecasteele, B., De Vis, R., Crappé, S., Van de Sande, T., Mechant, E., De Bolle, S., Willekens, K., De Neve, S., 2013. Fact sheets from the benchmark study on innovative techniques and strategies for reduction of nutrient losses in horticulture. NUTRIHORT - Nutrient management, innovative techniques and nutrient legislation in intensive horticulture for an improved water quality. September 16-18, 2013, Ghent. September 16-18, 2013, Ghent, 130 p. ISBN: 978-9040303470

Beeckman, A., Delanote, L., Reubens, B., De Neve, S., Vandecasteele, B., Willekens, K., 2012. Krijgen we de kring rond met biologische dierlijke mest? Resultaten van een bemestingsproef in prei. Deelrapport 2, ADLO-onderzoeksproject ‘Optimale aanwending van biologische mest van kippen en herkauwers voor een gezond biologisch gewas’. 25 p.

Coopman, F., Van Nevel, B., Van de Sande, T., Verhaeghe, M., De Reycke, L., Crappé, S., De Nies, J., Goovaerts, E., Elsen, A., Bries, J., Vandendriessche, H., De Neve, S., Ameloot, N., Willekens, K., Van Haecke, D., Boonen, M., Druyts, N., Van Mechelen, M., 2014. Het documenteren en milieukundig bijstellen van het KNS en andere bemestingsadviessystemen in de tuinbouw met het oog op een ruimere toepassing in de tuinbouw zoals voorzien in het Actieprogramma 2011-2014 (MAP4): Eindrapport, Studie uitgevoerd in opdracht van de Vlaamse Landmaatschappij (VLM), 233 p.

Nelissen, V., Viaene, J., Reubens, B., Vandecasteele, B., Willekens, K., 2015. Optimaliseren van de opslag en bewerking van runderstalmest op de kopakker. ILVO-studie met financiële ondersteuning van Boerenbond, 49 p.

Reubens, B., Vandecasteele, B., De Neve, S., Willekens, K., 2012. Behandeling van biologische dierlijke mest door compostering: resultaat van praktijkproeven. Deelrapport 1, ADLO-onderzoeksproject ‘Optimale aanwending van biologische mest van kippen en herkauwers voor een gezond biologisch gewas’. 62 p.

Reubens, B., Willekens, K., 2012. Beschikbaarheid en gebruik van biologische dierlijke mest in Vlaanderen: actuele situatie en toekomstperspectief. Deelrapport 3, ADLO-onderzoeksproject ‘Optimale aanwending van biologische mest van kippen en herkauwers voor een gezond biologisch gewas’. 84 p.

Reubens, B., Willekens, K., Beeckman, A., De Neve, S., Vandecasteele, B., Delanote, L., 2013. Optimale aanwending van biologische mest voor een gezond biologisch gewas: eindrapport. ILVO mededeling nr. 114, Instituut voor Landbouw- en Visserijonderzoek.

Ruysschaert, G., Vandecasteele, B., Willekens, K., Van Waes, J., Van Laecke, K., 2014. Bodem, nutriënten en compost: onderzoek voor een duurzame landbouw. ILVO Mededeling nr. 171, Instituut voor Landbouw- en Visserijonderzoek.

Vanden Nest, T., Vandaele, E., Lebuf, V., Snauwaert, E., Vanden Auweele, W., Willekens, K., Van Waes, C., Vandecasteele, B., 2015. De compostering van dikke fractie van digestaat. Het composteringsproces en karakterisering van de eindproduten.. 83 p.

Vanden Nest, T., Vandecasteele, B., Willekens, K., De Vliegher, A., Van Waes, C., 2014. Bepaling bemestingswaarde van verschillende vormen van digestaat. 50 p.

Viaene, J., Nelissen, V., Reubens, B., Vandecasteele, B., Willekens, K., 2015. Optimaliseren van de opslag en behandeling van vaste rundermest via compostering of inkuilen (Optimanure). Procesverloop en productkwaliteit. ILVO-studie met financiële ondersteuning van VCM, Boerenbond, Agriton en Orffa, 77 p.

Viaene, J., Nelissen, V., Reubens, B., Vandecasteele, B., Willekens, K., 2015. Optimaliseren van de opslag en behandeling van vaste rundermest via compostering of inkuilen (Optimanure). Bijlage: Effect van eindproducten op N mineralisatie en gewasopbrengst van Engels raaigras. ILVO-studie met financiële ondersteuning van VCM, Boerenbond, Agriton en Orffa, 9 p.

Viaene, J., Reubens, B., Vandecasteele, B., Willekens, K., 2014. Composteren als valorisatievorm van reststromen in de Vlaamse land- en tuinbouw: Knelpunten en opportuniteiten. ILVO mededeling nr. 167, Instituut voor Landbouw- en Visserijonderzoek.

Willekens, K., Vandecasteele, B., De Neve, S., 2010. Stikstofbenutting en gewaskwaliteit in functie van bodemconditie. Onderzoeksrapport 1. SYMBIOS-ILVO project, basisonderzoek bodem en bemesting. 10 p.

Willekens, K., Vandecasteele, B., De Neve, S., 2011. Stikstofbenutting en gewaskwaliteit in functie van bodemconditie. Onderzoeksrapport 2. SYMBIOS-ILVO project, basisonderzoek bodem en bemesting. 16 p.

Willekens, K., Vandecasteele, B., De Neve, S., 2012. Stikstofbenutting en gewaskwaliteit in functie van bodemconditie. Onderzoeksrapport 3. SYMBIOS-ILVO project, basisonderzoek bodem en bemesting. 20 p.

Chapters in scientific reports

Debode, J., De Tender, C., Wesemael, W., Viaene, N., Van Vaerenbergh, J., Heungens, K., Willekens, K., D'Hose, T., Ruysschaert, G., Vandecasteele, B., Maes, M., 2014. Bodembeheer in functie van ziekteweerbaarheid. In: Ruysschaert, G., Vandecasteele, B., Willekens, K., Van Waes, J., Van Laecke, K. (eds.) Bodem, nutriënten en compost: Onderzoek voor een duurzame landbouw. ILVO mededeling, nr. 171, Instituut voor Landbouw- en Visserijonderzoek. blz. 52-63.

D'Hose, T., Cougnon, M., De Vliegher, A., Vandecasteele, B., Willekens, K., Viaene, N., Dereycke, V., Haessaert, G., Cornelis, W., Van Bockstaele, E., Reheul, D., 2014. De relatie tussen duurzaam bodembeheer, bodemkwaliteit en gewasopbrengst: het gebruik van boerderijcompost en gewasrotatie. In: Ruysschaert, G., Vandecasteele, B., Willekens, K., Van Waes, J., Van Laecke, K. (eds.) Bodem, Nutriënten en Compost: Onderzoek voor een Duurzame Landbouw. ILVO Mededeling, nr. 171, Instituut voor Landbouw- en Visserijonderzoek, blz. 3-19.

Koopmans, C., P. Rietberg, K. Willekens, M. Grosse, J. Heß, W. Sukkel, F. X. Sans, C. David, B. van Gils, L. Talgre, P. Baldivieso Freitas, C. Amosse, F. Celette, D. van Balen, W. Haagsma, P. van Asperen, W. van den Berg , G. van der Burgt, A. Luik. 2014. Effect of grass clover ley, green manure and off-farm inputs on nutrient dynamics and crop performance under reduced tillage: Final-report for the CORE Organic II funded project. Work package 5.1. 2014-032 LbP Editie, Louis Bolk Instituut.

Pannecoucque, J., Van Waes, J., Willekens, K., 2010. Bio-relevant onderzoek bij rassenproeven van graangewassen voor de nationale rassencatalogus. In: De Cock, L., Erbout, N., Van Waes, J. (eds.) De biologische landbouw in Vlaanderen Onderzoek 2008-2010. NOBL - Netwerk Onderzoek Biologische Landbouw en Voeding, blz. 74-75.

Pannecoucque, J., Van Waes, J., Willekens, K., 2010. Rassenbeproeving van kuilmaïs voor de biologische teelt. In: De Cock, L., Erbout, N., Van Waes, J. (eds.) De biologische landbouw in Vlaanderen Onderzoek 2008-2010. NOBL - Netwerk Onderzoek Biologische Landbouw en Voeding, blz. 80-81.

Reubens, B., Willekens, K., 2010. Optimaal gebruik van biologische mest van kippen en herkauwers voor een gezond biologisch gewas. In: De Cock, L., Erbout, N., Van Waes, J. (eds.) De biologische landbouw in Vlaanderen Onderzoek 2008-2010. NOBL - Netwerk Onderzoek Biologische Landbouw en Voeding, blz. 42-43.

Reubens, B., Willekens, K., 2012. Optimaal gebruik van biologische mest van kippen en herkauwers voor een gezond biologisch gewas. In: De Cock, L., Van Waes, J. (eds.) De Biologische landbouw in Vlaanderen: Onderzoek 2011-2012. NOBL - Netwerk Onderzoek Biologische Landbouw en Voeding, blz. 38-39.

Reubens, B., Willekens, K., Vandecasteele, B., Nelissen, V., Viaene, J., 2014. Naar een optimalisatie van de opslag en behandeling van kippenmest en vaste rundermest via compostering. In: Ruysschaert, G., Vandecasteele, B., Willekens, K., Van Waes, J., Van Laecke, K. (eds.) Bodem, Nutriënten en Compost: Onderzoek voor een Duurzame Landbouw. ILVO Mededeling, nr. 171, Instituut voor Landbouw- en Visserijonderzoek, blz. 200-215.

Ruysschaert, G., D'Hose, T., Willekens, K., De Vliegher, A., Vandecasteele, B., Cornelis, W., Goeminne, M., Van Vaerenbergh, J., Viaene, N., 2014. Effect van niet-kerende bodembewerking en composttoepassing op de bodemkwaliteit, ziektedruk en gewasopbrengst in een gangbaar teeltsysteem met drijfmest - resultaten van de meerjarige BOPACT-proef. In: Ruysschaert, G., Vandecasteele, B., Willekens, K., Van Waes, J., Van Laecke, K. (eds.) Bodem, Nutriënten en Compost: Onderzoek voor een Duurzame Landbouw. ILVO Mededeling, nr. 171, Instituut voor Landbouw- en Visserijonderzoek, blz. 29-40.

Ruysschaert, G., Vandecasteele, B., D'Hose, T., Willekens, K., 2014. Niet-kerende bodembewerking, compost en biochar als bodemverbeterende praktijken. In: De Cock, L. (ed.) in De biologische landbouw in Vlaanderen : Onderzoek 2013-2014. NOBL - Netwerk Onderzoek Biologische Landbouw en Voeding, blz. 38-39.

Ruysschaert, G., Vandecasteele, B., Willekens, K., 2012. Organische stofbeheer en niet-kerende bewerking voor een duurzaam bodemgebruik. In: De Cock, L., Van Waes, J. (eds.) De Biologische landbouw in Vlaanderen: Onderzoek 2011-2012. blz. 30-31.

Viaene, J., Reubens, B., Willekens, K., Vandecasteele, B., 2014. GeNeSys: Valorisatie van groene en bruine nevenstromen op het landbouwbedrijf. In: Ruysschaert, G., Vandecasteele, B., Willekens, K., Van Waes, J., Van Laecke, K. (eds.) Bodem, Nutriënten en Compost: Onderzoek voor een Duurzame Landbouw. ILVO Mededeling nr. 171, Instituut voor Landbouw- en Visserijonderzoek, blz. 216-223.

Willekens, K., 2007. De invloed van de bemesting op de knolkwaliteit, % droogrot tijdens de bewaring en % niet uitlopers bij de gezonde knollen. In: Verslag onderzoeksresultaten 2006-2007 voor de Afdeling Duurzame Landbouwontwikkeling van het Departement Landbouw en Visserij, 4 p.

Willekens, K., De Vliegher, A., 2010. Boerderijcompost getest als hoofdbemesting in een meerjarige biologische akkerbouwrotatie. In: De Cock, L., Erbout, N., Van Waes, J. (eds.) De biologische landbouw in Vlaanderen Onderzoek 2008-2010. NOBL - Netwerk Onderzoek Biologische Landbouw en Voeding, blz. 44-45.

Willekens, K., De Vliegher, A., Debode, J., 2014. Bodembeheer en bodemkwaliteit in biologische teeltsystemen: kwestie van combineren, observeren en kwantificeren. In: De Cock, L. (ed.) De biologische landbouw in Vlaanderen : Onderzoek 2013-2014. NOBL - Netwerk Onderzoek Biologische Landbouw en Voeding, blz. 34-35.

Willekens, K., De Vliegher, A., Van Gils, B., 2012. Bodembeheer en bodemkwaliteit in biologische teeltsystemen. In: De Cock, L., Van Waes, J. (eds.) De Biologische Landbouw in Vlaanderen: Onderzoek 2011-2012. NOBL - Netwerk Onderzoek Biologische Landbouw en Voeding, blz. 32-33.

Willekens K., De Vliegher A., Vandecasteele B., Carlier L., 2007. Grote verschillen in gewasontwikkeling, opbrengst en stikstofresidu bij de biologische teelt van aardappelen in relatie tot de aard van de organische bemesting: compost versus dierlijke mest. In: Overzicht van het onderzoek biologische landbouw 2006 in Vlaanderen, Ed. Interprovinciaal Proefcentrum Voor De Biologische Teelt (PCBT), blz. 98-100.

Willekens, K., Reubens, B., Vandecasteele, B., Viaene, J., 2012. Waarde van compost voor de bodemvruchtbaarheid. In: De Cock, L., Van Waes, J. (eds.) De Biologische Landbouw in Vlaanderen: Onderzoek 2011-2012. NOBL - Netwerk Onderzoek Biologische Landbouw en Voeding, blz. 34-35.

Willekens, K., Van Gils, B., De Vliegher, A., Delanote, L., Beeckman, A., Vandecasteele, B., 2014. Niet-kerende bodembewerking en groenbemesting in de biologische landbouw. In: Ruysschaert, G., Vandecasteele, B., Willekens, K., Van Waes, J., Van Laecke, K. (eds.) Bodem, Nutriënten en Compost: Onderzoek voor een Duurzame Landbouw. ILVO Mededeling, nr. 171, Instituut voor Landbouw- en Visserijonderzoek, blz. 41-51.

Willekens, K., Vandecasteele, B., De Neve, S., 2014. Effecten van niet-kerende bodembewerking en composttoepassing op de bodemkwaliteit en de stikstofdynamiek in de intensieve groenteteelt - Resultaten van de meerjarige Vegtilco-proef. In: Ruysschaert, G., Vandecasteele, B., Willekens, K., Van Waes, J., Van Laecke, K. (eds.) Bodem, Nutriënten en Compost: Onderzoek voor een Duurzame Landbouw. ILVO Mededeling, nr. 171, Instituut voor Landbouw- en Visserijonderzoek, blz. 20-28.

Willekens, K., Vandecasteele, B., De Neve, S., 2014. 'Onderzoek naar stikstofdynamiek in relatie tot bodemconditie'. In: De Cock, L. (ed.) De biologische landbouw in Vlaanderen : Onderzoek 2013-2014. NOBL - Netwerk Onderzoek Biologische Landbouw en Voeding, blz. 54-55.

Vulgarization publications

Beeckman, A., Delanote, L., Willekens, K., Reubens, B., 2012. Bodem doet meer dan mest in biologische prei. *Proeftuinnieuws*, nr. 12, blz. 30-31.

Beeckman, A., Willekens, K., 2015. Roller-crimper, een nieuwe techniek om groenbedekkers te vernietigen. *BIOpraktijk – juni 2015*. 2 p.

D'Hose, T., Willekens, K., Ruysschaert, G., 2014. Werken aan bodemkwaliteit. *Management & Techniek*, vol 19, blz. 23-24.

Reubens, B., Viaene, J., Nelissen, V., Vandecasteele, B., Willekens, K., 2014. Lukt composteren en inkuilen van vaste mest? *Management & Techniek*, nr. 22, blz. 34-35.

Reubens, B., Willekens, K., Vandecasteele, B., 2012. Kringlopen sluiten met biologische kippenmest: uitdagingen en kansen. *Pluimvee*, blz. 6-8.

Reubens, B., Willekens, K., Vandecasteele, B., 2012. Naar een optimaal gebruik van biologische mest van kippen en geiten via compostering? *bioKennis bericht*, vol Bodemvruchtbaarheid 04, blz. 1-4.

Van Gils, B., Willekens, K., Beeckman, A., Delanote, L., 2014. Onderzoek naar niet-kerende bodembewerking en groenbemesters: resultaten veldproeven 2013. *Proeftuinnieuws*, nr. 11, blz. 34-35.

Van Gils, B., Willekens, K., Delanote, L., Beeckman, A., 2013. Onderzoek naar niet-kerende bodembewerking en groenbemesters: resultaten veldproeven 2012. *BIOpraktijk – feb2013*, 3 p.

Van Gils, B., Willekens, K., Delanote, L., Beeckman, A., 2014. Onderzoek naar niet-kerende bodembewerking en groenbemesters: resultaten veldproeven 2013. *BIOpraktijk – apr2014*, 3 p.

Vandermersch, M., Gillijns, K., Ruysschaert, G., Willekens, K., Vermang, J., Swerts, M., Van de Ven, G., Vandergeten, J., Coopman, F., Pollentier, A., Coussement, T., De Reycke, L., Winnepeninckx, R., Haesaert, G., Govers, G., 2014. Niet-kerende bodembewerking: wat leren de veldproeven in Vlaanderen ons? *Landbouwleven*, 30/08/2014. 1 p.

Willekens, K., 2007. Bodembiologie inzetten in land- en tuinbouw. *Seizoenen* april-mei, blz. 27-30.

Willekens, K., 2007. Afsluitende vergadering FarmCOMPOST. *Landbouwleven* 29/06/2007. 1 p.

Willekens, K., 2007. Boerderijcompostering in Vlaanderen. *Boer&Tuinder* 06/07/2007. 1 p.

Willekens, K., 2008. Gewasbescherming door bodembeheer. *Landbouw en Techniek* nr. 10, blz. 41-43.

Willekens, K., 2015. Maaimeststoffen, een nieuwe plantaardige bemestingsvorm te winnen op het eigen bedrijf. *BIOpraktijk – juni 2015*. 1 p.

Willekens, K., Janmaat, L., 2014. Compost levert complete bemesting. *bioKennis bericht*, vol Bodemvruchtbaarheid 05, blz. 1-4.

Willekens, K., Janmaat, L., 2014. Wat is goede compost? *bioKennis bericht* , vol Bodemvruchtbaarheid 06, blz. 1-4.

Willekens, K., Sukkel, W., van Balen, D., 2014. Gereduceerde bodembewerking voor biologische teelten. vol. 07, *bioKennis bericht*, vol Bodemvruchtbaarheid 07, blz. 1-4.

Willekens, K., Van Gils, B., Beeckman, A., 2014. Biologische telen met NKG en groenbedekkers. *Management & Techniek*, nr. 21, blz. 11-13.

Winnepeninckx, R., Volckaert, A., Willekens, K., 2010. Invloed van bodembewerking en koolstofinput op de opbrengst van ijsbergsla. *Proeftuinnieuws* nr. 21, blz. 36-37.

Current and previous research and knowledge transfer projects

Agneessens, L., Vandecasteele, B., Van De Sande, T., Goovaerts, E., Crappé, S., Elsen, A., Willekens, K., De Neve,.S., 2012-2014. Onderzoek naar het beheer van oogstresten bij vollegrondsgroenten en mogelijkheden van vanggewassen en teeltrotaties met het oog op de waterkwaliteitsdoelstellingen van het Actieprogramma 2011-2014 (MAP4). VLM-project.

Bijttebier, J., Schotte, L., Strubbe, M., Willekens, K., Marchand, F., 2012-2015. Bio in beeld: ontwikkelen van kengetallen via systeemgericht onderzoek en participatorisch traject. ADLO-project.

Coopman, F., Van Nevel, B., Van de Sande, T., Verhaeghe, M., De Reycke, L., Crappé, S., De Nies, J., Goovaerts, E., Elsen, A., Bries, J., Vandendriessche, H., De Neve, S., Ameloot, N., Willekens, K., Van Haecke, D., Boonen, M., Druyts, N., Van Mechelen, M., 2012-2014. Het documenteren en milieukundig bijstellen van het KNS en andere bemestingsadviessystemen in de tuinbouw met het oog op een ruimere toepassing in de tuinbouw zoals voorzien in het Actieprogramma 2011-2014 (MAP4). VLM-project.

Reubens, B., Willekens, K., De Neve, S., Buchan, D., Delanote, L., Beeckman, A., 2010 -2012. Optimale aanwending van biologische mest van kippen en herkauwers voor een gezond biologisch gewas. ADLO-project.

Willekens, K., 1999-2002. Nutriëntenstromen en mineralenbalansen op biologische en gangbare melkveebedrijven. DWTC-project.

Willekens, K., 2002-2003. Traceerbaarheid doorheen de biologische productieketen. ALT-studie.

Willekens, K., De Ridder K., Delanote, L., Cornelissen, K., Krosenbrink, E., 2004. Begeleiding en ontwikkeling van de werking van de databank 'biologisch zaaizaad en vegetatief teeltmateriaal' in de opstartfase. ALT-project.

Willekens, K., Debode, J., Beeckman, A., Vercammen, J., Landuyt, C., Hendrickx, Y., Dewitte, J., Dhoore, K., 2014-2015. Effecten van bodembeheer en bemesting op de bodemmicrobiologie. Zoektocht naar een eenvoudige indicator voor bodemkwaliteit. CCBT-project.

Willekens, K., Jamart, A., Vandevannet, N., Bouden, D., 2003-2007. Technologische adviseerdienst FarmCOMPOST. IWT-project. Cofinanciering telerorganisatie SYMBIOS.

Willekens, K., Nelissen, V., De Neve, S., Ameloot, N., Delanote, L., Beeckman, A., Vervisch, B., Dewitte, J., 2015-2017. Stikstofwerking van maaimeststoffen in relatie tot toedieningswijze en bodemconditie. ADLO-project.

Willekens, K., Van Gils, B., Delanote, L., Beeckman, A., 2011-2014. Reduced Tillage and Green Manures for Sustainable Organic Cropping Systems - TILMAN-ORG, CORE Organic II ERA-NET.

Willekens, K., Van Waes, J., Casteels, H., De Swaef, T., Debode, J., Lootens, P., Viaene, N., Wesemael, W., Witters, J., De Neve, S., Ameloot, N., Delanote, L., Beeckman, A., Vervisch, B., 2015-2018. Improving soil conservation and resource use in organic cropping systems for vegetable

production through introduction and management of Agro-ecological Service Crops (ASC's) – SOILVEG. CORE Organic PLUS ERA-NET.

Willekens, K., Vandenhecke, K., Marynissen, B., Delanote, L., Cornelissen, K., Krosenbrink, E., 2006-2007. Technische en inhoudelijke aanpassingen van een databank biozaad gekoppeld aan www.organicXseeds.be. ALT-project.

Supervision of graduate and master students

Bert, W., Borgonie, G. Willekens, K., 2007. Karakterisering en populatiedynamiek van nematoden in een composteringsproces. Scriptie Steel, H., Master/ Licentiaat in de Biologie, Richting Dierkunde, academiejaar 2006-2007, Universiteit Gent, Faculteit van de Wetenschappen, Vakgroep Biologie.

Cornelis, W., Willekens, K., 2011. Impact of tillage and compost on soil quality and crop yield of a sandy loam soil in Belgium. Dissertation Ngantcha Ngantcha D., Master of Science in Physical Land Resources, academic year 2012-2013, Interuniversity Programme University Ghent and Vrije Universiteit Brussel.

Mekers, O., Willekens, K., 2007. Effect van compostsubstraat en compostthee op de teelt van keukenkruiden in pot. Afstudeerproject Dewitte, J., Industrieel Ingenieur in Landbouw en Biotechnologie, Optie tuinbouw, academiejaar 2006-2007, Hogeschool Gent, Departement Biowetenschappen en Landschapsarchitectuur.

Op De Beeck, A.M., Willekens, K., 2007. Boerderijcompost als alternatief voor dierlijke mest. Afstudeerproject Bloeyaert, K., Bachelor Agro- en Biotechnologie, academiejaar 2006-2007, Hogeschool Gent, Departement Biowetenschappen en Landschapsarchitectuur.